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DIVISIÓN DE EDUCACIÓN CONTINUA

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CURSOS INSTITUCIONALES

DIPLOMADO EN MEDICIÓN DE HIDROCARBUROS

MOD. III SISTEMAS DE GAS NATURAL Y L.P.G.

Del 15 al 19 de octubre de 2001

APUNTES GENERALES

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DIPLOMADO DE MEDICION DE HIDROCARBUROS.
SISTEMAS DE MEDICION DE GAS NATURAL BAJO NORMA API.

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Densidad de una mezcla de líquidos ideales

La densidad de una mezcla de líquidos ideales (aquellos que al mezclarse no reducen su volumen) puede calcularse a partir de:

$$\frac{1}{\rho\text{mezcla}} = \frac{X_1}{\rho_1} + \frac{X_2}{\rho_2} + \dots + \frac{X_n}{\rho_n}$$

X_n = fracción masa del líquido n.
ρ_n = densidad del líquido puro n.

Densidad en los gases

La manera común de obtener la densidad de un gas es a través de una ecuación de estado que relaciona su presión, temperatura y volumen. Los gases ideales obedecen la ecuación:

$$PV = nRT = \frac{M}{PM}RT$$

$$\rho\text{gas} = \frac{M}{V}$$

$$\rho\text{gas} = \frac{P \cdot PM}{RT}$$

P = presión$(=)ML^{-1}\,\theta^{-2}$
V = volumen$(=)L^3$
T = temperatura$(=)T$
R = constante de los gases (tabla II, apéndice)
n = número de moles
M = masa $(=)$ M
PM = peso molecular$(=)M\,mol^{-1}$

Los gases siguen esta ley a temperaturas reducidas mayores de 2 y a presiones reducidas menores de 1, es decir, a presiones menores de 10 atm y temperaturas mayores a 0°C.

$$Pr = \frac{P}{Pc} \qquad Tr = \frac{T}{Tc}$$

Pr = presión reducida $(=)$ adimensional
Pc = presión crítica $(=)$ $ML^{-1}\,\theta^{-2}$ $(=)$ FL^{-2}
Tr = temperatura reducida $(=)$ adimensional
Tc = temperatura crítica $(=)$ T

Table 6.1 Flowmeter Selection Table

		Gases (vapors)		Liquids					
								Slurries	
Flowmeter	**Pipe size, in (mm)**	Clean	Dirty	Clean	Viscous	Dirty	Corrosive	Fibrous	Abrasive
		SQUARE-ROOT SCALE: MAXIMUM SINGLE RANGE 4:1							
Orifice		□	□	□	□	□	□	□	□
Square-edged	>1 5 (40)	■	□	■	□	▨	▨	□	□
Honed meter run Foxboro IFOA	0 5-1 5 (12 40)	■	□	■	▨	□	▨	□	□
Integral	<0 5 (12)	■	□	■	■	□	▨	□	□
Quadrant/conic edge	>1 5 (40)	□	□	■	■	▨	▨	□	□
Eccentric	>2 (50)	▨	■	▨	□	■	▨	□	□
Segmental	>4 (100)	▨	■	▨	□	■	▨	□	□
Annular	>4 (100)	▨	■	▨	□	■	▨	□	□
Target	>0 5-4 (12-100)	■	■	■	■	■	▨	□	□
Venturi	>2 (50)	■	▨	■	▨	▨	▨	▨	▨
Flow nozzle	>2 (50)	■	▨	■	▨	▨	▨	□	□
Lo-Loss	>3 (75)	■	□	■	□	□	■	□	□
Pitot	>3 (75)	■	□	■	▨	□	▨	□	□
Multiport averaging	>1 (25)	■	▨	■	▨	□	▨	□	□
Elbow	>2 (50)	■	▨	■	□	■	■	■	■
		LINEAR SCALE: TYPICAL RANGE 10:1							
Magnetic	0 1-72 (25-1800)	□	□	■	■	■	■	■	■
Mass flowmeter Coriolis		▨	□	■	■	■	▨	□	□
Positive displacement	<12 (300)	■	□	■	□	□	▨	□	□
Turbine	0 25-24 (6-600)	■	□	■	□	□	▨	□	□
Ultrasonic		□	□	□	□	□	□	□	□
Time of flight	>0 5 (12)	□	□	■	▨	□	■	□	□
Doppler	>0 5 (12)	□	□	□	▨	■	■	■	■
Variable area	≤3 (75)	■	□	■	■	□	▨	□	□
Vortex	0 5 – 16 (12 – 400)	■	▨	■	□	▨	▨	□	□

■ = designed for this application, ▨ = normally applicable; □ = not designed for this application

E) PLACA DE ORIFICIO

Esta es la forma más común de reducción del área de circulación para producir diferencia de presiones y sus características son:

a) Máxima pérdida de presión permanente.
b) Es el más comúnmente usado.
c) Más fácil de instalar.
d) Fácilmente reproducible.
e) Requiere inspección periódica.
f) Es el de más bajo costo.

Este tipo de elemento primario de medición para medir flujo es una placa delgada de metal con una abertura generalmente redonda y concéntrica como se muestra en la fig. 1-21.

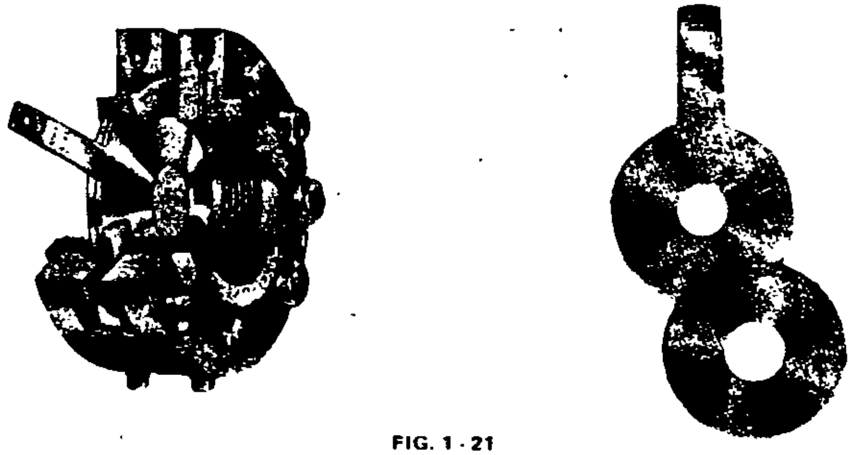
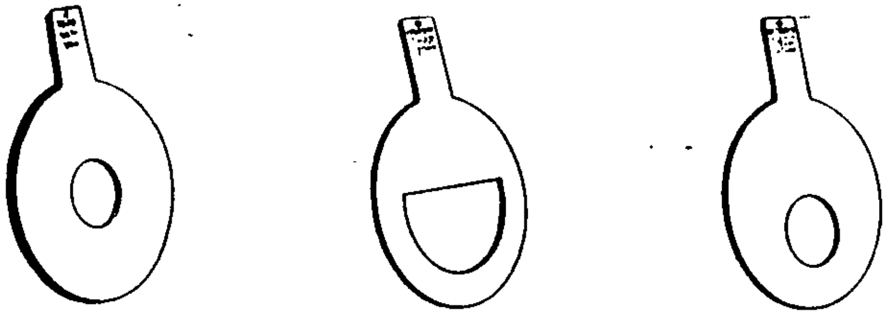


FIG. 1 - 21

Placa de orificio y unión de brida. (Cortesía The Bristol Co.)

Placa de orificio tipo Daniel. (Cortesía de Daniel Inc.).



Orificio concéntrico

Orificio segmental

Orificio excéntrico

FIG. 1 - 21A

(Cortesía The Foxboro Co.)

Date of issue: July 1991

Affected Publication: *Manual of Petroleum Measurement Standards*, Chapter 14, "Natural Gas Fluids Measurement," Section 3, "Concentric, Square-Edged Orifice Meters," Part 1, "General Equations and Uncertainty Guidelines," Third Edition, September 1990

ERRATA

On page 2, Footnote 1 should read as follows:

[1] American National Standards Institute, 11 West 42nd Street, New York, New York 10036.

On page 3, Figure 1-1 should appear as follows (that is, the letters PE *should be used to represent the downstream static pressure element):*

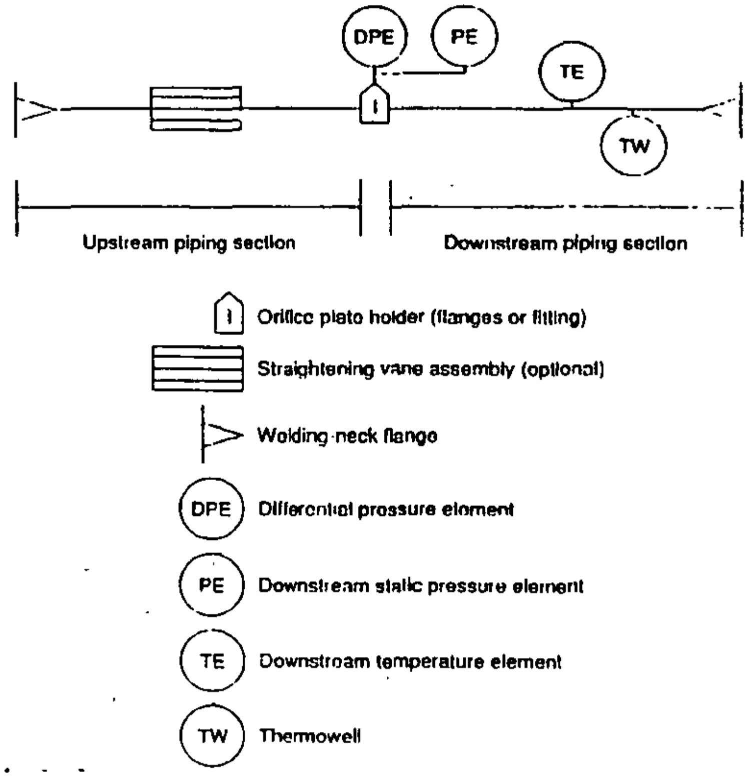


Figure 1-1—Orifice Meter

On page 13, the first paragraph should read as follows (that is, the word Ohio *should replace the word* Oklahoma*):*

Although it does not mean that other data are of inferior quality, it is known that insufficient information exists to determine whether the independent variables were controlled and quantified. Some examples of comparison quality data are the Ohio State University Data Base (303 flange-tapped points), the 1983 NBS Boulder Experiments, the Foxboro Columbus–Daniel 1000-Point Data Base, and the Japanese Water Data Base.

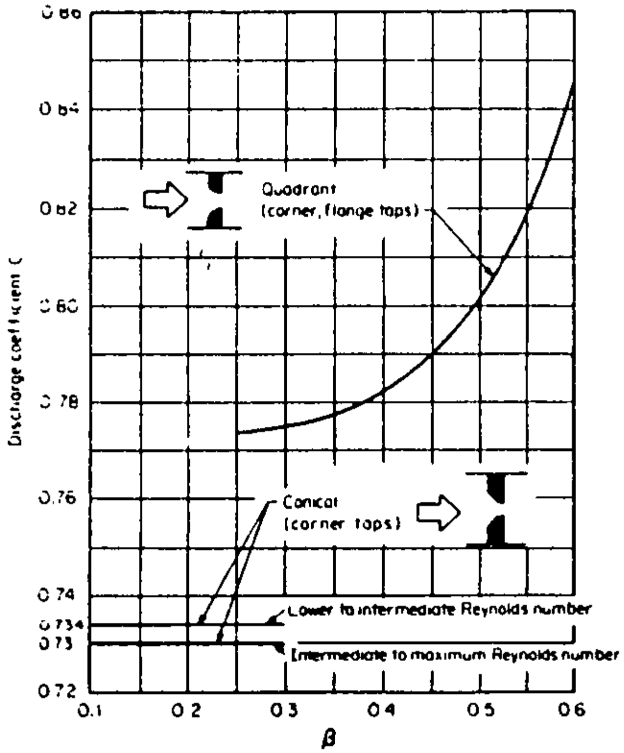


Figure 10.38 Discharge coefficient for quadrant and conical orifices.

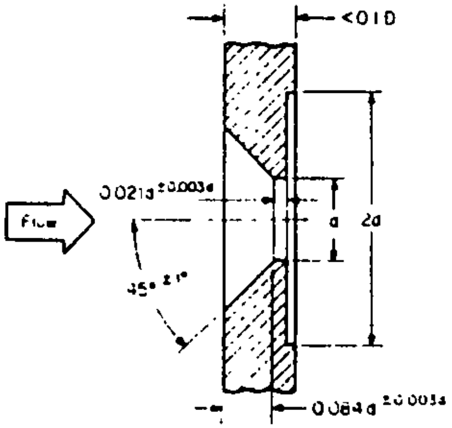


Figure 10.39 Conical-entrance orifice.

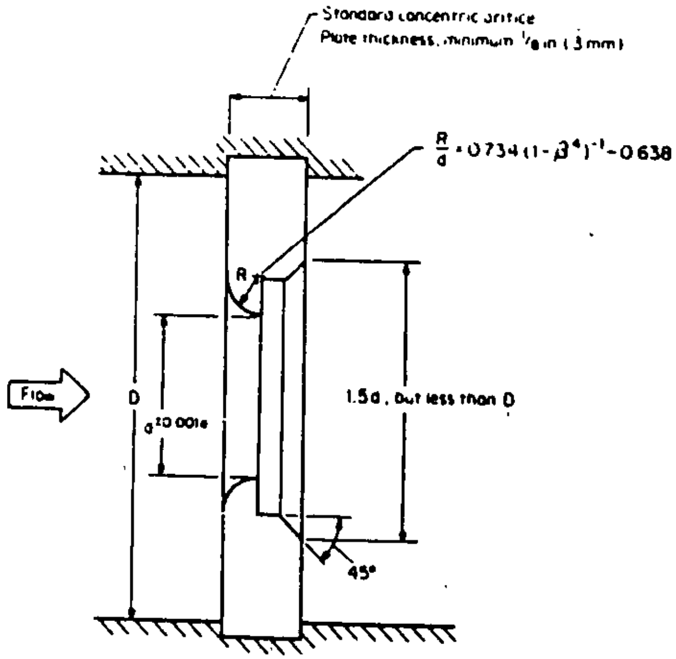


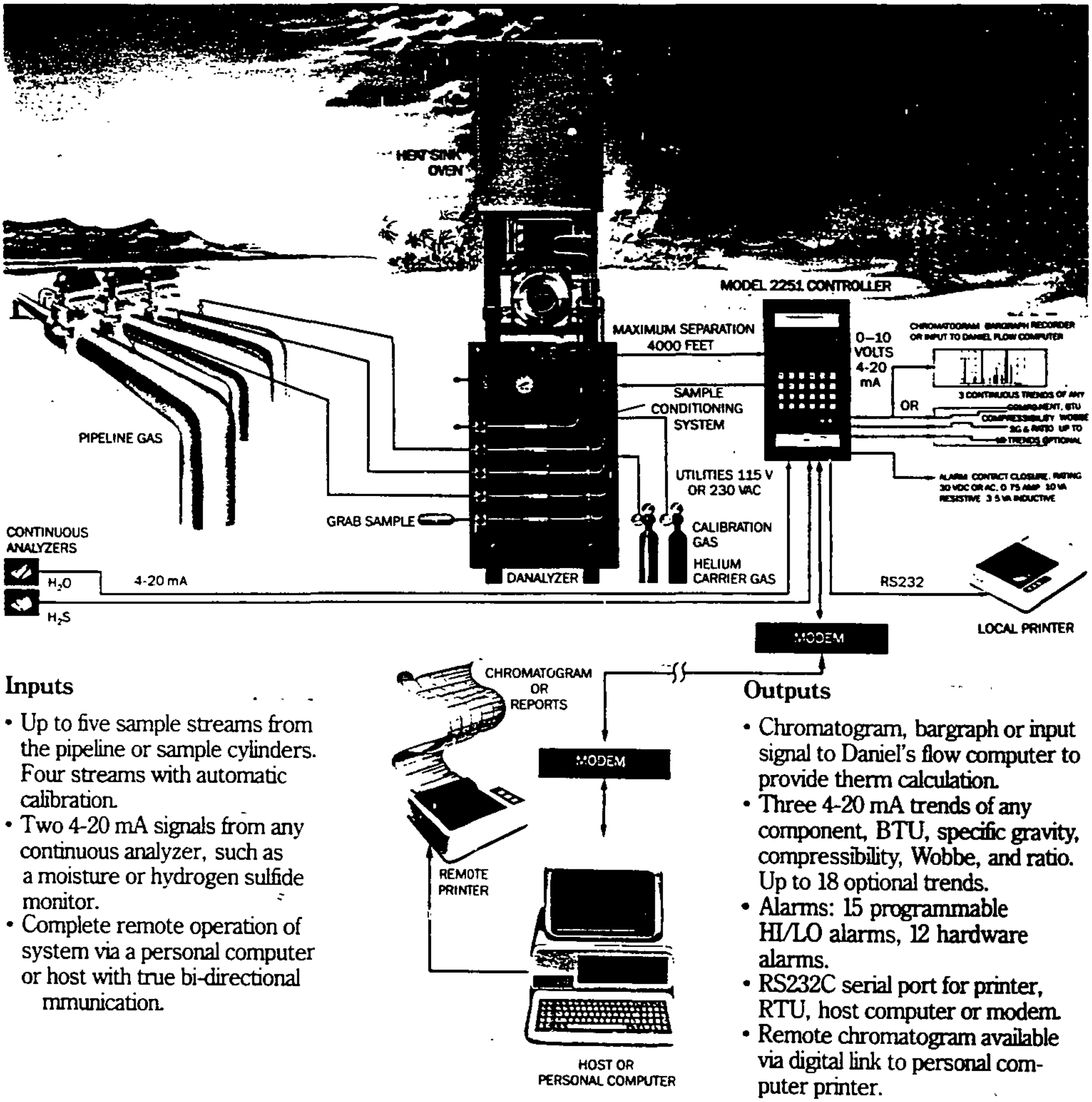
Figure 10.36 Quadrant (quarter-circle) concentric orifice.

An Overview of the Daniel Danalyzer System.

The Danalyzer measures the BTU of gas to within ± ½ BTU in 1000 over the full ambient range of 0–130°F.

The system includes:

• Sample conditioning system • Analyzer • Model 2251 controller



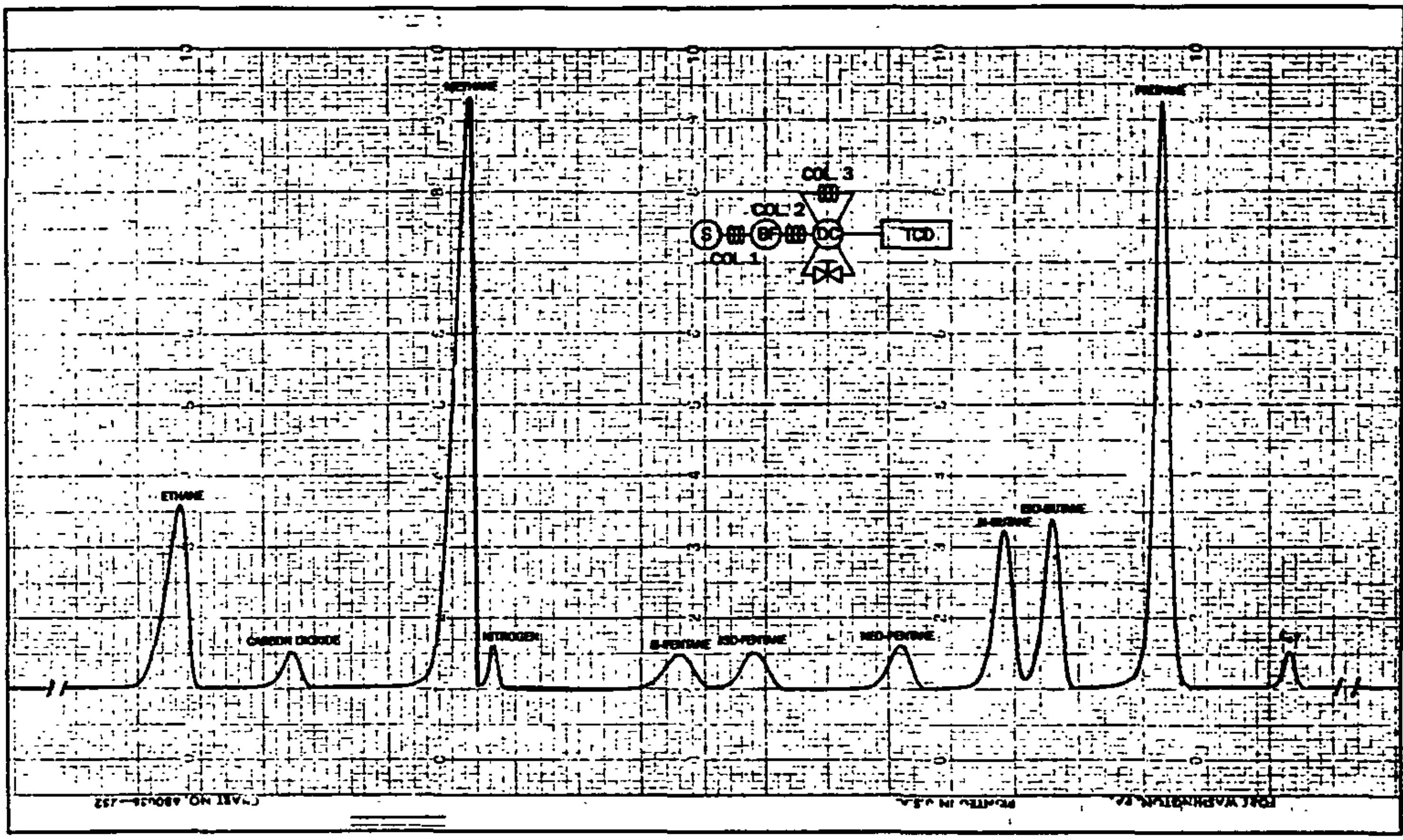
Inputs

- Up to five sample streams from the pipeline or sample cylinders. Four streams with automatic calibration.
- Two 4-20 mA signals from any continuous analyzer, such as a moisture or hydrogen sulfide monitor.
- Complete remote operation of system via a personal computer or host with true bi-directional mmunication.

Outputs

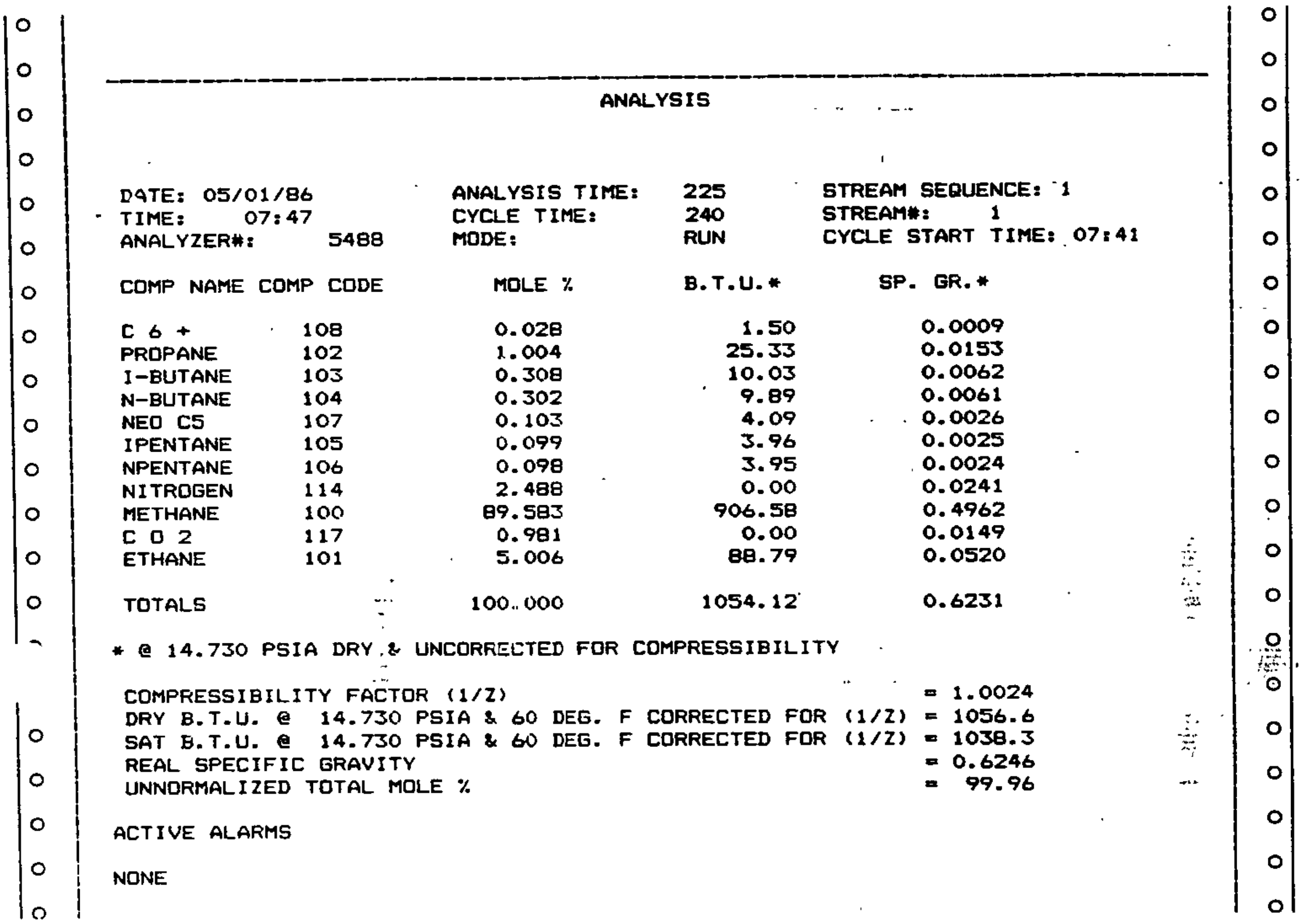
- Chromatogram, bargraph or input signal to Daniel's flow computer to provide therm calculation.
- Three 4-20 mA trends of any component, BTU, specific gravity, compressibility, Wobbe, and ratio. Up to 18 optional trends.
- Alarms: 15 programmable HI/LO alarms, 12 hardware alarms.
- RS232C serial port for printer, RTU, host computer or modem.
- Remote chromatogram available via digital link to personal computer printer.

Chromatogram.



Chromatogram. Complete Separation in Four Minutes, ± ½ BTU Repeatability.
The chromatogram is a graphic representation of the measured components' concentration in the gas. Each peak represents a component. The area under a peak is proportional to the component's concentration. Notice how each peak is clearly separated from the others. The Danalyzer easily performs the tough nitrogen/methane/carbon dioxide separation. To provide the best repeatability available from any BTU analyzer, Daniel directly measures each peak. The Danalyzer is the only BTU analyzer that will provide you repeatable results to within ± ½ BTU in 1000 over the complete ambient temperature range of 0–130°F. Only the Danalyzer can provide the highest repeatability available over a wide ambient temperature range within a 4 minute analysis time.

Reports.



```
                                   ANALYSIS

DATE: 05/01/86             ANALYSIS TIME:    225      STREAM SEQUENCE: 1
TIME:     07:47            CYCLE TIME:       240      STREAM#:     1
ANALYZER#:       5488      MODE:             RUN      CYCLE START TIME: 07:41

COMP NAME COMP CODE          MOLE %          B.T.U.*       SP. GR.*

C 6 +          108           0.028              1.50        0.0009
PROPANE        102           1.004             25.33        0.0153
I-BUTANE       103           0.308             10.03        0.0062
N-BUTANE       104           0.302              9.89        0.0061
NEO C5         107           0.103              4.09        0.0026
IPENTANE       105           0.099              3.96        0.0025
NPENTANE       106           0.098              3.95        0.0024
NITROGEN       114           2.488              0.00        0.0241
METHANE        100          89.583            906.58        0.4962
C O 2          117           0.981              0.00        0.0149
ETHANE         101           5.006             88.79        0.0520

TOTALS                     100.000           1054.12        0.6231

* @ 14.730 PSIA DRY & UNCORRECTED FOR COMPRESSIBILITY

COMPRESSIBILITY FACTOR (1/Z)                                  = 1.0024
DRY B.T.U. @  14.730 PSIA & 60 DEG. F CORRECTED FOR (1/Z)     = 1056.6
SAT B.T.U. @  14.730 PSIA & 60 DEG. F CORRECTED FOR (1/Z)     = 1038.3
REAL SPECIFIC GRAVITY                                         = 0.6246
UNNORMALIZED TOTAL MOLE %                                     =  99.96

ACTIVE ALARMS

NONE
```

80-Column Format for complete data presentation and easy operator review.

Analysis Report provides complete compositional analysis and BTU factors for diagnostic purposes.

Short Report allows operator the ability to select or edit for printout of any data available in the analysis report. For example, the operator can select BTU only to be printed or the 24-hour average printed or any combination of the analysis report variables. The short report allows the operator to see only the data of specific interest without burdening him with the complete analysis report each printout.

Extended Averages
36 extended averages are available. The extended averages can be hourly, daily or monthly. The extended average provides the high, average and low value that occurred during that period. Each extended average will be stored for three time periods.

Calibration report first checks the calibration gas. Once the calibration gas concentration is determined to be within operator-selectable limits, the controller calibrates the analyzer's output. The Danalyzer measures the calibration gas before calibrating, ensuring reliable results.

INTRODUCCION.

El término norma o estándar se define como una regla establecida, por la que se rige la mayoría de las personas, para caracterizar un producto o método de trabajo. Así, un estándar puede llegar a definir las condiciones técnicas de fabricación, operación y verificación de un determinado equipo o sistema.

Hoy en día, no es posible concebir un sistema de medición de flujo de gases y líquidos sin considerar el empleo de estándares que regulen su manufactura, diseño, calibración, prueba, operación y mantenimiento. La importancia del empleo de los estándares se fundamenta en dos actividades principalmente; una es el mantener cierta uniformidad dentro del equipo de trabajo y la otra es el contar con el mínimo de fuentes potenciales de incertidumbre en la medición. Ambas actividades repercuten directamente en el aspecto económico de toda aquella industria cuyo principal ingreso y/o egreso monetario se encuentra en función de la comercialización de algún fluido, como es el caso de la industria petrolera.

Todas y cada una de las reglas que se establecen en los estándares están respaldadas por un gran número de pruebas de laboratorio y por un gran número de revisiones y verificaciones del desempeño obtenido. Con esto se garantiza que al seguir de forma rigurosa los lineamientos de un estándar, el sistema de medición a ser diseñado, integrado y probado tendrá de forma implícita una serie de pruebas de desempeño superadas. Esta afirmación se basa en la Ley de Similitud, la cual especifica que todos aquellos resultados obtenidos en instalaciones experimentales pueden ser obtenidos nuevamente si existe una similitud dinámica y geométrica entre la instalación del medidor en proceso y la instalación donde se obtuvieron los datos experimentales. La similitud geométrica requiere que el sistema de flujo experimental sea un modelo a escala de las instalaciones de campo, mientras que la similitud dinámica implica una correspondencia de las fuerzas del fluido entre el sistema de flujo experimental y el sistema de campo. Hoy en día está ley es el principio básico para presentar resultados teóricos y experimentales de la mecánica de fluidos.

Los estándares de medición emitidos por el Instituto Americano del Petróleo (API) determinan como punto de entrada las siguientes notas aclaratorias:

1. Las publicaciones API visualizan problemas de tipo general. Para situaciones de tipo particular, leyes y/o regulaciones locales, estatales y federales deben ser consultadas.
2. Las publicaciones API no tratan de definir las obligaciones de empleados, fabricantes o suministradores. La información relacionada a precauciones y medidas de seguridad con respecto a materiales y prácticas de ingeniería, deberán ser obtenidas del fabricante o en su caso de la hoja de datos del material o producto que se esté manejando.
3. Nada de lo escrito en alguna publicación API está orientado a una marca o patente específica. (Al contrario, los fabricantes o patentes tratan de apegarse a lo que dicen las normas API).
4. Generalmente las publicaciones API son revisadas cada cinco años, o antes en caso de ser necesario. En algunos casos se adicionan dos años más a este ciclo.
5. Todas las publicaciones de API han sido desarrolladas bajo los procedimientos de estandarización API, los cuales aseguran una apropiada participación y documentación durante el proceso de desarrollo.
6. Los estándares API tienen por objetivo el facilitar una amplia disponibilidad de adecuadas prácticas de ingeniería, operación y prueba de los equipos y sistemas a ser habilitados.
7. El fabricante que marca sus productos con la leyenda de conformidad con algún estándar API, es el único responsable de que el producto efectivamente haya sido desarrollado tal y como lo marca el

estándar. Esto quiere decir que API no garantiza ningún material que este marcado con la leyenda de conformidad con los estándares API.

8. Las recomendaciones estipuladas en las publicaciones API pueden ser seguidas por quién así quiera hacerlo, por lo que su aplicación es enteramente voluntaria.
9. El instituto ha hecho esfuerzos por asegurar la exactitud y fiabilidad de los datos contenidos en sus publicaciones, razón por la cual los estándares API consideran solo diseños, técnicas, procesos y materiales que han demostrado ser satisfactorios para el servicio requerido. Innovaciones en estos campos, serán consideradas por los estándares cuando pruebas de desempeño son disponibles.
10. El Instituto Americano del Petróleo instituto no se responsabiliza por pérdidas o daños resultantes que podrían llegar a generase por el empleo de los estándares, o bien, por si llegara a violarse alguna ley o regulación local, estatal o federal

Las características de tipo general del Manual de Estándares en la Medición del Petróleo (MPMS) emitidos por el API son:

- Incluyen definiciones y terminología dentro de sus lineamientos para evitar ambigüedades.
- Describen los principios, características y limitantes de desempeño de los equipos o dispositivos que estén involucrados en el estándar. Asimismo, establecen los procedimientos de instalación y prueba de los equipos mencionados.
- En algunos casos, determinar el nivel de exactitud de los equipos o dispositivos, por posibles variaciones en el medio ambiente o en las condiciones de instalación, operación y mantenimiento.
- Describen cuando es primordial seguir las recomendaciones de los fabricantes.
- Son imparciales y no involucran aspectos de tipo comercial.

Los principales beneficios que pueden ser obtenidos por el empleo y seguimiento de los lineamientos de los estándares API son:

- Permiten definir de forma clara los términos de un producto o servicio que ha sido contratado, y de lo que ha sido o será suministrado.
- Permite determinar con un alto nivel de certidumbre la fiabilidad y exactitud de un producto o servicio desde la etapa de diseño y conceptualización.
- Permiten realizar adquisiciones de equipo de diferentes orígenes. (Dispositivos intercambiables y compatibles).
- Permiten minimizar la capacitación del personal. (Ya que la terminología y métodos de prueba son comunes para todos los fabricantes).
- Permite reducir costos de los equipos o dispositivos. (Ya que los diseños o características finas del producto se han definido por consenso de varios expertos y fabricantes de dispositivos).
- Permiten eliminar "estándares propietarios" emitidos de manera unilateral por un fabricante.

Los presentes apuntes, sólo son un resumen de los siguientes capítulos del MPMS. Capítulo 4 "Sistemas de Prueba". Capítulo 5 "Medición. Capítulo 6 "Ensambles de Medición", Capítulo 7 "Determinación de temperatura". Capítulo 8 "Muestreo. Capítulo 10 "Agua y Sedimento", Capítulo 12 "Cálculo de cantidades de petróleo" y el Capítulo 14 "Medición de fluidos de gas natural". Todos las notas y comentarios existentes en estos apuntes, están orientados a los sistemas de medición de flujo (pipeline systems) para aplicaciones de transferencia de custodia. Si el lector desea un mayor detalle de la información contenida en estos apuntes, es necesario consultar directamente las normas correspondientes.

En el Anexo A de este documento, se incluye un sumario de todos los estándares que conforman el MPMS. Este sumario se extrajo directamente de la página del API en internet. En el Anexo B de este documento, se incluye un glosario de términos de tipo general donde el autor de estos apuntes considera que son de vital importancia para el mejor entendimiento de los estándares. Para ver a detalle todo el glosario de términos que maneja el MPMS, se recomienda consultar el Capítulo 1 "Vocabulario" de este manual del MPMS.

CAPITULO 14. MEDICION DE FLUIDOS DEL GAS NATURAL.

SECCION 14.0. PROLOGO.

El Capítulo 14 del *Manual de Estándares en la Medición de Petróleo (MPMS)* es una guía para el diseño, instalación, calibración y operación de los sistemas de medición de fluidos del gas natural.

El capítulo 14 se divide en las secciones siguientes:

14.1 Recolección y manejo de muestras de gas natural para transferencia de custodia.
14.2 Factores de compresibilidad del Gas Natural y otros hidrocarburos gaseosos relacionados.
14.3 Medición de gas natural y de otros hidrocarburos relacionados, mediante medidores de orificio.
14 4 Convirtiendo masa de líquidos y vapores de gas natural a su equivalente en volumen liquido.
14.5 Cálculo de la capacidad calorífica (Gross Heating Value), Densidad Relativa (Gravedad específica)y del Factor de compresibilidad de Mezclas de Gas Natural a partir de su análisis composicional.
14.6 Medición continua de densidad.
14.7 Estándar para la medición de masa de Líquidos de Gas Natural.
14.8 Medición de Gas Licuado de Petróleo.

Para fines didácticos, dentro de estos apuntes se cambia la secuencia del orden de los estándares para una mejor comprensión de los sistemas de medición de fluidos de gas natural. Siendo así, la secuencia de exposición será como sigue:

Sección 14.3 Medición de gas natural y de otros hidrocarburos, mediante medidores de orificio.
Sección 14.2 Factores de compresibilidad del Gas Natural y otros hidrocarburos gaseosos relacionados.
Sección 14.4 Convirtiendo masa de líquidos y vapores de gas natural a su equivalente en volumen liquido.
Sección 14.5 Cálculo de la capacidad calorífica, Densidad Relativa y del Factor de compresibilidad de Mezclas de Gas Natural a partir de su análisis composicional.
Sección 14.1 Recolección y manejo de muestras de gas natural para transferencia de custodia.
Sección 14.6 Medición continua de densidad.
Sección 14.7 Estándar para la medición de masa de Líquidos de Gas Natural.
Sección 14.8 Medición de Gas Licuado de Petróleo.

Se hace notar que los estándares contenidos en este capítulo están fuertemente ligados con los estándares y lineamientos emitidos por organizaciones especializadas en el manejo y medición del gas natural, como lo es, Gas Research Institute (GRI), Gas Processors Association (GPA) y American Gas Association (AGA). De forma particular y a manera de información se menciona que la American Gas Association ha emitido estándares dirigidos hacia la medición de gas natural mediante otros tipos de medidores como son los medidores de tipo turbina (AGA Reporte No. 7) y los medidores de tipo ultrasónico (AGA Reporte No. 9).

SECCION 14.3 MEDICION DE GAS NATURAL Y DE OTROS HIDROCARBUROS MEDIANTE MEDIDORES DE ORIFICIO.

El estándar se desarrolló en conjunto por API, AGA, GPA y con valiosas contribuciones de CMA (Chemical Manufactureres Association), CGA (Canadian Gas Association), EC (European Community) y diversas organizaciones de Japón y Noruega. El estándar está organizado en cuatro partes. La parte 1, 2 y 4 aplican en la medición de cualquier fluido Newtoniano de la industria petrolera y química (incluyendo líquidos). La parte 3 se enfoca a la aplicación de las partes 1, 2 y 4 en la medición de gas natural.

En general la sección 14.3 del MPMS aplica para fluidos que prácticamente son considerados como limpios, de una fase, homogéneos, Newtonianos y con Número de Reynolds ≥ 4000. Todos los gases, la mayoría de los líquidos y la mayoría de los fluidos en fase densa asociados con la industria del petróleo, petroquímicas y de gas natural son usualmente considerados como fluidos Newtonianos.

El estándar da especificaciones y requerimientos de instalación de placas de orificio, portaplacas, tomas barrenadas para sensores (tap hole), tubos de medición, termopozos y acondicionadores de flujo. Para aplicaciones de transferencia de custodia, los medidores de orificio y su tubería adyacente deberán apegarse, estrictamente, a los requerimientos del estándar, ya que posibles desviaciones invalidarán los estimados de incertidumbre que se especifican.

Se hace notar que la incertidumbre del sistema de medición no depende únicamente del "hardware" que se emplee, sino que también dependerá del desempeño del "hardware y "software", del método, equipo y procedimientos de calibración y sobre todo, del factor humano. Para construir, operar y mantener las instalaciones de un sistema de medición dentro de un nivel de incertidumbre deseado, el usuario debe definir este nivel de incertidumbre desde la etapa de diseño, ya que la exactitud en la medición depende de la combinación de:

a. El diseño, instalación y operación de las instalaciones del medidor de orificio.
b. La selección del equipo de medición.
c. El medio de transmisión de los datos.
d. El procedimiento de cálculo y el medio de cómputo.
e. Los efectos de las condiciones ambientales sobre el equipo de operación y/o de calibración.
f. La variación de temperatura y presión del fluido.
g. El tiempo de respuesta.
h. Las fuerzas de gravitación locales.
i. La cadena de trazabilidad asociada con los patrones portátiles de campo.

1. ECUACIONES GENERALES Y LINEAMIENTOS DE INCERTIDUMBRE.

1.1 Resumen.

En esta parte del estándar se describen las ecuaciones para determinar la razón de flujo de masa y de volumen a condiciones estándar. Se presentan las ecuaciones empíricas para determinar el coeficiente de descarga y el factor de expansión, se definen las propiedades físicas del fluido que influyen directamente en la medición de flujo y se describen los lineamientos que permiten estimar la incertidumbre asociada al diseño, instalación y mantenimiento de los medidores de orificio.

1.2 Algunas definiciones.

MEDIDOR DE ORIFICIO. El medidor de orificio es un dispositivo que infiere una razón de flujo mediante la diferencial de presión que produce en el fluido. El medidor consiste de los elementos que se describen a continuación:

a) Una placa con orificio concéntrico de borde cuadrado.
b) Fittings o bridas para sujetar la placa equipadas con las apropiadas tomas para el sensado de la presión diferencial.
c) Un tubo de medición que conforma las secciones de tubería adyacentes a la placa.

COEFICIENTE DE DESCARGA DE LA PLACA DE ORIFICIO (C_d). Es la relación que existe entre el flujo real y el flujo teórico que pasa a través del orificio de la placa. Se aplica en la ecuación de flujo teórica para obtener el flujo real. En otras palabras, es un factor de compensación entre el flujo teórico y el real.

FACTOR DE EXPANSION (Y). Es una expresión empírica usada para corregir la razón de flujo por la reducción en la densidad que un fluido compresible experimenta cuando pasa a través del orificio de una placa. Para fluidos incompresibles el factor de expansión es igual a 1.0

VELOCIDAD DE ACERCAMIENTO (E_V). Es la expresión matemática que relaciona la velocidad del fluido en el tubo de medición aguas arriba y la velocidad del fluido en el orificio de la placa.

FACTOR DE COMPRESIBILIDAD (Z). Es el factor de ajuste usado para contabilizar la desviación que experimenta un fluido gaseoso con respecto a la ley de los gases ideales.

EXPONENTE ISENTROPICO (k) Es una propiedad termodinámica que establece la relación entre la densidad y la presión de un fluido cuando pasa a través del orificio de la placa.

VISCOSIDAD. Es la medición de las fuerzas intermoleculares de un fluido para resistir su deformación cortante. Para muchas aplicaciones con alto número de Reynolds las variaciones de viscosidad son prácticamente ignoradas ya que no repercute en mayor manera en el cálculo del flujo. Para aplicaciones con bajo número de Reynolds es de vital importancia el determinar con exactitud el valor de la viscosidad y las variaciones que puede llegar a sufrir con los cambios de condiciones de operación, ya que si influye de manera significativa en el cálculo del flujo.

DENSIDAD. Es la masa por unidad de volumen del fluido que está siendo medido a determinadas condiciones de temperatura y presión. La densidad puede ser obtenida ya sea mediante la aplicación de una ecuación de estado, o bien, mediante la aplicación de un densitómetro en línea. Para la instalación, operación y calibración de densitómetros empleados en la medición de densidad de 0.30 gr/cm^3, refiérase al API MPMS 14.6; para valores de densidad menores refiérase a los manuales del fabricante. Los fabricantes del densitómetro deberán demostrar que la operación de éste no interfiere con las operaciones básicas del medidor de orificio. Para fluidos cuya densidad cambia rápidamente por cambios en la temperatura del fluido, para fluidos a baja velocidad y/o para minimizar los efectos de la transferencia de calor debido a la temperatura ambiental, se recomienda aislar térmicamente el tubo de medición entre el elemento primario y la toma de lectura de temperatura.

1.3 Ecuaciones para determinar la razón de flujo.

La ecuación aceptada para determinar el flujo másico a través de un medidor de orificio es:

$$q_m = C_d E_v Y(\pi / 4) d^2 \sqrt{2 g_c \rho_{t,p} \Delta P} \tag{1}$$

Donde:
C_d = *Coeficiente de descarga de la placa de orificio.*
d = *Diámetro del orificio de la placa calculado la temperatura del fluido (T_f).*
ΔP = *Presión diferencial provocada por la placa de orificio.*
E_v = *Velocidad de acercamiento* = $\frac{1}{\sqrt{1-\beta^4}}$
g_c = *Constante de conversión dimensional.*
π = *Constante universal = 3.14159*
q_m = *Razón de flujo de masa.*
$\rho_{t,p}$ = *Densidad del fluido a las condiciones de fluido (P_f, T_f)*
Y = *Factor de expansión*

Para determinar la razón de flujo volumétrico, a condiciones del fluido y a condiciones base (estándar), se emplea la expresión:

$$q_v = \frac{q_m}{\rho_{t,p}} \tag{2}$$

$$Q_v = \frac{q_m}{\rho_b} \tag{3}$$

Donde:

q_v = Flujo volumétrico a condiciones de temperatura y presión del fluido.
Q_v = Flujo volumétrico a condiciones de temperatura y presión base (estándar).
$\rho_{t,p}$ = Densidad de masa a condiciones de temperatura y presión del fluido.
ρ_b = Densidad de masa a condiciones base (estándar) del fluido.

El coeficiente de descarga y el factor de expansión son funciones empíricas obtenidas a partir de datos experimentales. El coeficiente de descarga depende del número de Reynolds, de la localización de las tomas de presión, del diámetro del tubo de medición y de la relación de diámetros β. La ecuación para determinar el coeficiente de descarga es aplicable para tubos mayores o iguales a 50 mm (2 in) y relaciones β de 0.1-0.75, por lo que los orificios de las placas de orificio deberán ser mayores a 11.4 mm (0.45 in) y número de Reynolds mayores o iguales a 4000. La ecuación del coeficiente de descarga está dada por:

$$C_d(FT) = C_i(FT) + 0.000511\left[\frac{10^6\beta}{\mathrm{Re}_D}\right]^{0.7} + (0.0210 + 0.0049A)\beta^4 C \tag{4}$$

$$C_i(FT) = C_i(CT) + TapTerm \tag{5}$$

$$C_i(CT) = 0.5961 + 0.291\beta^8 + 0.003(1-\beta)M \tag{6}$$

$$TapTerm = Upstrm + Dnstrm \tag{7}$$

$$Upstrm = \left[0.0433 + 0.712e^{-8.5L_1} - 0.1145e^{-6.0L_1}\right](1 - 0.23A)B \tag{8}$$

$$Dnstrm = -0.0116\left[M_2 - 0.52M_2^{1.3}\right]\beta^{1.1}(1 - 0.14A) \tag{9}$$

$$B = \frac{\beta^4}{1-\beta^4} \tag{10}$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4}, 0.0\right) \tag{11}$$

$$M_2 = \frac{2L_2}{1-\beta}; \qquad A = \left[\frac{19{,}000\beta}{\mathrm{Re}_D}\right]^{0.8}; \qquad C = \left[\frac{10^6}{\mathrm{Re}_D}\right]^{0.35} \tag{12}$$

Donde:

$\beta = d/D$ = Relación existente entre el diámetro del orificio de la placa y el diámetro del tubo de medición.
$d = d_r\left[1 + \alpha_1(T_f - T_r)\right]$ $\qquad$ $d_r = d_m\left[1 + \alpha_1(T_r - T_m)\right]$
$D = D_r\left[1 + \alpha_2(T_f - T_r)\right]$ $\qquad$ $D_r = D_m\left[1 + \alpha_2(T_r - T_m)\right]$
T_f = Temperatura del fluido a condiciones de flujo.
T_r = Temperatura referencia para determinar el diámetro del orificio de la placa y del tubo de medición, para propósito de este estándar, se considera que T_r = 68°F (20°C).
T_m = Temperatura de la placa de orificio y del tubo de medición a la hora de medir sus diámetros.

α_1 = *Coeficiente de expansión térmica para el material de la placa de orificio.*
α_2 = *Coeficiente de expansión térmica para el material del tubo de medición.*
d_r = *Diámetro del orificio de la placa a temperatura* T_r.
d_m = *Diámetro del orificio de la placa a temperatura* T_m
d = *Diámetro del orificio de la placa a la temperatura de flujo* T_f.
D_r = *Diámetro interior del tubo de medición a temperatura* T_r.
D_m = *Diámetro interior del tubo de medición a temperatura* T_m
D = *Diámetro interior del tubo de medición a la temperatura de flujo* T_f.

Re_D = *Número de Reynolds* = $\frac{4q_m}{\pi\mu D}$.
μ = *Viscosidad absoluta del fluido.*
$C_d(FT)$ = *Coeficiente de descarga a un especificado* Re_D *para un medidor de orificio con bridas barrenadas para toma de presión.*
$C_i(FT)$ = *Coeficiente de descarga a un infinito* Re_D *para un medidor de orificio con bridas barrenadas para toma de presión.*
$C_i(FT)$ = *Coeficiente de descarga a un infinito* Re_D *para un medidor de orificio con esquinas barrenadas para toma de presión.*
e = *Constante universal* = 2.71828.
L_1 = *Corrección dimensional para la localización de los barrenos* = L_2 = N_4/D *para bridas barrenadas.*
N_4 = *1.0 cuando D está en pulgadas ó 25.4 cuando D está en milímetros.*

Desde un punto de vista práctico, se define que la expansión de un fluido es reversible y adiabática (sin ganancia o pérdida de calor. Para gases perfectos (gas ideal con calores específicos constantes) el exponente isentrópico k_p es igual a k_i evaluado a las condiciones base. Para un gas real, el exponente isentrópico k_r es una función de las condiciones de presión y temperatura del fluido.). Dentro de rangos de operación prácticos de presión diferencial, presión estática y temperatura del fluido, el factor de expansión es insensible al exponente isentrópico por lo que asume la existencia de un exponente isentrópico ideal, esto es que, como $k_i \cong k_p \cong k_r$ entonces es común emplear k_i en las ecuaciones de flujo. Para un gas ideal el exponente isentrópico es igual a la relación de calores específicos a presión y volumen constante, siendo independiente de la presión i.e.

$$k_i = \frac{c_p}{c_v} \tag{16}$$

Donde:

k_i = *Coeficiente isentrópico de un gas ideal.*
C_p = *Calor especifico a presión constante.*
C_v = *Calor especifico a volumen constante.*

Teniendo este concepto como referencia se estipula que existen dos métodos para determinar el factor de expansión de un fluido. El primer método (Y_1) se recomienda por su simplicidad. El segundo método (Y_2) es más exacto que el primero ya que considera la presión estática del fluido antes y después de la placa de orificio. Las expresiones matemáticas que determina el factor de expansión son:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\frac{x_1}{k} \tag{13}$$

$$Y_2 = Y_1\sqrt{\frac{P_{f_1}Z_{f_2}}{P_{f_2}Z_{f_1}}} \tag{14}$$

Donde.

$$x_1 = \begin{cases} \frac{\Delta P}{N_3 P_{f_1}} & \textit{para cuando se mide la presión estática aguas arriba} \\ \frac{\Delta P}{N_3 P_{f_2} + \Delta P} & \textit{para cuando se mide la presión estática aguas abajo} \end{cases}$$

x_1 = *Relación entre presión diferencial y presión estática absoluta aguas arriba o aguas abajo de la placa.*

ΔP = *Diferencial de presión provocada por la placa de orificio.*
N_3 = *Factor de conversión de unidades = 1.0 cuando la presión se mide en lbs/in² ó en Pascales.*
P_{f1} = *Presión estática absoluta aguas arriba de la placa.*
P_{f2} = *Presión estática absoluta aguas abajo de la placa.*
k = *Exponente isentrópico.*

La ecuación presentada para el factor de expansión es válida bajo las siguientes condiciones:

- Relaciones β que estén dentro del rango de 0.10 a 0.75
- Idéntica temperatura del fluido aguas arriba y aguas abajo de la placa.
- Que se cumplan las siguientes criterios de relación de presiones:

$$0 < \frac{\Delta P}{N_3 P_{f_1}} < 0.20; \qquad 0.8 < \frac{P_{f_2}}{P_{f_1}} < 1.0 \tag{15}$$

1.4 Condiciones de Flujo.

Las condiciones de flujo pueden afectar significativamente la exactitud en la medición. El estado del tubo de medición, el acoplamiento de la tubería, las tomas de la presión diferencial, las longitudes de tubería recta aguas arriba y aguas abajo de la placa de orificio y varios detalles más relacionados a la instalación, son factores que influyen en las condiciones de flujo. Para garantizar exactitud en la medición dentro de un nivel de incertidumbre definido, deben asegurarse como mínimo, las siguientes condiciones de flujo:

a) El flujo debe aproximarse a condiciones de fluido en estado estable. El fluido debe ser limpio, de una fase, homogéneo y Newtoniano.
b) No deberá existir ningún cambio de fase en el fluido cuando pase a través del orificio del medidor.
c) El flujo deberá ser subsónico cuando pase a través del orificio y del tubo de medición.
d) El número de Reynolds deberá estar dentro de las limitaciones que especifican los coeficientes empíricos del coeficiente de descarga y del factor de expansión.
e) El flujo debe entrar al orificio de la placa con un perfil de velocidad completamente desarrollado.
f) No deberá existir en ninguno de los casos un bypass de flujo alrededor del medidor de orificio.

Las mediciones de flujo tomadas por un medidor de orificio no son confiables cuando existen pulsaciones apreciables en el punto de medición, ya que provocan cambios repentinos en la velocidad, presión y densidad del fluido. Las fuentes más comunes de pulsación en el flujo de fluidos son las que se mencionan a continuación:

a) Intercambiadores, compresores, impulsores y/o motores.
b) Bombeo y reguladores de presión mal dimensionados.
c) Válvulas, configuraciones de tubería y elementos similares en mal estado o mal instalados.
d) Movimientos irregulares de agua o aceites condensados en la línea.
e) Cavidades en la línea provocados por malos terminados en las juntas de la tubería.
f) Basura o residuos en los separadores y/o goteos.

Hasta la fecha, no existen ajustes teóricos o empíricos que permitan compensar los efectos que causan las pulsaciones en la medición de flujo, por lo que se recomienda eliminar o disminuir la presencia y/o efectos de tales pulsaciones. Algunas de las acciones que se pueden llevar a cabo para lograr este cometido son:

a) Reubicar el tubo de medición en un lugar más adecuado, o bien, incrementar la distancia existente entre el medidor de orificio y la fuente de las pulsaciones.
b) Insertar entre el medidor de orificio y la fuente de las pulsaciones filtros diseñados específicamente para la causa, o en su caso, tanques (capacitores de volumen) y restricciones de flujo.
c) Adicionar al instrumento de medición de presión diferencial, manifolds de aproximadamente el mismo tamaño de las tomas de presión.

d) Reemplazar la placa de orificio por una que tenga el diámetro del orificio más pequeño, o en su caso, concentrar el flujo que pasa a través de varios medidores a través de un número restringido de ellos.
e) Usar tubos de medición más pequeños y mantener en esencia el mismo diámetro del orificio de la placa, de tal forma que se mantengan los límites de la presión diferencial.

1.5 Ley de Similitud

Los coeficientes empíricos calculados como se especifica en el presente estándar son válidos si existe una similitud dinámica y geométrica entre la instalación del medidor en proceso y la instalación donde se obtuvieron los datos experimentales. A este concepto se le denomina Ley de Similitud. Hoy en día está ley es el principio básico para presentar resultados teóricos y experimentales de la mecánica de fluidos.

La similitud geométrica requiere que el sistema de flujo experimental sea un modelo a escala de las instalaciones de campo. Esto incluye las especificaciones mecánicas del tubo de medición, la placa de orificio, las bridas para la sujeción de la placa, los requerimientos de tubería recta aguas arriba y aguas abajo del elemento primario, el acondicionador de flujo y la instalación del termopozo.

La similitud dinámica implica una correspondencia de las fuerzas del fluido entre el sistema de flujo experimental y el sistema de campo. Para el medidor de orificio, las fuerzas inerciales y viscosas son consideradas como significativas dentro de este estándar. Como resultado, se debe verificar que el número de Reynolds de los dos sistemas de medición sea similar.

1.6 Calibración "*In-Situ*".

Para asegurar la exactitud de las mediciones de flujo, el usuario debe llevar a cabo calibraciones del medidor *In-Situ:* Se entiende por calibración *In-Situ* a aquella calibración que se lleva a cabo bajo condiciones de operación normales, con la misma configuración de tubería, con el mismo fluido y con la placa de orificio y sistema de registro de mediciones que se encuentran realmente instalados en la estación de medición del fluido. Preferiblemente, las calibraciones *In-Situ* deben ser realizadas sobre todo el rango de flujo, temperatura y presión para asegurar un alto nivel de confidencialidad en todo el rango de variación de las condiciones de flujo.

La calibración *In-Situ* requiere el uso de un sistema de medición de referencia cuya incertidumbre total sea menor que la incertidumbre total del sistema de medición que se está calibrando. Este sistema puede ser portátil o instalado permanentemente (medidor maestro que haya sido calibrado con un sistema primario de flujo másico).

La calibración *In-Situ* provee un factor del medidor (MF) que puede ser utilizado para corregir la razón de flujo de masa calculada por el sistema de medición. El Factor del Medidor se define como:

$$MF = \frac{q_{m_r}}{q_{m_i}} = \frac{q_{m_r}}{q_{v_i} q_{t,p}} \tag{16}$$

Donde:

q_{m_r} = *Razón de flujo de masa determinado por el sistema de medición de referencia.*

q_{m_i} = *Razón de flujo de masa determinado por el sistema de medición que está siendo calibrado.*

q_{v_i} = *Razón de flujo volumétrico indicado por el sistema de medición que está siendo calibrado.*

$\rho_{t,p}$ = *Densidad de masa del fluido a condiciones de temperatura y presión T_f y P_f.*

Cuando se obtienen diferentes factores del medidor para varias condiciones de operación, se recomienda trazar una curva de la variación del factor del medidor contra la variación del número de Reynolds. Si el factor del medidor se emplea en la medición de cantidades de flujo para propósitos de transferencia de custodia, entonces las calibraciones *In-Situ* deben realizarse de forma periódica para asegurar mediciones exactas. Una nueva calibración deberá llevarse a cabo siempre que el sistema de medición sufra cambios físicos o de condiciones de operación que sean significativos.

Los resultados de la calibración pueden ser empleados para verificar que el sistema de medición se encuentra dentro de los niveles de incertidumbre considerados para su diseño. Si el factor del medidor está fuera de los límites de $0.9 \leq MF \leq 1.1$, entonces se deberá verificar el sistema de medición hasta determinar y corregir las causa físicas que propiciaron dicha desviación.

La calibración de la instrumentación secundaria también contribuye a la incertidumbre total de la medición de flujo. Los estándares de calibración de esta instrumentación normalmente no consideran correcciones en las lecturas por la fuerza de gravedad local o alguna otra corrección que se indique en los estándares que rigen su calibración. Todos estos factores deben de incluirse dentro del cálculo de flujo, ya que es más exacto este procedimiento que el de permitir que la persona que está llevando a cabo la calibración realice las compensaciones fuera de línea.

1.7 Incertidumbre.

Existen muchos factores que contribuyen a la incertidumbre total de la medición de flujo mediante un medidor de orificio. Entre estos factores se enuncian las tolerancias de construcción de los componentes del medidor, las tolerancias de los coeficientes empíricos de descarga, variaciones en las propiedades físicas del fluido, incertidumbres asociadas con la instrumentación secundaria e incertidumbre asociada con los procedimientos de calibraciones de los dispositivos. En la Fig. 14.1 se muestra una guía de tipo general para valorar el nivel combinado de la incertidumbre asociada a los siguientes parámetros:

a. Coeficiente de descarga.
b. Efectos del Perfil de velocidad.
c. Rugosidad de la tubería, excentricidad de la placa con el tubo de medición y filo del borde del orificio de la placa.

Como se muestra en la Fig. 14.1, las mejores mediciones de flujo se obtienen dentro del rango de $0.10 < \beta < 0.60$ y que el límite de un nivel de incertidumbre aceptable se da para relaciones β de hasta 0.75. NOTA: El nivel de incertidumbre que se muestra en la Fig. 14.1 considera que el perfil de velocidad está libre de efectos de tipo swirl.

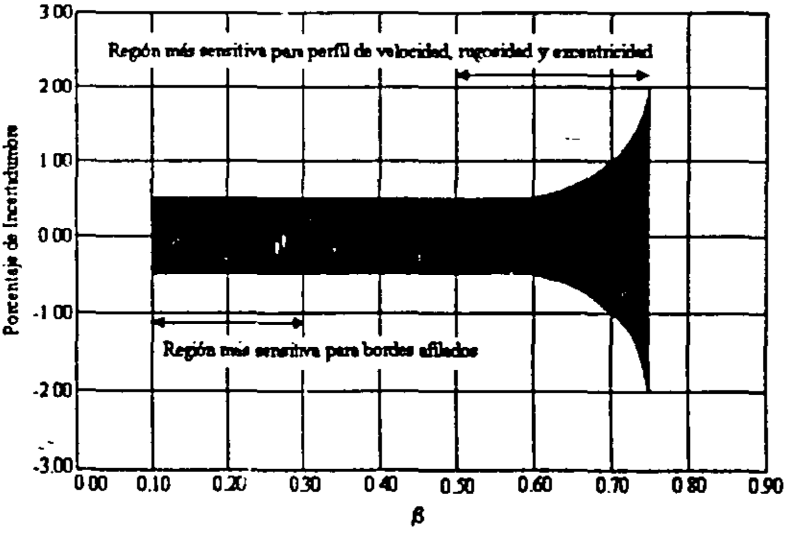


Fig. 14-1 Niveles de Incertidumbre asociados a las condiciones de instalación del medidor de orificio.

La incertidumbre total en la medición de flujo se determina mediante la suma cuadrática de las incertidumbres asociadas a cada una de las variables que intervienen el cálculo del flujo. De la ecuación (1) se tiene que la razón de flujo de masa es una función de

$$q_m = f\left(C_d, Y, \Delta P, d, D, \rho_{t,p}\right)$$

La incertidumbre asociada al coeficiente de descarga está en función de la relación β y del Re_D y su valor será igual al valor que se obtienen de las gráficas que se muestran en la Fig. 14-2 y 14-3. Las placas con diámetro de orificio menor de 11.4 mm (0.45 in) pueden llegar a tener un 3.0% de incertidumbre asociada al coeficiente de descarga, este aumento en incertidumbre se debe a los problemas que existen con el filo de borde del orificio.

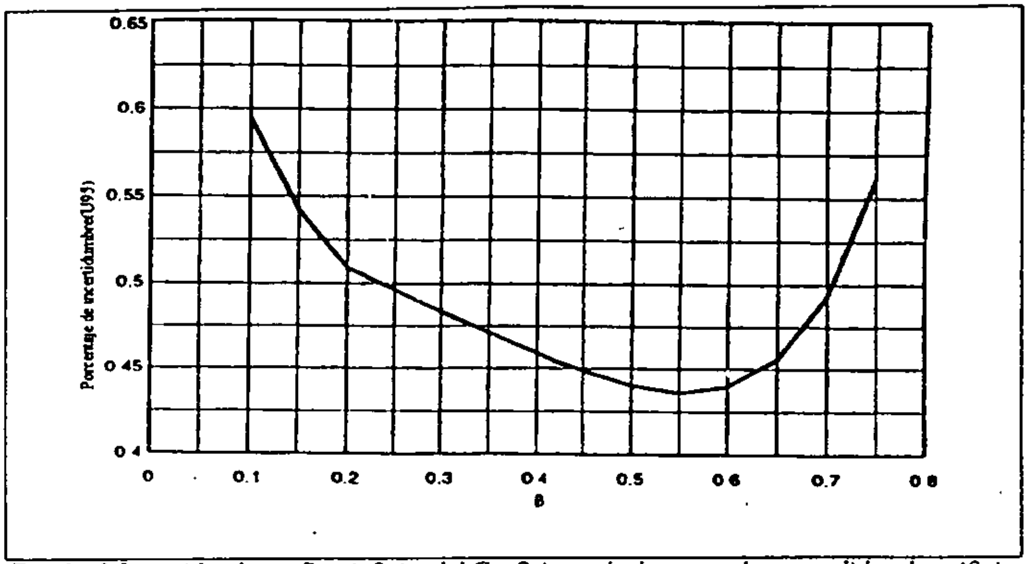


Fig. 14-2 Incertidumbre a Re_D infinito del Coeficiente de descarga de un medidor de orificio.

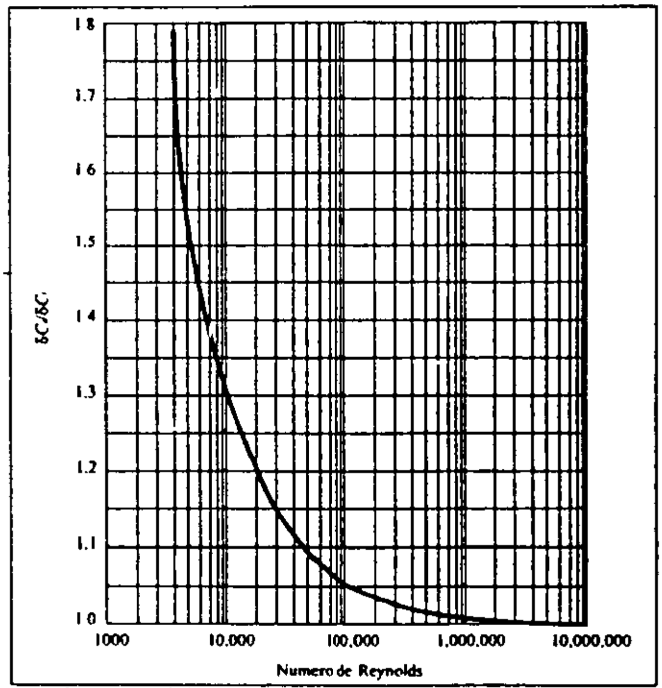


Fig. 14-3 Factor de ajuste del nivel de incertidumbre del coeficiente de descarga

La incertidumbre asociada al factor de expansión se presenta en la Tabla 14-1. Para fluidos que no son compresibles el factor de expansión es 1.0 y su incertidumbre es cero.

TABLA 14.1 Determinación del nivel de incertidumbre asociado al Factor de Expansión Empírico.

Common U. S. Units									
ΔP	Expansion Factor Uncertainty (%) When P_f (psia) Equals								
(inches H_2O_{60})	Psid	50	100	250	500	750	1000	1250	1500
10	0.36	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
50	1.80	0.14	0.07	0.03	0.01	0.01	0.01	0.01	0.00
100	3.61	.29	0.14	0.06	0.03	0.02	0.01	0.01	0.01
150	5.41	0.43	0.22	0.09	0.04	0.03	0.02	0.02	0.01
200	7.22	0.58	0.29	0.12	0.06	0.04	0.03	0.02	0.02
250	9.02	0.72	0.36	0.14	0.07	0.05	0.04	0.03	0.02
300	10.83	0.87	0.43	0.17	0.09	0.06	0.04	0.03	0.03
Common SI Units									
ΔP	Expansion Factor Uncertainty (%) When P_f (psia) Equals								
(inches H_2O_{60})	kPa	0.3	0.7	1.7	3.4	5.2	6.9	8.6	10.3
10	2.49	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
50	12.44	0.14	0.07	0.03	0.01	0.01	0.01	0.01	0.00
100	24.88	0.29	0.14	0.06	0.03	0.02	0.01	0.01	0.01
150	37.33	0.43	0.22	0.09	0.04	0.03	0.02	0.02	0.01
200	49.77	0.58	0.29	0.12	0.06	0.04	0.03	0.02	0.02
250	62.21	0.72	0.36	0.14	0.07	0.05	0.04	0.03	0.02
300	74.65	0.87	0.43	0.17	0.09	0.06	0.04	0.03	0.03

La incertidumbre asociada al diámetro del plato de orificio y del diámetro interno del tubo de medición puede ser determinada a partir del proceso de la medición del diámetro. Para esto, se emplea la siguiente ecuación:

$$\mu d_m = \frac{\delta d_m}{d_m} = \frac{\left[\sum_{i=1}^{n}(\delta d_m)^2 \big/ n-1\right]^{0.5}}{d_m} \text{ X } 100 \qquad (17)$$

$$\mu D_m = \frac{\delta D_m}{D_m} = \frac{\left[\sum_{i=1}^{n}(\delta D_m)^2 \big/ n-1\right]^{0.5}}{D_m} \text{ X } 100 \qquad (18)$$

Donde:

δd_m = *Diferencia del diámetro del orificio con respecto al valor promedio de las mediciones tomadas a* T_m

δD_m = *Diferencia del diámetro del tubo de medición con respecto al valor promedio de las mediciones tomadas a* T_m

μd_m = *Incertidumbre asociada al diámetro del orificio de la placa.*

μD_m = *Incertidumbre asociada al diámetro del tubo de medición.*

La incertidumbre asociada a la presión diferencial (Δp) se obtiene a partir del propio análisis de incertidumbre que se lleva a cabo para el proceso de toma de lecturas de la presión diferencial. Este análisis debe considerar entre sus parámetros la incertidumbre especificada en el certificado de calibración del instrumento, y los efectos de la temperatura ambiental, mecanismos de manejo y el tiempo de respuesta del instrumento. Se hace notar que la selección del instrumento para la medición de la presión diferencial, se basa en el nivel de incertidumbre que se desea tener asociado a este proceso. Para fines prácticos, se asume que la incertidumbre asociada a este parámetro es de 0.5%.

La incertidumbre asociada a la densidad del fluido se obtiene a partir del propio análisis de incertidumbre que se lleva a cabo para el proceso de toma de lecturas de la densidad del fluido; ya sea que la densidad se obtenga por una correlación empírica, tal como se describe en el estándar API MPMS 11.3 para líquidos o la descrita en el estándar API MPMS 14.2 para gases, o bien, que se obtenga a partir de un densitómetro en línea.

2. ESPECIFICACIONES MECANICAS Y REQUERIMIENTOS DE INSTALACION.

Esta parte del estándar provee especificaciones para el diseño y construcción de los sistemas de medición de flujo que emplean medidores de orificio. Es estándar detalla las tolerancias mecánicas caracterizadas por resultados experimentales disponibles.

2.1 Especificaciones de la placa de orificio.

2.1.1 En la Fig. 14.4 se muestra un esquema de las partes que conforman una placa de orificio.

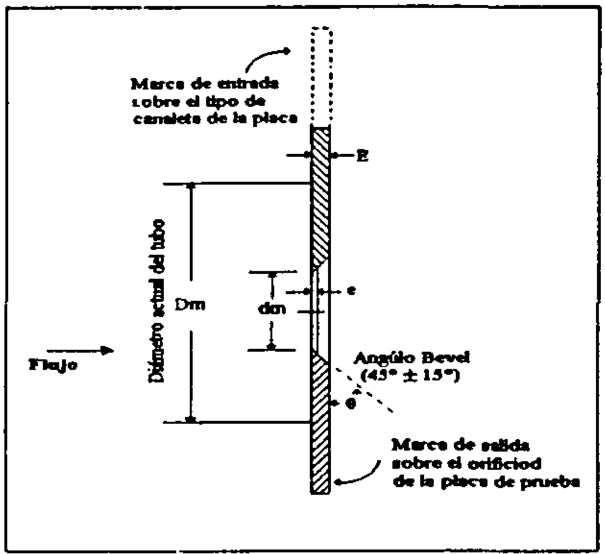


Fig. 14-4 Esquema y símbolos de los componentes de una placa de orificio.

2.1.2 Las superficies de la placa de orificio deberán ser planas. La máxima desviación de planicidad es igual al 1% de la altura del terraplén formado por la superficie de la placa aguas abajo. La altura del terraplén se puede calcular por la expresión $(D_m - d_m)/2$. Esta especificación aplica para cualesquiera dos puntos de la superficie de la placa de orificio que estén dentro del diámetro del tubo de medición. La rugosidad de las superficies de la placa no deberá tener abrasiones o ralladuras que sean visibles a simple vista y que excedan en 50 micropulgadas. La placa deberá mantenerse siempre limpia y libre de acumulaciones de suciedad o de cualquier otro material extraño.

2.1.3 El borde del orificio de la placa de la superficie que está aguas arriba deberá ser cuadrado y afilado. Se considera que el borde es inadecuado para llevar a cabo mediciones con alta exactitud si llega a reflejar un haz de luz desde cualquier perspectiva, o cuando un haz de luz se llega a filtrar cuando se sobrepone contra una placa de orificio con borde calibrado. Los bordes de la placa de orificio (aguas arriba y aguas abajo) deberán estar libres de defectos visibles a simple vista tales como manchas, rugosidades, rebabas, muescas, ralladuras o protuberancias.

2.1.4 La medición del diámetro del orificio (d_m) se define como el promedio aritmético de cuatro lecturas independientes del diámetro. Ninguna de las lecturas puede variar del valor promedio determinado más allá de las tolerancias que se muestran en la Tabla 14.2. La temperatura a la que se encuentra la placa de orificio debe ser tomada al mismo tiempo que se realizan las mediciones de diámetro. El diámetro del orificio (d_r) se define como el diámetro de referencia calculado a la temperatura de referencia (T_r) y se determina como se especifica en la sección 1.3. dentro de la descripción de parámetros de la ecuación de coeficiente de descarga.

TABLA 14.2 Tolerancia de redondez en la medición del diámetro del orificio de una placa.

d_m (in)	Tolerancia (± in)
≤0.250	0.0003
0.376 – 0.375	0.0004
0.376 – 0.500	0.0005
0.501 – 0.625	0.0005
0.626 – 0.750	0.0005
0.751 – 0.875	0.0005
0.876 – 1.000	0.0005
>1.000	0.0005 in por pulgada de diámetro

2.1.5 La superficie interior del orificio de la placa deberá ser de la forma de un cilindro de diámetro constante y no deberá tener defectos tales como ranuras, picaduras o grumos visibles a simple vista. La altura del cilindro es el grosor del orificio de la placa (*e*). El mínimo grosor del orificio de la placa será igual al valor más grande que se obtenga de las siguientes desigualdades.

$$e \geq 0.01\, d_m$$
$$e > 0.005 \text{ in}$$

El máximo grosor del orificio de la placa será igual al valor más pequeño que se obtenga de las siguientes desigualdades.

$$e \leq 0.02\, D_m$$
$$e \leq 0.125\, d_m$$

De cualquier forma el grosor del orificio (*e*) no deberá ser mayor que el grosor de la placa.

2.1.6 El mínimo, máximo y recomendado valor del grosor de la placa de orificio (*E*), para placas de orificio de acero inoxidable se definen en la Tabla 14-3. Los valores de la tabla son válidos para presiones diferenciales que no excedan 200 inH_2O y que las temperaturas de operación no sean mayores de 150°F.

2.1.7 El ángulo de biselado del orificio de la placa (θ) se define como el ángulo entre el biselado y la superficie aguas abajo de la placa. El ángulo permisible del bisel es de 45 ±15 grados.

TABLA 14.3 Especificación de Grosor de una placa de orificio.

Diámetro interior (in)	2	3	4	6	8	10	12	16	20	24	30
Mínimo	0.115	0.115	0.115	0.115	0.115	0.115	0.175	0.175	0.240	0.240	0.370
Máximo	0.130	0.130	0.130	0.163	0.254	0.319	0.379	0.490	0.505	0.505	0.562
Recomienda	0.125	0.125	0.125	0.125	0.125	0.250	0.250	0.375	0.375	0.375	0.500

2.2 Especificaciones del tubo de medición.

2.2.1 El tubo de medición se define como el conjunto que conforma los tramos de tubería recta aguas arriba y aguas abajo de la placa de orificio, los acondicionadores de flujo y el portaplaca, todos ellos deben ser del mismo diámetro. A lo largo del tubo de medición, no deben existir conexiones de tubería a excepción de las tomas de presión y de temperatura, y el acoplamiento del acondicionador de flujo el cual deberá ser bridado.

2.2.2 La rugosidad de la superficie interna del tubo de medición debe ser verificada en aproximadamente las mismas localizaciones axiales que se emplean para determinar y verificar el diámetro interno del tubo. La rugosidad interna del tubo de medición no deberá exceder las siguientes tolerancias:

a) 300 micropulgadas si la relación β es menor que 0.6
b) 250 micropulgadas si la relación β es mayor o igual que 0.6

2.2.3 No deberán existir irregularidades, tales como surcos, raspaduras o arrugas provocadas por uniones, soldaduras, distorsiones y compensaciones que afecten el diámetro interno del tubo de medición más allá de las tolerancias especificadas en la sección 2.2.6. Cuando estas tolerancias sean excedidas, las irregularidades deben ser corregidas. El interior del tubo de medición deberá estar siempre limpio y libre de acumulaciones de contaminantes o de sustancias extrañas.

2.2.4 La medición del diámetro interno del tubo de medición (D_m) se define como el promedio aritmético de cuatro lecturas independientes del diámetro del tubo en un solo plano. La temperatura a la que se encuentra el tubo de medición deberá ser tomada al mismo tiempo que se realizan las mediciones del diámetro. El diámetro interno del tubo de medición (D_r) se define como el diámetro de referencia calculado a la temperatura de referencia (T_r) y se determina como se especifica en la sección 1.3. dentro de la descripción de parámetros de la ecuación de coeficiente de descarga:

2.2.5 Se deberá verificar el diámetro interno del tubo de medición en un mínimo de dos secciones transversales adicionales. Una de las secciones adicionales de verificación deberá estar localizado en una región que tenga como mínimo, dos diámetros nominales de distancia de la superficie de la placa de orificio aguas abajo. La otra sección de verificación deberá localizarse en cualquier región intermedia del tubo de medición aguas arriba de la placa de orificio. Estas mediciones son utilizadas para verificar la uniformidad del diámetro interno del tubo de medición y no deben formar parte de la determinación del valor promedio del diámetro interno del tubo como se especifica en el punto 2.2.4.

2.2.6 Tolerancias y restricciones.

a) El valor absoluto de la diferencia porcentual existente entre la medición del diámetro interno del tubo de medición D_m y cualquier medición individual dentro de la distancia de un diámetro nominal de la superficie aguas arriba de la placa de orificio no deberá exceder del 0.25% de D_m.
b) La diferencia porcentual entre el máximo y mínimo valor de medición de diámetro interno del tubo de medición aguas arriba de la placa de orificio no deberá exceder de 0.5%.
c) El valor absoluto de la diferencia porcentual existente entre la medición del diámetro interno del tubo de medición D_m y cualquier medición individual del diámetro interno del tubo de medición aguas abajo de la placa de orificio no deberá exceder de 0.5%.
d) No deberán existir cambios abruptos en la superficie interna del tubo de medición (protuberancias resultantes por juntas o sellos, compensaciones, crestas, soldaduras y/o uniones).
e) No deben existir rebajos, provocados por una junta o sellado, mayores a 0.25 pulgadas de profundidad. Cuando existan rebajos mayores a 0.25 pulgadas, el nivel de incertidumbre especificado en la sección 1 puede aumentar considerablemente.
f) Todos los dispositivos de sellado y de sujeción de la placa de orificio deberán tener el mismo diámetro interno que el tubo de medición.

2.2.7 El aislamiento térmico del tubo de medición puede ser requerido en caso de que existan extremas diferencias entre la temperatura ambiente y la temperatura del fluído, o bien, para el caso de que los fluidos que están siendo medidos estén cerca de su punto crítico, donde pequeños cambios de temperatura provocarán significativos cambios en la densidad del fluido.

2.3 Especificación de las Bridas.

2.3.1 Las bridas para la instalación del tubo de medición deberán ser construidas y acopladas de tal forma que las especificaciones mecánicas del tubo de medición sean consideradas.

2.4 Especificación de las Tomas de Presión.

2.4.1 Las tomas de presión en las bridas (para la presión diferencial) deberán estar localizadas a 1 pulgada de la superficie de la placa de orificio. La tolerancia de la ubicación de las tomas de presión en las bridas se muestra en la Fig. 14-5. Por ninguna circunstancia. estas tomas deberán ocuparse para alguna otra aplicación que no sea la de la toma de presión.

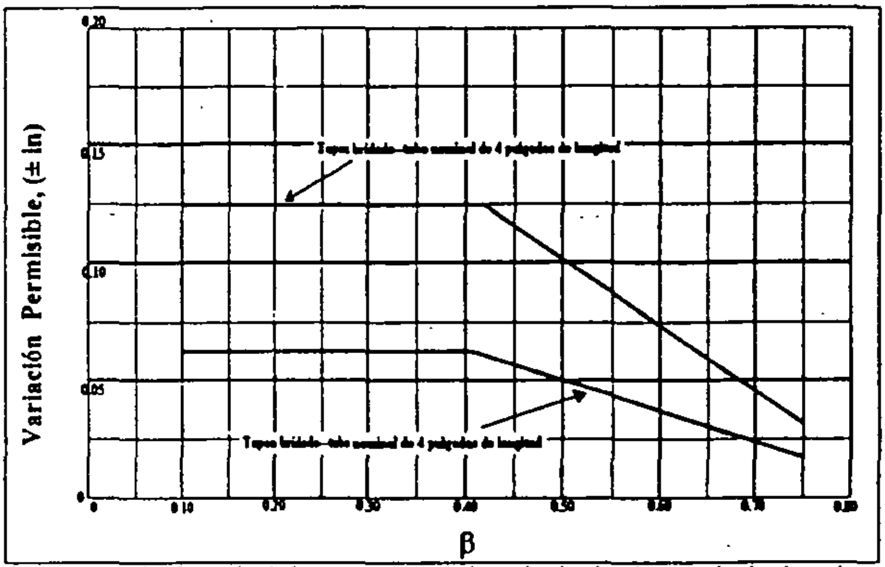


Fig. 14-5 Tolerancias en la ubicación de las tomas de presión en las bridas de sujeción de placa de orificio.

2.4.2 El diámetro de las tomas de presión, medido en la superficie interna del tubo de medición, deberá ser de *3/8 ± 1/64 in* para tubos con diámetro nominal de 2 ó 3 pulgadas y de *½ ± 1/64 in* para tubos de 4 pulgadas o mayores.

2.4.3 El acabado de las tomas de presión, en la superficie interna del tubo de medición, deberá estar libre de rebabas por lo que puede ser ligeramente redondeado.

2.5 Especificación de Acondicionadores de Flujo tipo "Tube Bundle".

2.5.1 Tomando como referencia la Fig. 14-6 se especifica que la sección transversal (*a)* de las venas del acondicionador no deberá ser mayor a un cuarto del diámetro (*D*,) del tubo de medición. El área de la región existente entre cada vena (*A*) no deberá ser mayor a un dieciseisavo del área del tubo de medición. La longitud (*L*) de las venas, deberá ser como mínimo 10 veces la máxima longitud de (*a*). La longitud (*L*) no deberá exceder un medio de la distancia C' que se muestra en las Figs. 14-7, 14-8, 14-9, 14-10 y 14-11; en el dado caso de que esto llegase a suceder, entonces las distancias C' y A' en dichas figuras deberán ser incrementadas. No necesariamente todas las venas deben ser del mismo tamaño; más sin embargo, su arreglo siempre debe ser simétrico.

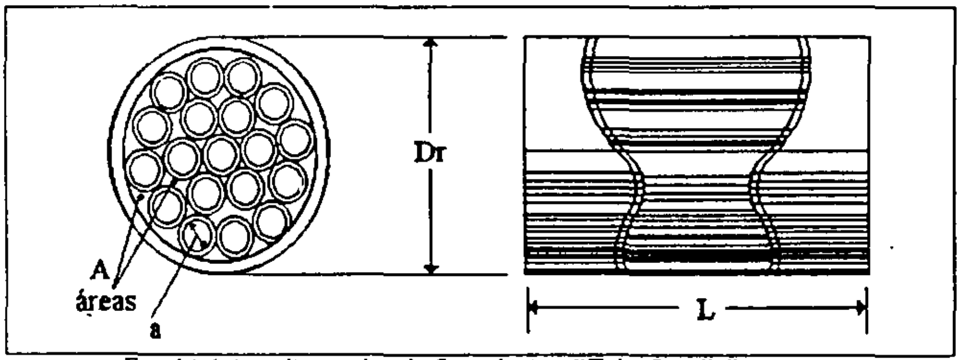


Fig. 14-6 Acondicionador de flujo de tipo "Tube-Bundle".

2.5.2 Las venas pueden ser construidas de tubos de pared delgada, con material de uniforme suavidad y pueden tener forma circular, hexagonal o cuadrada. Deberán estar sujetados con un anillo en cada uno de sus extremos de tal forma que puedan deslizarse dentro del tubo de medición.

2.5.3 La sujeción al tubo de medición deberá ser segura y firme y deberá tenerse cuidado de no distorsionar la simetría de las venas dentro del tubo de medición.

2.5.4 La especificación de otro tipo de acondicionadores, deberá estar soportada por datos de desempeño técnico y las partes involucradas en la medición deberán estar de acuerdo con su empleo. Este estándar no presenta especificaciones de otro tipo de acondicionador de flujo.

2.5.5 Los acondicionadores de flujo deberán mantenerse limpios y libres de residuos que pueden irse acumulando conforma pasa el tiempo.

2.5.6 El empleo de acondicionadores de flujo no garantiza la eliminación de los efectos swirl en el perfil de velocidad, por lo que si esto llegase a suceder entonces existiría un incremento en el nivel de incertidumbre de la medición de flujo.

2.6 Especificaciones de Instalación de la Placa de Orificio.

2.6.1 La placa de orificio deberá ser concéntrica, aguas arriba y aguas abajo, con el elemento de sujeción de la placa de orificio. La excentricidad de la placa de orificio, medida en paralelo a los ejes de las tomas de presión, deberá ser menor o igual que la tolerancia definida por la siguiente ecuación:

$$\varepsilon \leq \frac{0.0025D_m}{0.1 + 2.3\beta^4} \tag{19}$$

Donde:
ε = Excentricidad del orificio de la placa.

2.6.2 La excentricidad de la placa medida perpendicularmente a los ejes a los de las tomas de presión puede ser hasta cuatro veces la cantidad calculada por la ecuación (19).

2.6.3 El dispositivo de sujeción de la placa de orificio, deberá mantener el plano de ésta a un ángulo de 90° con respecto al eje del tubo de medición.

2.6.4 La tolerancia de excentricidad especificada por la ecuación (19) puede ser aumentada al doble si las bridas de sujeción de la placa cuentan con dos tomas de presión (distanciadas 180°) de tal forma que la presión que se obtiene de ellas sea promediada.

2.6.5 La excentricidad relativa en la superficie que está aguas arriba es la más crítica.

2.7 Especificación de Termopozos.

2.7.1 Tomando como referencia las Figs. 14-7, 14-8, 14-9, 14-10 y 14-11; los termopozos deberán localizarse aguas abajo de la placa de orificio y no deberán instalarse a una distancia menor que B y mayor que 4B a partir de la superficie de la placa de orificio.

2.8 Especificación de Longitudes de Tubos de Medición.

NOTA. Existen evidencias de que los efectos de swirl en el flujo requieren 100 o más diámetros de tubería recta para decaer. Dado que no hay datos empíricos que predigan con exactitud el incremento de incertidumbre debido a este efecto, la información que se presenta en esta parte del estándar es sólo una guía para el diseñador de un sistema de medición. En la actualidad, el estudio de los efectos swirl en los sistemas de medición, son un tema de investigación.

2.8.1 Cualquier variación significativa del perfil de flujo provocará errores en la medición. Previniendo esta situación, el estándar presenta una guía para determinar las longitudes mínimas de tubería recta aguas arriba y aguas abajo del elemento primario de medición. Las configuraciones que el estándar presenta se muestran en las Figs. 14-7, 14-8, 14-9, 14-10 y 14-11. Se especifica que para todas aquellas instalaciones que no estén cubiertas explícitamente en alguna de las figuras mostradas, el arreglo de la Fig. 14-7 deberá ser seguido.

2.8.2 Las gráficas que acompañan a las figuras indican los mínimos de longitud de tubo de medición, el cual va variando en función de la relación de diámetros β.

2.8.3 El criterio de diseño para instalaciones nuevas deberá considerar que la relación de diámetros β es igual a 0.75.

2.8.4 Las dimensiones C y C' no deberán ser menores a las que se indican en las gráficas, aun cuando se usen tubos de medición equipados con acondicionadores de flujo y que excedan las especificaciones que se muestran en las gráficas correspondientes.

2.8.5 En la Fig. 14-7 se muestra el arreglo básico de longitudes del tubo de medición. En esta instalación se considera una restricción parcial en la tubería aguas arriba de la placa de orificio.

2.8.6 En la Fig. 14-8 se muestran dos codos en ángulos rectos uno del otro (no en el mismo plano) separados uno del otro por menos de 10D de tubería recta y localizados antes de la tubería recta que conforma el tubo de medición. Cuando la distancia entre los dos codos es muy cercana (menos que 3D) y que están precedidos por un tercer codo que no está en el mismo plano, los requerimientos de tubería recta estipulados para A deben de ser doblados.

2.8.7 La Fig. 14-9 muestra dos codos (en el mismo plano) y separados uno del otro por menos de 10D de tubería recta, localizados antes de la tubería recta que conforma el tubo de medición.

2.8.8 La Fig. 14-10 muestra dos codos (en el mismo plano) y separados uno del otro por más de 10D de tubería recta, localizados antes de la tubería recta que conforma el tubo de medición.

2.8.9 La Fig. 14-11 muestra el empleo de un reductor o expansor de diámetro localizados antes de la tubería recta que conforma el tubo de medición. En este caso la longitud *A' = A + Longitud del acondicionador de flujo*. Esta figura aplica solo para reductores o expansores concéntricos. Cuando los expansores o reductores son excéntricos las longitudes de tubería recta corresponderán a las indicadas en la Fig. 14-7.

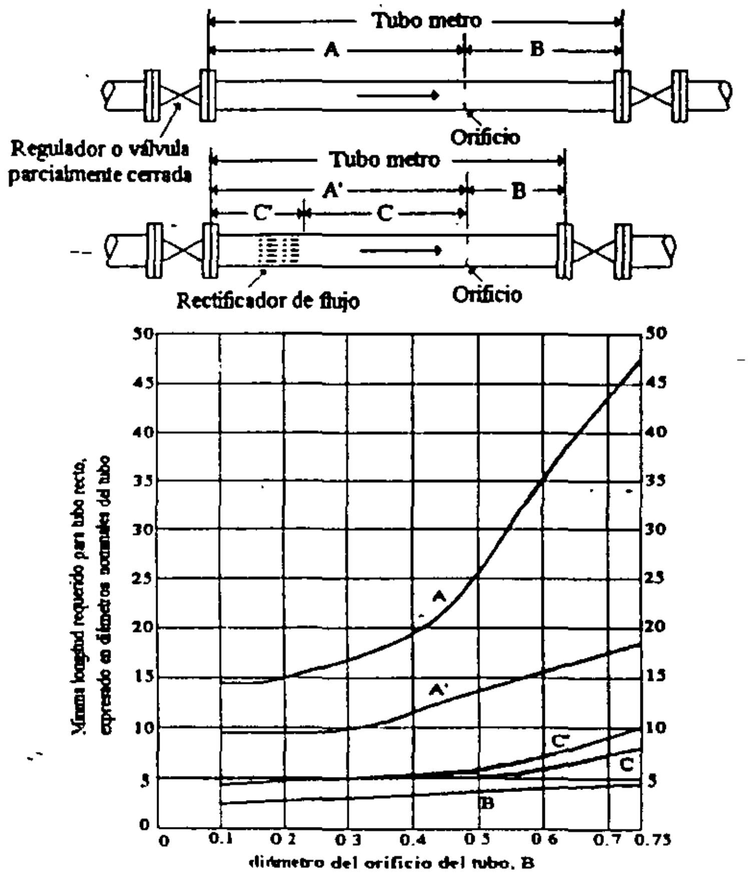


Fig. 14-7 Longitudes del tubo de medición considerando una válvula parcialmente cerrada aguas arriba de la placa de orificio.

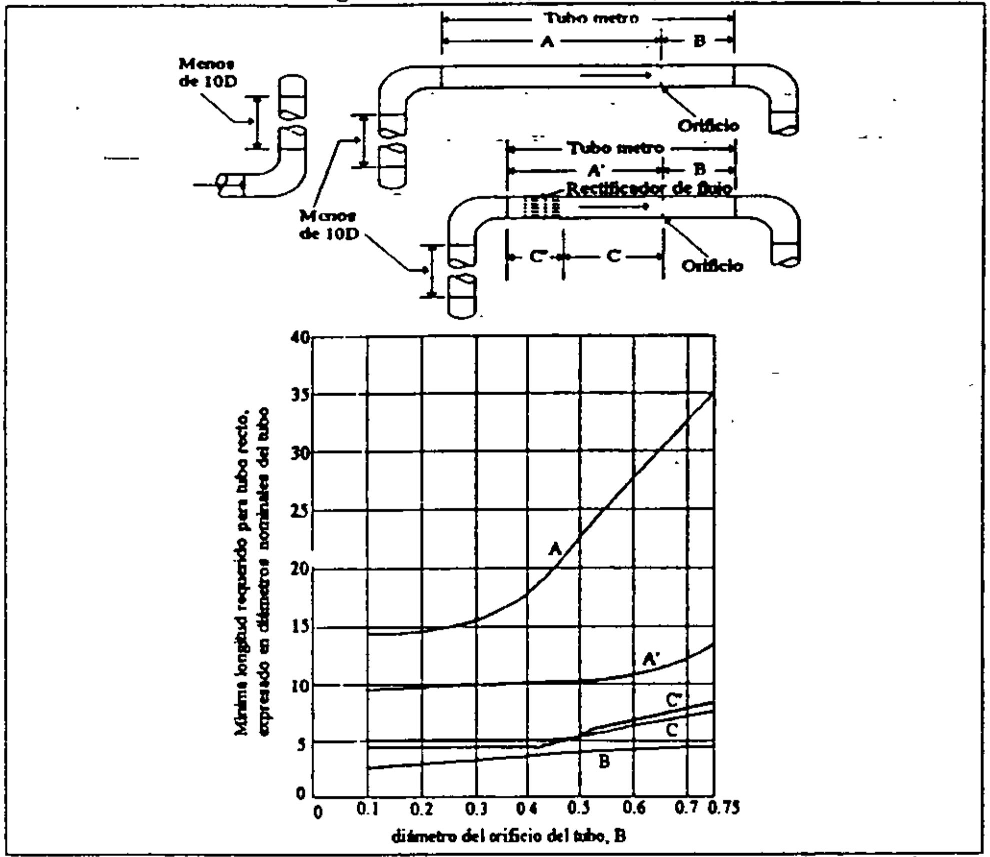


Fig 14-8 Longitudes del tubo de medición considerando dos codos (no en el mismo plano) aguas arriba de la placa de orificio.

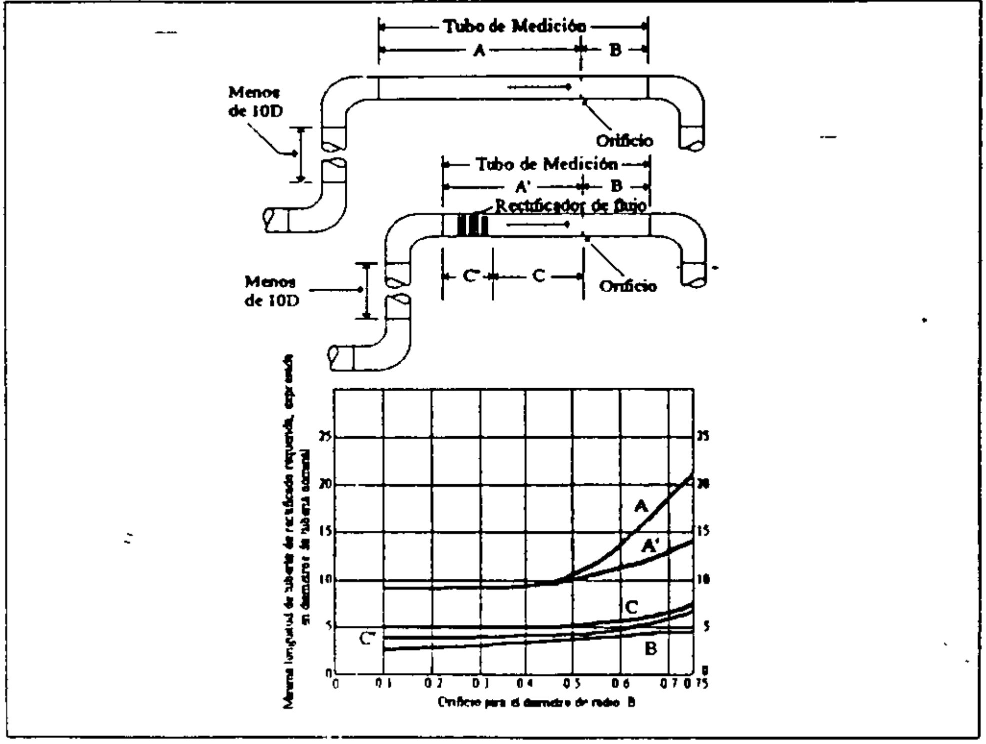


Fig. 14-9 Longitudes del tubo de medición considerando menos de 10D de tubería recta entre dos codos (en el mismo plano) ubicados aguas arriba de la placa de orificio.

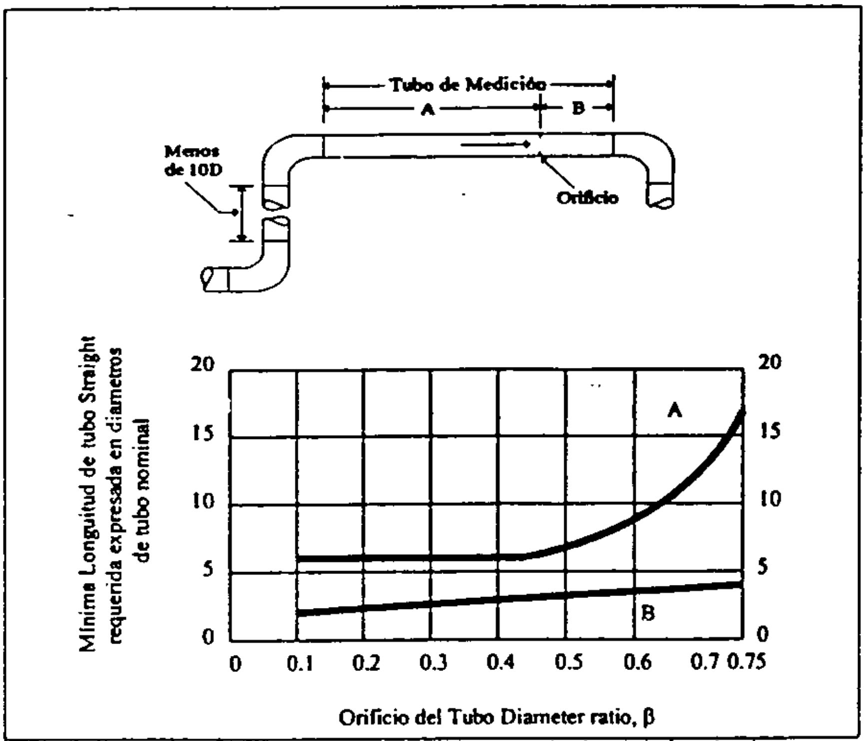


Fig. 14-10 Longitudes del tubo de medición considerando más de 10D de tubería recta entre dos codos (en el mismo plano) ubicados aguas arriba de la placa de orificio.

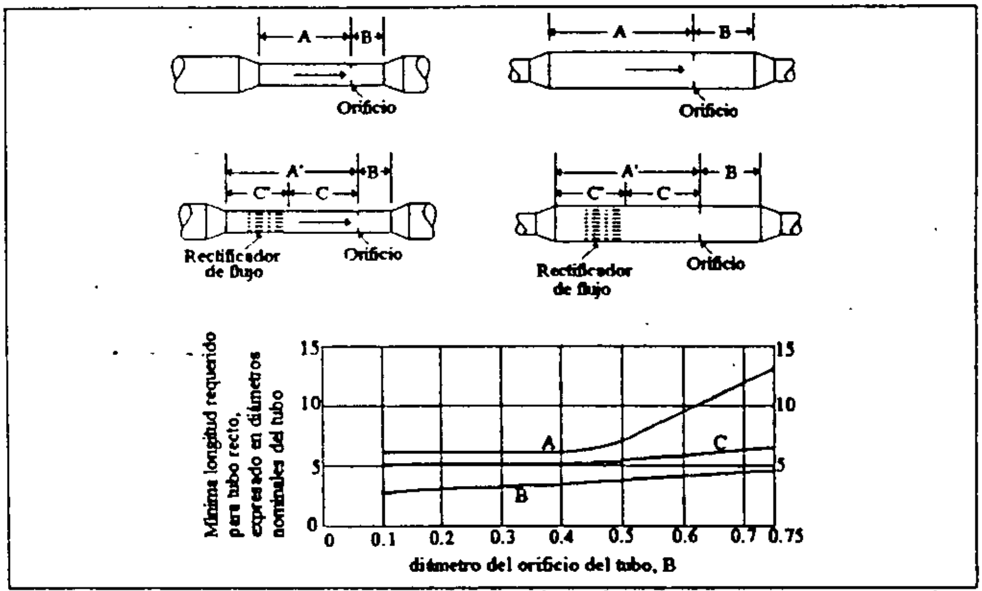


Fig. 14-11 Longitudes del tubo de medición considerando reducciones o expansiones de diámetro en el tubo de medición aguas arriba de la placa de orificio.

3 APLICACION DEL ESTANDAR EN LA MEDICION DE GAS NATURAL.

En esta parte del estándar se presenta una aplicación específica del la Parte 1 del estándar a la medición de gas natural. Las mezclas de gas natural que contempla este estándar son aquellas cuyas composiciones en mol se encuentran dentro de los rangos que se especifican en el estándar API MPMS 14.2. El estándar está orientado al empleo de unidades del sistema inglés. En caso de que se requiera conocer el flujo de masa o volumétrico en el sistema métrico, deberá aplicarse un factor de conversión al final de los cálculos, ya que conversiones intermedias de unidades, pueden no llegar a conducir a resultados consistentes. El medidor de orificio debe ser construido e instalado de acuerdo a los lineamientos que se estipulan en la Parte 2 de este estándar.

NOTA. Los cálculos especificados en esta parte del estándar, son consistentes con los mostrados en la Parte 1; por lo que solo se hará referencia a aquellos cálculos o conceptos que estén directamente relacionados con la medición de gases naturales.

3.1 Razón de flujo de masa de un gas natural.

La razón de flujo de masa de un gas natural, puede ser calculada en función de la densidad del fluido a condiciones de flujo, de la densidad relativa de un gas ideal o de la densidad relativa de un gas real. La ecuación que determina la razón de flujo de masa en función de la densidad del fluido es:

$$Q_m = 359.072 C_d (FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w} \tag{20a}$$

Para calcular la razón de flujo de masa en función de la densidad relativa de un gas ideal es:

$$Q_m = 589.885 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{G_i P_{f_1} h_w}{Z_{f_1} T_f}} \tag{20b}$$

Para calcular la razón de flujo de masa en función de la densidad relativa de un gas real se asume que las condiciones base de referencia son 14.73 psia y 519.67°R (60°F), por lo que la compresibilidad del aire se incorpora a la constante numérica de la ecuación. Así, la ecuación de flujo de masa que está en función de la densidad relativa de un gas real es:

$$Q_m = 590.006 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{Z_s G_r P_{f_1} h_w}{Z_{f_1} T_f}} \tag{20c}$$

Donde:

Q_m = Razón de flujo de masa (lb_m/h).
T_f = Temperatura del fluido (°R).
h_w = Presión diferencial provocada por la placa de orificio (inH_2O a 60 °F).
P_{f_1} = Presión de flujo medida en la toma de presión aguas arriba de la placa de orificio (psia).
ρ_{t,p_1} = Densidad del fluido a condiciones de flujo aguas arriba de la placa de orificio (P_{f_1}, T_f, y Z_{f_1}). (lb_m/ft^3).
ρ_s = Densidad del fluido a condiciones estándar (P_s, T_s). (lb_m/ft^3)
G_i = Densidad relativa de un gas ideal (gravedad especifica).
G_r = Densidad relativa de un gas real (gravedad especifica).
Z_s = Compresibilidad a condiciones estándar (P_s, T_s).
Z_{f1} = Compresibilidad a condiciones de flujo aguas arriba de la placa de orificio (P_{f1}, T_f).

Las respectivas ecuaciones para calcular la razón de flujo volumétrico de gas natural a condiciones estándar, son:

$$Q_v = \frac{359.072 C_d (FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_s} \tag{21a}$$

$$Q_v = 7711.19 C_d (FT) E_v Y_1 d^2 Z_s \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}} \tag{21b}$$

$$Q_v = 7709.61 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \tag{21c}$$

En la ecuación (21c) se incorpora dentro de la constante numérica el valor de compresibilidad del aire ($Z_{b_{air}}$ = *0.99959*) a condiciones estándar de referencia. Para propósitos de la Parte 3 del estándar, se asume que las condiciones base y las condiciones estándar de referencia son las mismas. En el caso de que llegasen a ser diferentes, la razón de flujo volumétrico calculada a condiciones estándar puede ser convertida a condiciones base a través de la siguiente relación:

$$Q_b = Q_v \left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \tag{22}$$

Donde:
Q_b = *Razón de flujo volumétrico a condiciones base* (ft^3/h).
Q_v = *Razón de flujo volumétrico a condiciones estándar* (ft^3/h).
P_b = *Presión base (psia).*
P_s = *Presión estándar (psia.).*
T_b = *Temperatura base (°R)*
T_s = *Temperatura estándar (°R)*
Z_b = *Compresibilidad a condiciones base* (P_b, T_b).
Z_s = *Compresibilidad a condiciones estándar* (P_s, T_s).

La relación de diámetros *β*, el coeficiente de descarga *FT*(C_d), el factor de velocidad de acercamiento E_V y el factor de expansión *Y* se obtienen tal y como se especifica en la Parte 1 de este estándar. El número de Reynolds del flujo de un gas natural, se obtiene directamente de la expresión

$$R_{e_D} = 0.0114541 \left(\frac{Q_b P_b G_r}{\mu D T_b Z_{b_{air}}}\right) \tag{23}$$

Usando un valor promedio para la viscosidad del gas de μ = 0.0000069 lb_f/ft-s, y sustituyendo las condiciones estándar de P_s = *14.73 psia* y T_s = *519.67°R (60°F)*, la ecuación (23) se reduce a

$$R_{e_D} = 47.0723 \frac{Q_v G_r}{D} \tag{24}$$

3.2 Propiedades del gas.

El estándar incluye dentro de uno de sus anexos, un resumen del estándar GPA 2172 (API MPMS 14.5) en donde se especifican los procedimientos de calculo para calcular la capacidad calorífica, la densidad relativa y el factor de compresibilidad de una mezcla de gas natural a partir de su análisis composicional. En el estándar GPA 2172 (API MPMS 14.5) se incluye una lista de propiedades físicas de los componentes predominantes de un gas natural. La lista está considerada como la base de datos más actualizada y completa con respecto a las propiedades físicas de los gases naturales. La lista está tomada del estándar GPA 2145-91.

COMPRESIBILIDAD (Z).

Partiendo de las leyes de los gases ideales·

$$144PV = nRT \tag{25a}$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \tag{25b}$$

Donde·

P = Presión absoluta del gas.
V = Volumen del gas
T = Temperatura absoluta del gas.
R = Constante universal de los gases = 1545.35 (lbf-ft).(lbmol-°R).
n = Número de moles que componen el gas.
144 es una constante numérica requirida para poder manejar la presión en psia.
El sufijo 1 indica que un volumen de gas es medido a determinadas condiciones de presión y temperatura y el sufijo 2 indica que se esta midiendo el mismo volumen de gas a diferentes condiciones de presión y temperatura.

Se define como compresibilidad a la desviación que tienen los gases con respecto a la ley de los gases ideales. El estándar AGA No. 8 (API MPMS 14.2) detalla el método para determinar su valor. Aplicando el término de compresibilidad en la ley de los gases ideales, se obtiene la expresión que representa a los gases reales

$$144PV = nZRT \tag{26a}$$

$$\frac{P_1V_1}{Z_1T_1} = \frac{P_2V_2}{Z_2T_2} \tag{26b}$$

De la ecuación (26b) se deduce la expresión que permite convertir V_{f_1} a V. i.e.

$$V_b = V_{f_1}\left(\frac{P_{f_1}}{P_b}\right)\left(\frac{Z_b}{Z_{f_1}}\right)\left(\frac{T_b}{T_f}\right) \tag{27}$$

Donde:
V_b = Volumen de un gas a condiciones base (P_b, T_b) (ft^3).
V_f = Volumen de un gas a condiciones de flujo (P_f, T_f) (ft^3).

La relación que existe entre Z_b y Z_f, se le denomina factor de supercompresibilidad (F_{pv}). Matemáticamente, se define como

$$F_{pv} = \sqrt{\frac{Z_b}{Z_{f_1}}} \tag{28}$$

DENSIDAD RELATIVA. (GRAVEDAD ESPECIFICA).

La densidad relativa G se define como un número adimensional que expresa la relación que existe entre la densidad del fluido y la densidad de un gas de referencia a las mismas condiciones de temperatura y presión. La industria del gas ha designado como su gas de referencia al aire y las condiciones de referencia de temperatura y presión son 14.73 psia y 519.67°R (60°F).

La densidad relativa de un gas ideal G_i se define como la relación que existe entre la densidad ideal de un gas y la densidad ideal del aire seco a las mismas condiciones de temperatura y presión. Como las densidades ideales son referidas a las mismas condiciones de presión y temperatura, la relación se reduce a una relación de masas molares, por lo que G_i. Puede obtenerse a partir de

$$G_i = \frac{Mr_{gas}}{Mr_{air}} = \frac{Mr_{gas}}{28.9625} \tag{29}$$

Donde:
Mr_{air} = Masa en moles (peso molecular) del aire = 28.9625 (lb_m / lb_{mol}).
Mr_{gas} = Masa en moles (peso molecular) del gas (lb_m / lb_{mol})

DENSIDAD REALTIVA DE UN GAS REAL. (GRAVEDAD ESPECIFICA REAL).

La densidad relativa de un gas real G_r se define como la relación que existe entre la densidad real del gas con la densidad real del aire seco determinadas amabas a las mismas condiciones de temperatura y presión. Para aplicar correctamente G_r al calculo de flujo, las condiciones de referencia para la determinación de G_r deben ser las mismas que las condiciones de referencia para el cálculo de flujo. A condiciones de referencia (P_b, T_b) la densidad relativa de un gas real se expresa como sigue:

$$G_r = \left(\frac{Mr_{gas}}{Mr_{air}}\right)\left(\frac{Z_{b_{air}}}{Z_{b_{gas}}}\right) = G_i\left(\frac{Z_{b_{air}}}{Z_{b_{gas}}}\right) \tag{30}$$

Cuando G_r se determina directamente por sistema de medición de densidad, deberá asegurarse que las mediciones de densidad del gas y del aire sean llevadas a cabo bajo las mismas condiciones de presión y temperatura.

DENSIDAD DEL FLUIDO A CONDICIONES DE FLUJO.

La densidad del flujo ($\rho_{t,p}$) se define como la masa por unidad de volumen a las condiciones de presión y temperatura del fluido. El valor de $\rho_{t,p}$ puede ser calculada por ecuaciones de estado o medida por densitómetros comerciales. Idealmente la densidad debe medirse en la misma lugar donde su ubican las tomas que se emplean para medir la caída de presión en la placa de orificio (flange hole tap), como esto no es posible, entonces debe tenerse presente que si existe una variación significativa de la presión y temperatura entre el punto donde se encuentra la placa de orificio y el punto donde se toma la muestra para el análisis de densidad, entonces puede ser que exista una variación significativa de la incertidumbre en la medición de flujo. Para verificar la operación del densitómetro, se recomienda hacer una comparación entre los valores reportados por el densitómetro y por los valores obtenidos de la ecuación de estado.

Cuando la composición del gas es conocida, la densidad del fluido a condiciones de flujo ($\rho_{t,p}$) y la densidad del gas a condiciones base (ρ_b) pueden ser obtenidas a partir del peso molecular del gas, como sigue. El Peso molecular de un gas se obtiene por la expresión

$$Mr_{gas} = \Phi_1 Mr_1 + \Phi_2 Mr_2 + \ldots + \Phi_w Mr_w = \sum_{i=1}^{w} \Phi_i Mr_i \tag{31}$$

Donde:

Φ_i = Fracción molar del i-seavo componente.

Mr_i = Masa en moles (peso molecular) del i-seavo componte (lb_m / lb_{mol})

De (31) se deduce que

$$n = \frac{m}{Mr_{gas}} \tag{32}$$

Sustituyendo (32) en (26a) y despejando los componentes de volumen y masa, se tiene que

$$\rho_{t,p_1} = \frac{m}{V_{f_1}} = \frac{144 P_{f_1} Mr_{gas}}{Z_{f_1} R T_f} \tag{33}$$

$$\rho_b = \frac{m}{V_b} = \frac{144 P_b Mr_{gas}}{Z_b R T_b} \tag{34}$$

Para determinar $\rho_{t,p}$ y ρ_b a partir de la densidad relativa del gas ideal, es necesario despejar Mr_{gas} de (29) y sustituirlo en (33) y (34), obteniéndose que

$$\rho_{t,p_1} = (2.69881)\frac{P_f G_i}{Z_{f_1} T_f} \tag{35}$$

$$\rho_b = (2.69881)\frac{P_b G_i}{Z_b T_b} \tag{36}$$

Para determinar $\rho_{t,p}$ y ρ_b a partir de la densidad relativa del gas real, es necesario despejar G_i de (30) y sustituirlo en (35) y (36), obteniéndose que

$$\rho_{t,p_1} = \frac{2.69881 P_{f_1} G_r Z_{b_{gas}}}{Z_{f_1} T_f Z_{b_{air}}} \tag{35}$$

$$\rho_b = \frac{2.69881 P_b G_r}{T_b Z_{b_{gas}}} \tag{36}$$

3.3 Cálculo de la razón de flujo empleando el método de factores.

El método de factores puede proveer cálculos de flujo idénticos a los que se obtienen por el método descrito a lo largo del estándar. Aunque el método de los factores, es y ha sido el método más empleado en las instalaciones de medición de flujo, tiene la desventaja de que es mucho más estricto que el método formal, esto se debe principalmente a que los valores obtenidos para cada factor son únicamente válidos para aquellos valores de variables que se ajustan exactamente a los especificados dentro de las bases de datos que se incluyen en el estándar. El manejo de conversiones de unidades debe llevarse a cabo con sumo cuidado y la extrapolación de los datos mostrados en las tablas de datos no es permitida.

El método de factores tiene como finalidad el calcular la razón de flujo a condiciones estándar mediante el empleo de bases de datos que evitan el manejo de una gran cantidad de cálculos que pueden propiciar errores o retardos en el cálculo. Para este propósito se asumen las siguientes condiciones estándar o base.

$$\begin{aligned} G_{r_{air}} &= 1.000 \\ P_b &= P_s = 14.73 psia \\ T_b &= T_s = 519.67°R \\ T_f &= 519.67°R \\ Z_b &= Z_s \\ Z_{b_{air}} &= 0.999590 \end{aligned} \tag{37}$$

A partir de la ecuación de razón de flujo a condiciones base

$$Q_b = 218.573 C_d (FT) E_v Y_1 d^2 \frac{T_b}{P_b}\sqrt{\frac{P_{f_1} Z_b Z_{b_{air}} h_w}{G_r Z_{f_1} T_f}} \tag{32}$$

Si ahora se sustituye (32) y (37) en (22) y se resuelve para Q_v se tiene que

$$Q_v = 218.573\left(\frac{519.67}{14.73}\right)\sqrt{\frac{1}{519.67}}C_d(FT)E_vY_1d^2\left(\frac{T_b}{519.67}\right)\sqrt{0.999590}\times\left(\frac{14.73}{P_b}\right)\sqrt{\left(\frac{519.67}{T_f}\right)\left(\frac{1}{G_r}\right)\left(\frac{Z_b}{Z_{f_1}}\right)}\sqrt{P_{f_1}h_w} \qquad (32)$$

reagrupando se tiene que

$$Q_v = F_n\left(F_c + F_{sl}\right)Y_1F_{pb}F_{tb}F_{tf}F_{gr}F_{pv}\sqrt{P_{f_1}h_w} \qquad (32)$$

Donde:

Cada uno de estos factores puede ser calculado individualmente a partir de las siguientes expresiones

$$F_n = \frac{338.196D^2\beta^2}{\sqrt{1-\beta^4}} \qquad (33)$$

$$F_C = C_i(FT) = f(\beta, \mathrm{Re}_D, D) \qquad (34)$$

$$F_{sl} = 0.000511\left[\frac{10^6\beta}{\mathrm{Re}_D}\right]^{0.7} + (0.0210 + 0.0049A)\beta^4C = f(\beta, \mathrm{Re}_D) \qquad (35)$$

$$F_{pb} = \frac{14.73}{P_b} \qquad (36)$$

$$F_{tb} = \frac{T_b}{519.67} \qquad (37)$$

$$F_{tf} = \sqrt{\frac{519.67}{T_f}} \qquad (38)$$

$$F_{gr} = \sqrt{\frac{1}{G_r}} \qquad (39)$$

$$F_{pv} = \sqrt{\frac{Z_b}{Z_{f_1}}} \qquad (40)$$

El estándar incluye tablas de valores para diferentes datos de entrada de cada uno de los factores. Existen algunos limitantes para el empleo de cada una de las tablas. La tabla de valores para F_n, F_C y F_{sl} consideran que $T_f = 68$°F, $G_r = 0.6$, $\mu = 0.000069$, $k = 1.3$, $P_b = 14.73$ psia y $T_b = 519.67$°R. La tabla para F_{pv} sólo aplica para gases con gravedad específica de 0.6 y que no contengan nitrógeno o dióxido de carbono. Por ninguna razón debe interpolarse algún dato, es su caso, se recomienda seguir el procedimiento de cálculo que se enuncia en el estándar AGA No. 8 (API MPMS 14.2).

4. ANTECEDENTES, DESARROLLO, PROCEDIMIENTOS DE IMPLEMENTACION Y DOCUMETNACION DE SUBRUTINAS.

En esta parte del estándar se describen los antecedentes e historia del desarrollo del estándar. Además, se recomienda un método prototipo para solucionar las ecuaciones de masa y/o de volumen que se mencionan en la parte 1 del estándar.

4.1 Reseña histórica del estándar.

En 1924, la Natural Gas Association (Posteriormente llegó a ser el Natural Gas Department del AGA) conformo un comité de trabajo (Gas Measuremnt Committee) que se abocaría exclusivamente a la medición de gas natural. Los objetivos iniciales fueron:

- Determinar los correctos métodos de instalación de medidores de orificio.

- Determinar los requerimientos operativos y los factores de corrección necesarios para el empleo de los medidores de orificio en la medición.

En 1927 el comité presentó su primer reporte, el cual fue publicado hasta 1930. En la introducción de dicha publicación se especificaba que aunque se habían encontrado resultados coherentes, era necesario continuar con los estudios analíticos y experimentales, aun inclusive sobre los resultados ya encontrados, ya que había algunos datos que no habían quedado del todo cerrados.

En 1931 el comité comenzó a trabajar en conjunto con el Special Research Committee of Fluid Meters de la ASTM con la principal finalidad de que las publicaciones de estos dos comités estuvieran en armonía. El segundo reporte del Gas Measurement Committee fue publicado en 1935 y la gran diferencia que existía con respecto al primero el rango de condiciones de aplicación era mucho más amplio. Este segundo reporte estuvo basado en un reporte técnico elaborado en conjunto por AGA/ASME.

Fue hasta 1955 cuando apareció el Reporte No. 3 del comité. En este se incluían las especificaciones de medidores de orificio de mayor diámetro y se consideraban los adelantos que tenía la industria para fabricar las placar de orificio. En 1969 hubo una revisión del Rporte No. 3, la cual no tuvo mayores cambios y solo se adicionó información que había sido desarrollada desde su publicación original.

En 1975 el Committee on Petroleum Measurement de la API adoptó el Reporte No. 3 como parte de su manual de estándares en la medición del petróleo (MPMS) y lo aprobó para publicarlo como el capitulo 14.3 del MPMS. El API sometió el Reporte No. 3 al ANSI para convertirlo en un estándar nacional. El ANSI aprobó el Reporte No. 3 en 1977 y fue identificado como ANSI/API 2530.

Durante 1982-1983 el API trabajó en conjunto con el AGA y la GPA para revisar el estándar. La revisión de 1983 provocó cambios de forma ya que el formato original fue alterado para proveerlo de mayor claridad y facilidad en su aplicación. Asimismo, se adicionaron varias representaciones equivalentes de las fórmulas que determinan la razón de flujo. La ecuación de estado para el gas natural y un amplio trabajo relacionado al cálculo del factor de compresibilidad también fue incluido dentro de esta revisión. Todo el trabajo relacionado al cálculo del factor de compresibilidad fue adoptado por el AGA y lo emitió como su Reporte No. 8. ANSI aprobó la revisión de 1983 en 1985.

En la actual revisión, la principal actualización consistió en la ecuación que determina el coeficiente de descarga. Esta nueva ecuación está soportada por una extensa colección de datos de alta calidad. Las condiciones de instalación no han cambiado desde la revisión de 1983. Actualmente, los grupos de investigación están trabajando sobre este particular, pudiendo ser posible que nuevas especificaciones de niveles de incertidumbre sean provistos en la nueva revisión.

4.2 Procedimientos de implementación.

Los procedimientos de implementación que se presentan consisten en razones de flujo calculadas a partir de diferentes datos de entrada. Se detalla el procedimiento de tipo general que se sigue para obtener tales resultados; posteriormente, y mediante un programa de computadora, se obtiene una serie de resultados, los cuales pueden ser empleados para verificar cualquier programa de cómputo desarrollado para llevar a cabo los cálculos que se presentan dentro del estándar. El procedimiento de implementación detalla dos casos específicos; la aplicación de los cálculos presentados en la parte uno del estándar (aplicación de tipo general) y la aplicación de los cálculos presentados en la parte tres del estándar (aplicación para gases naturales).

SECCION 14.2 FACTORES DE COMPRESIBILIDAD PARA GAS NATURAL Y OTROS GASES DE HIDROCARBUROS.

1. RESUMEN.

La medición de flujo de gas requiere para su cálculo el factor de compresibilidad a condiciones de flujo (Z_f) y el factor de compresibilidad a condiciones base (Z_b); asimismo, requiere la densidad del fluido a condiciones de flujo y a condiciones base (ρ_f y ρ_b).

En este estándar se precisan los cálculos para estimar, con una alta exactitud, las densidades y los factores de compresibilidad del gas natural y/o de otros hidrocarburos que se encuentren en forma gaseosa como lo es el metano, etano, nitrógeno, dióxido de carbono, hidrógeno y mezclas de gas de hasta 21 componentes. Las ecuaciones de estado que se presentan describen su incertidumbre asociada, la cual, forma parte del total de incertidumbre asociada a la medición de flujo.

La metodología que se presenta en este estándar puede ser aplicada directamente en los cálculos de volumen y/o de razón de flujo de gas. Asimismo, puede ser empleada en todo aquel cálculo donde sea importante o predominante la relación entre temperatura, presión y volumen de gas, como es el caso de estudios de capacidad calorífica, entalpía, entropía, factor de flujo crítico, diseño de toberas sónicas, diseño de intercambiadores de calor, etc.

El alcance del estándar, contempla a todas aquellas mezclas de gases que estén dentro de los rangos de propiedades físicas y de composiciones molares que se muestran en la Tabla 1. NO SE RECOMIENDA EMPLEAR LOS CALCULOS DESCRITOS EN ESTE ESTÁNDAR PARA AQUELLOS CASOS DONDE LAS COMPOSICIONES MOLARES DE LOS GASES ESTEN FUERA DE LOS RANGOS ESTIPULADOS EN LA TABLA 1. LOS CALCULOS SOLO APLICAN PARA AQUELLOS FLUIDOS QUE SE ENCUENTREN EN FASE GASEOSA Y QUE SE ENCUENTREN DENTRO DEL RANGO DE TEMPERATURAS DE -130°C a 400°C (-200°F a 760°F) Y CON PRESIONES DE HASTA 280 MPa (40000 psia). EL USO DE LOS METODOS DE CALCULO NO SE RECOMIENDA CUANDO LAS CONDICIONES DEL GAS ESTEN DENTRO DE LA VECINDAD DEL PUNTO CRITICO.

Tabla 1 Características y Rangos de mezclas de gas, que aplican en el presente estándar.

Cantidad	Rango Normal	Rango Expandido
Densidad Relativa*	0.554 a 0.87	0.07 a 1.52
Capacidad calorífica bruta**	477 a 1150 Btu/scf	0 a 1800 Btu/scf
Capacidad calorífica bruta***	18.7 a 45.1 MJ/m^3	0 a 66 MJ/m^3
%mol de Metano	45.0 a 100.0	0 a 100 .0
%mol de Nitrógeno	0 a 50.00	0 a 100.0
%mol de Dióxido de Carbono	0 a 30.0	0 a100.0
%mol de Etano	0 a 10.0	0 a 100.0
%mol de Propano	0 a 4.0	0 a 12.0
%mol de Butano	0 a 1.0	0 a 6.0
%mol de Pentano	0 a 0.3	0 a 4.0
%mol de Hexano +	0 a 0.2	0 a punto de condensación
%mol de Helio	0 a 0.2	0 a 3.0
%mol de Hidrógeno	0 a 10.0	0 a 100.0
%mol de Monóxido de Carbono	0 a 3.0	0 a 3.0
%mol de Argón	#	0 a 1.0
%mol de Oxígeno	#	0 a 21.0
%mol de Agua	0 a 0.05	0 a punto de condensación
%mol de Acido Sulfhídrico	0 a 0.02	0 a 100.0

* *Condición de referencia: Densidad relativa a 60°F y 14.73 psia.*
** *Condición de referencia: Combustión a 60°F y 14.73 psia; densidad a 60°F y 14.73 psia.*
*** *Condición de referencia: Combustión a 25°C y 0.101325 MPa; densidad a 0°C y 0.101325 MPa.*
 # El rango normal es considerado a ser cero para estos componentes.

En general, el estándar describe dos ecuaciones de estado. El "Método de Caracterización Detallado" y el "Método de Caracterización Grosso". La diferencia entre los dos métodos son los datos de entrada que necesita cada ecuación. En el primer caso, se debe conocer a detalle la composición del gas por lo que puede ser empleado dentro de todo el rango de presiones, temperaturas y composiciones que se especifican en la Tabla 1. El segundo método solo requiere un conocimiento grosso de la composición del gas (dado por la capacidad calorífica (H_{CH}) y/o por la densidad relativa) y se recomienda su uso para aquellos gases que se encuentren dentro del rango de temperatura de 0°C a 55°C (32°F a 130°F) y presiones de hasta 8.3 MPa (1200 psia), además de que sus características físicas estén dentro de las que se estipulan en la columna de "Rango Normal" de la Tabla 1.

NOTA 1. Ambos métodos requieren el empleo de temperatura y presión en unidades absolutas, así como un análisis inicial del gas para determinar el método que puede ser aplicado.

NOTA 2. La capacidad calorífica de una mezcla de gas (H_{CH}) puede ser calculada a partir del valor ideal de capacidad calorífica bruta de los componentes del hidrocarburo. Cuando la composición del gas natural no es conocida, H_{CH} puede ser estimado a partir de datos de caracterización del gas natural. (Véase estándar GPA 2172/API MPMS 14.5). Los datos necesarios de caracterización son la densidad relativa del gas natural (G_r), la capacidad calorífica bruta por unidad de volumen (HV), la cantidad existente en la mezcla de gas de dióxido de carbono y de Nitrógeno.

2. MÉTODO DE CARACTERIZACIÓN DETALLADO.

Este método fue desarrollado para describir con una alta exactitud el comportamiento de la presión-temperatura-densidad de las mezclas de gas natural, así como el de ciertos componentes puros (en estado gaseoso) como lo es el metano, etano, dióxido de carbono, nitrógeno, hidrógeno sobre un amplio rango de condiciones físicas. Adicionalmente, se desarrolló una correlación de baja densidad para el propano e hidrocarburos más pesados, así como para aquellas mezclas binarias de éstos con el metano, etano, nitrógeno y dióxido de carbono. El método reduce la incertidumbre asociada al factor de compresibilidad y a los cálculos de densidad para gases naturales que provienen de separadores los cuales pueden llegar a contener más del 1% de %mol de hidrocarburos más pesados que el C_6+.

Correlaciones del comportamiento de la densidad del ácido sulfhídrico puro *(H_2S)*, así como mezclas binarias del H_2S con metano, etano, nitrógeno y dióxido de carbono, fueron desarrolladas para reducir el estimado de incertidumbre para gases naturales que contengan H_2S (Gases amargos).

Finalmente, se desarrollaron correlaciones viriales para el agua y mezclas binarias de agua con metano, etano, nitrógeno y dióxido de carbono para reducir el estimado de incertidumbre para gases naturales que contienen vapor de agua (Gases húmedos).

2.1 Ecuación de estado para determinar el factor de compresibilidad.

La ecuación de estado que se determina es el resultado de una formulación híbrida, ya que combina las características de una ecuación virial de estado para condiciones de bajas densidades (series de potencia en densidad) y funciones exponenciales para aplicaciones de altas densidades. La ecuación de estado provee una alta exactitud en un amplio rango de temperatura-presión-composición del gas y provee propiedades termodinámicas asociadas al gas. La ecuación de estado para determinar el factor de compresibilidad del gas está dada por:

$$Z = 1 + \frac{DB}{K^3} - D\sum_{n=13}^{18} C_n^* T^{-u_n} + \sum_{n=13}^{18} C_n^* T^{-u_n} \left(b_n - c_n k_n D^{k_n}\right) D^{b_n} \exp\left(-c_n D^{k_n}\right) \qquad (1)$$

Donde·

a_n, b_n, c_n, k_n, u_n, g_n, q_n, f_n, s_n, w_n = Constantes de Tablas
E, K, G, Q, F, S y W (Parametros caracterizados de Energia, Tamaño, Orientacion, Cuatripolos, Alta Temperaturaa.

Bibolos y Asociacion respectivamente) = Constantes de Tablas. E_{ij}, U_{ij}, K_{ij}, G_{ij} *Valores de parámetros empleados en la interacción binaria de los componentes = Constantes de Tablas..* d = *densidad molar* N = *Numero de componentes en la mezcla de gas* x = *Fracción molar de cada componente de la mezcla.*
$D = K^3 d$ ... *(Densidad reducida)*
$K^5 = \left[\sum_{i=1}^{N} x_i K_i^{\frac{5}{2}}\right]^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} x_i x_j (K_{ij}^5 - 1)(K_i K_j)^{\frac{5}{2}}$
$B = \sum_{n=1}^{18} a_n T^{-u_n} \sum_{i=1}^{N}\sum_{j=1}^{N} x_i x_j E_{ij}^{u_n} (K_i K_j)^{\frac{3}{2}} B_{nij}^*$
$C_n^* = a_n (G + 1 - g_n)^{g_n} (Q^2 + 1 - q_n)^{q_n} (F + 1 - f_n)^{f_n} U^{u_n}$
$B_{nij}^* = (G_{ij} + 1 - g_n)^{g_n} (Q_i Q_j + 1 - q_n)^{q_n} (F_i^{\frac{1}{2}} F_j^{\frac{1}{2}} + 1 - f_n)^{f_n} (S_i S_j + 1 - s_n)^{s_n} (W_i W_j + 1 - w_n)^{w_n}$
$E_{ij} = E_{ij}^* (E_i E_j)^{\frac{1}{2}}$
$G_{ij} = \frac{G_{ij}^* (G_i + G_j)}{2}$
$U^5 = \left[\sum_{i=1}^{N} x_i E_i^{\frac{5}{2}}\right]^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} x_i x_j (U_{ij}^5 - 1)(E_i E_j)^{\frac{5}{2}}$
$G = \sum_{i=1}^{N} x_i G_i + \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} x_i x_j \left(G_{ij}^* - 1\right)\left(G_i + G_j\right)$
$Q = \sum_{i=1}^{N} x_i Q_i$
$F = \sum_{i=1}^{N} x_i^2 F_i$

Cuando la composición, temperatura y presión (absoluta) del gas son conocidas, lo que se requiere es determinar la densidad molar. Para esto se sustituye la ecuación de estado en la expresión de densidad molar, dando como resultado:

$$P = dRT\left[1 + Bd - D\sum_{n=13}^{18} C_n^* T^{-U_n}\left(b_n - c_n k_n D^{k_n}\right) D^{b_n} \exp\left(-c_n D^{k_n}\right)\right] \qquad (2)$$

La densidad molar se obtendrá empleando procedimientos iterativos apropiados sobre la ecuación (2). Como se puede observar, antes de calcular la densidad molar será necesario obtener los coeficientes B y C_n los cuales deben ser calculados a partir de la composición y la temperatura del gas.

3. MÉTODO DE CARACTERIZACIÓN GROSSO.

En este método la caracterización del gas natural es ya sea por un análisis composicional, o bien, usando una combinación de las características a, b y c; o una combinación de las características a, b y d que se enuncian a continuación:

a) La capacidad calorífica bruta por unidad de volumen a condiciones de referencia de 77°F, 14.696 psia para moles ideales y de 32°F, 14.696 psia para densidad molar.
b) La densidad relativa (gravedad específica) a condiciones de referencia de 32°F, 14.696 psia.
c) La fracción en moles de dióxido de carbono.
d) La fracción en moles de Nitrógeno.

Este método fue desarrollado considerando las características de gas natural que se muestran en la Tabla 2, para calcular con exactitud los factores de compresibilidad de gases naturales dulces y secos. Se recomienda usar este método para cálculos de factores de compresibilidad y densidades de gases que se encuentren a temperatura de 32°F a 130°F, presiones de hasta 1200 psia y que sus características físicas estén dentro de las que se estipulan en la columna de "Rango Normal" de la Tabla 1.

Tabla 2 Rangos nominales de características de gas natural a partir datos usados en la prueba de los métodos detallado y grosso para la obtención del factor de compresibilidad

Cantidad	**Rango**
Densidad Relativa*	0.554 a 0.87
Capacidad calorífica bruta**	477 a 1150 Btu/scf
Capacidad calorífica bruta***	18.7 a 45.1 MJ/m^3
%mol de Metano	45.2 a 98.3
%mol de Nitrógeno	0.3 a 53.6
%mol de Dióxido de Carbono	0.04 a 28.94
%mol de Etano	0.24 a 9.53
%mol de Propano	0.02 a 3.57
%mol de Butano	0.01 a 1.08
%mol de Pentano	0.002 a 0.279
%mol de Hexano +	0.0005 a 0.1004
%mol de Helio	0 a 0.158

*, **, *** se definen de la misma forma que en la Tabla 1.

3.1 Ecuación de estado para factor de compresibilidad.

La ecuación de estado determina con una alta exactitud los factores de compresibilidad para gases naturales cuyas concentraciones de componentes están dentro de los rangos dados en la Tabla 2, con menos de 0.1% de moles de agua y 0.05% de moles de ácido sulfhídrico. La ecuación de estado es de tipo virial ya que es una expansión polinomial de la densidad. Cada término de la densidad es precedido por un coeficiente virial. Los coeficientes viriales son función de la temperatura y de la composición. Aplicando la metodología descrita por SGERG, la ecuación virial es truncada después del tercer término de la serie. Este método provee alta exactitud en la determinación del factor de compresibilidad en líneas de transmisión de gas normal, pero esta limitada su aplicación para sistemas con densidades y presiones moderadas.

El método grosso trata a una mezcla de gas como una mezcla de solo tres componentes. Un hidrocarburo equivalente, nitrógeno y dióxido de carbono. El hidrocarburo equivalente CH representa a todos los hidrocarburos que se encuentran en la mezcla de gas. El nitrógeno y el dióxido de carbono son los diluentes. El método puede también incluir hidrógeno y monóxido de carbono con una relación fija. En el caso del estándar, estos últimos no son considerados ya que el gas que se emplea en USA raramente contiene estos elementos.

El método grosso expresa el factor de compresibilidad en términos de la densidad molar y del segundo y tercer coeficiente virial de la mezcla (B_{mix} y C_{mix} respectivamente). Matemáticamente, la expresión para determinar el factor de compresibilidad es:

$$Z = 1 + B_{mix}d + C_{mix}d^2 \qquad (3)$$

Donde:

d = densidad molar

N = Número de componentes en la mezcla de gas.

x_i, x_j, x_k = Fraccion molar de cada componente de la mezcla.

B_{mix} = Segundo coeficiente Virial de la mezcla.

C_{mix} = Tercer coeficiente Virial de la mezcla

$$B_{mix} = \sum_{i=1}^{N}\sum_{j=1}^{N} B_{ij}x_i x_j$$

$$C_{mix} = \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{N} C_{ijk}x_i x_j x_k$$

Sólo se consideran tres componentes en la mezcla del gas (componentes i, j y k) los cuales son CO_2, N_2 y CH. donde los dos primeros son los diluentes. Los términos B_{ij} y C_{ijk} y son funciones que dependen de la temperatura absoluta en una forma de ecuación cuadrática. Para los coeficientes viriales del Nitrógeno y del Dióxido de Carbono la expresión que los determina es:

$$B_{ij} = b_0 + b_1 T + b_2 T^2 \tag{4}$$

$$C_{ijk} = c_0 + c_1 T + c_2 T^2 \tag{5}$$

Donde:
b_0, b_1, b_2, c_0, c_1, c_2, se obtienen de la Tabla 3.
T = Temperatura absoluta

Para los coeficientes viriales del CH se emplea

$$\begin{gathered} B_{CH-CH} = B_0 + B_1 H_{CH} + B_2 H_{CH}{}^2 \\ B_i = b_{i0} + b_{i1} T + b_{i2} T^2, \quad \mathrm{i} = 0,1,2 \end{gathered} \tag{6}$$

$$\begin{gathered} C_{CH-CH-CH} = C_0 + C_1 H_{CH} + C_2 H_{CH}{}^2 \\ C_i = c_{i0} + c_{i1} T + c_{i2} T^2, \quad \mathrm{i} = 0,1,2 \end{gathered} \tag{7}$$

Donde:
B_{i0}, b_{i1}, b_{i1}, c_{i0}, c_{i1}, c_{i2}, se obtienen de la Tabla 4.
H_{CH} = Capacidad calorífica bruta molar.

La Capacidad calorífica bruta molar se obtiene a partir de dos diferentes métodos iterativos, los cuales toman como datos de entrada la densidad relativa (G_r), la composición del dióxido de carbono y la capacidad calorífica por unidad de volumen (HV) o la composición del nitrógeno.

Tabla 3 Constantes para determinar los coeficientes viriales del Nitrógeno y Dióxido de Carbono

Fluido para B_{ij}	**b_0 (dm^3/mol)**	**b_1 (dm^3/mol K)**	**b_2 (dm^3/mol K^2)**
N_2-N_2	-0.144600	0.740910X10^{-3}	-0.911950X10^{-6}
CO_2-CO_2	-0.868340	0.403760X10^{-2}	-0.516570X10^{-5}
CO_2-N_2	-0.339693	0.161176X10^{-2}	-0.204429X10^{-5}
Fluido para B_{ijK}	**c_0 (dm^6/mol^2)**	**c_1 (dm^6/mol^2 K)**	**C_2 (dm^6/mol^2 K^2)**
N_2-N_2-N_2	0.784980X10^{-2}	-0.398950X10^{-4}	0.611870X10^{-7}
CO_2-CO_2-CO_2	0.205130X10^{-2}	0.348880X10^{-4}	-0.837030X10^{-7}
CO_2-N_2-N_2	0.552066X10^{-2}	-0.168609X10^{-4}	0.157169X10^{-7}
CO_2-CO_2-N_2	0.358783X10^{-2}	0.806674X10^{-5}	-0.325798X10^{-7}

Tabla 4 Constantes para determinar los coeficientes viriales del Hidrocarburo equivalente CH.

	i	**b_{i0}**	**b_{i1}**	**b_{i2}**
B_0(dm^3/mol)	0	-0.425468	0.286500X10^{-2}	-0.462073X10^{-5}
B_1(dm^3/kJ)	1	0.877118X10^{-3}	-0.556281X10^{-5}	0.881510X10^{-8}
B_2(dm^3 mol/kJ^2)	2	-0.824747X10^{-6}	0.431436X10^{-8}	-0.608319X10^{-11}
	i	**c_{i0}**	**c_{i1}**	**c_{i2}**
C_0(dm^6/mol^2)	0	-0.302488	0.195861X10^{-2}	-0.316302X10^{-5}
C_1(dm^6/mol-kJ)	1	0.646422X10^{-3}	-0.422876X10^{-5}	0.688157X10^{-8}
C_2(dm^6/kJ^2)	2	-0.332805X10^{-6}	0.223160X10^{-8}	-0.367713X10^{-11}

4. INCERTIDUMBRE.

La evaluación de la incertidumbre del factor de compresibilidad calculado ya sea por el método detallado o grosso. se dedujeron a partir de la comparación de los resultados que arroja el método contra los factores de compresibilidad definidos en las tablas de datos emitidos por el GRI y el GERG. Las bases de datos se obtuvieron mediante procedimientos experimentales con gas natural cuyas características físicas son las que se describen en la Tabla 2. También se hicieron comparaciones con datos experimentales de componentes puros y mezclas binarias.

l valor de incertidumbre asociado al factor de compresibilidad calculado por el método de caracterización detallado son los que se muestran en la Fig. 1 siempre y cuando los gases se encuentren dentro de los rangos estipulados en la columna de "Rango Normal" de la Tabla 1. Para aquellos gases cuyas propiedades físicas están dentro de los rangos estipulados en la columna de "Rango expandido" de la Tabla 1 la incertidumbre asociada a la aplicación del método será mayor que los que se describen en la Fig. 1, quedando particularmente fuera de la Región 1.

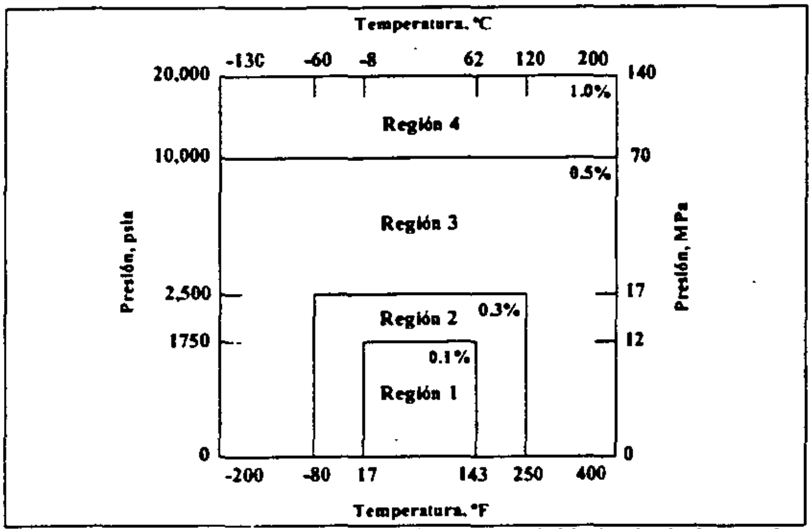


Fig. 1. Estimación de incertidumbre para factores de compresibildad calculados mediante el método de caracterización detallado.

Cuando el factor de compresibilidad es calculado mediante el empleo del método de caracterización grosso, el valor de incertidumbre asociado será el que se muestra en la Fig. 1 dentro de la Región 1 siempre que se emplee este método para gases naturales cuyas características físicas estén dentro de las que se describen en la columna de "Rango Normal" de la Tabla 1. EL METODO NO DEBERA SER EMPLEADO FUERA DE ESTOS LIMITES. Se sobrentiende que el valor de incertidumbre que se muestra en la Fig. 1 ya aglutina todas las posibles fuentes de error que pueden incurrir en la aplicación de las ecuaciones que se describen en el estándar.

5. PROGRAMAS DE CÓMPUTO DE LOS FACTORES DE COMPRESIBILIDAD, DE SUPERCOMPRESIBILIDAD Y DE DENSIDADES.

En la Fig.2 se muestra un diagrama a bloques sobre la secuencia que debe llevar un programa para determinar computacionalemente el factor de compresibilidad, el factor de supercompresibilidad, la densidad molar y la densidad de masa de una mezcla de gas, empleando el método de caracterización detallado. Si se desea incluir este procedimiento computacional a un programa en línea de la medición de gas entonces se deberá tener presente la secuencia de subrutinas que se muestran en la Fig. 3 para optimizar los tiempos de cálculo y desempeño del algoritmo. Para el caso del cálculo por el método de caracterización grosso, se muestran las figuras 4 y 5.

El estándar presenta un algoritmo detallado para poder implementar los procedimientos de calculo descritos dentro de un programa de computadora. Los algoritmos presentados consideran el empleo de unidades de ingeniería en el Sistema Métrico por lo que la temperatura absoluta estará dada en Kelvins (K), presión en Megapascales (MPa), densidad molar en moles por decímetro cúbico (mol/dm^3), la capacidad calorífica por unidad de volumen de un gas real en Kilojoules por decimetro cúbico (kJ/dm^3) y la capacidad calorífica por moles ideales de un gas real en Kilojoules por mol (kJ/mol).

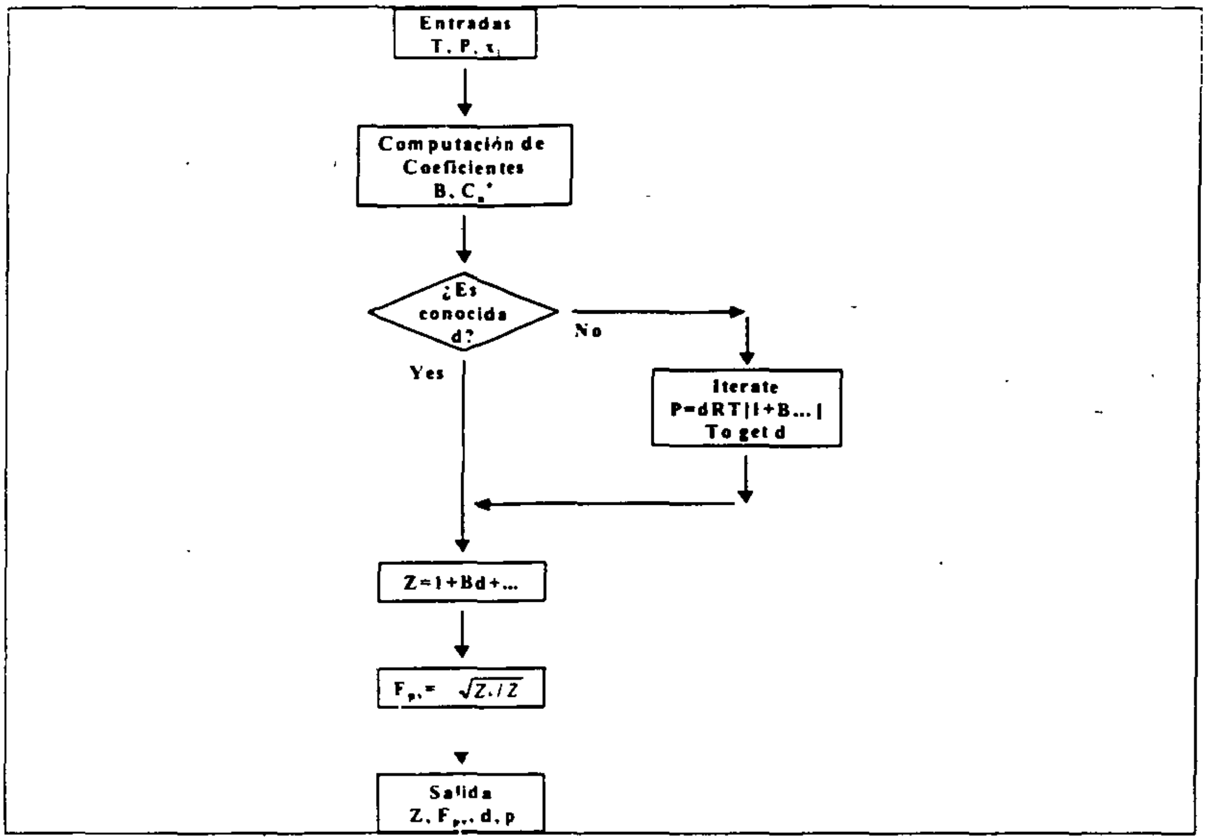


Fig. 2. Fig 4. Procedimiento para calcular Z, F_{pv}, d y ρ, por el método de caracterización detallado.

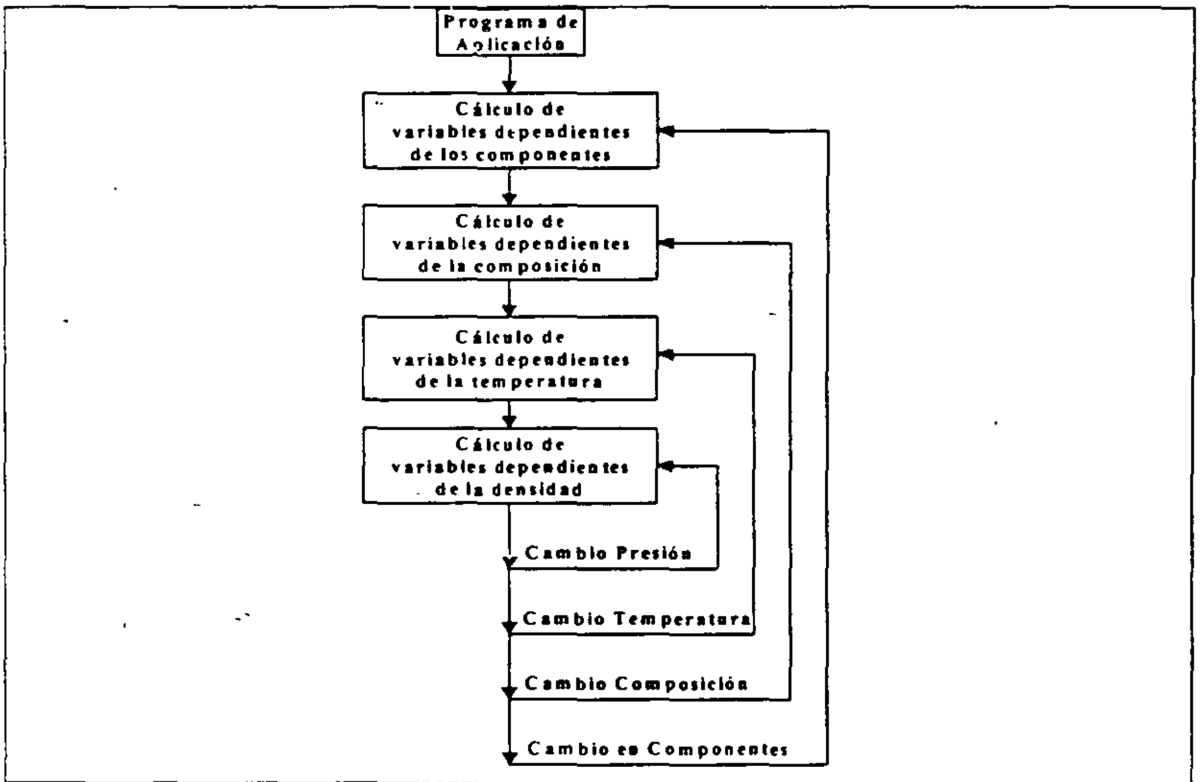


Fig. 3 Secuencia de programa de computadora para el método de caracterización detallado.

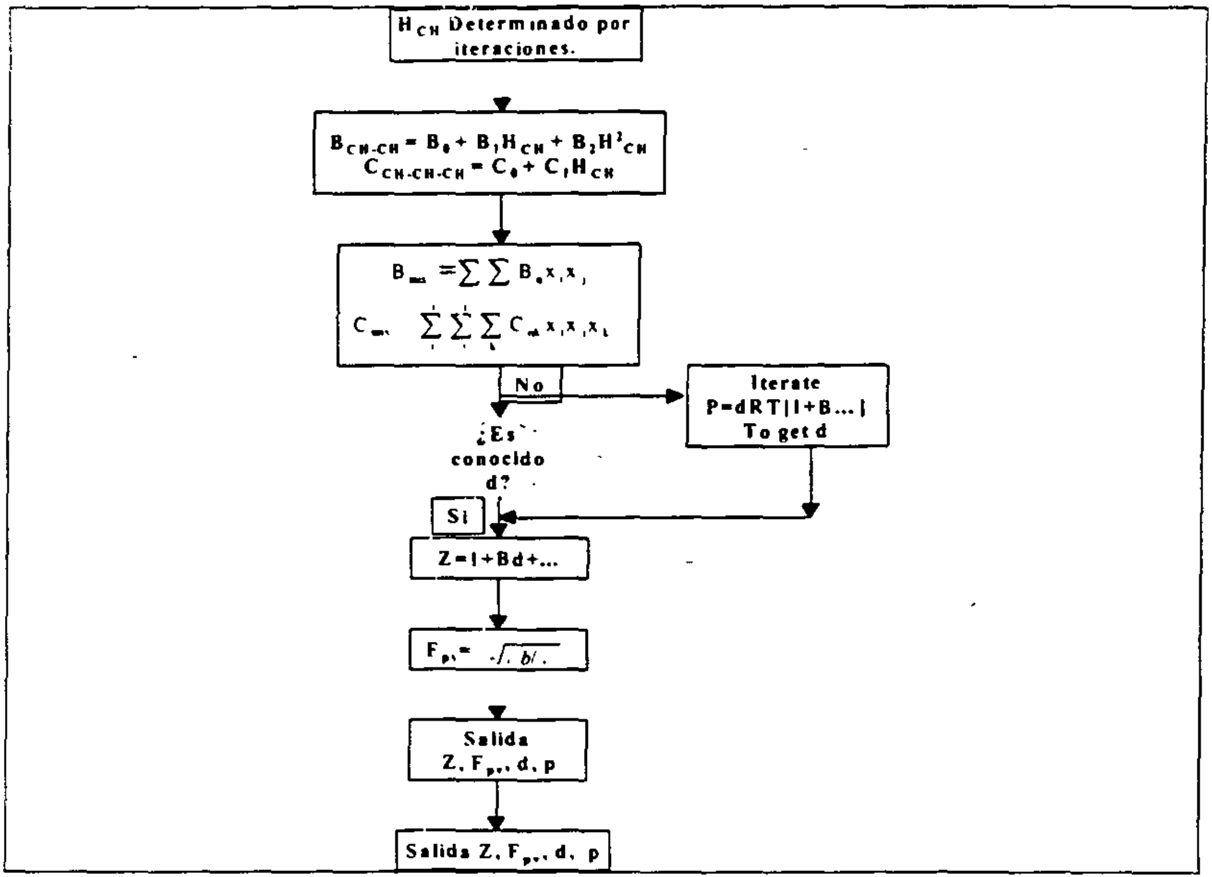


Fig. 4. Procedimiento para calcular Z, F_{pv}, d y ρ, por el método de caracterización grosso.

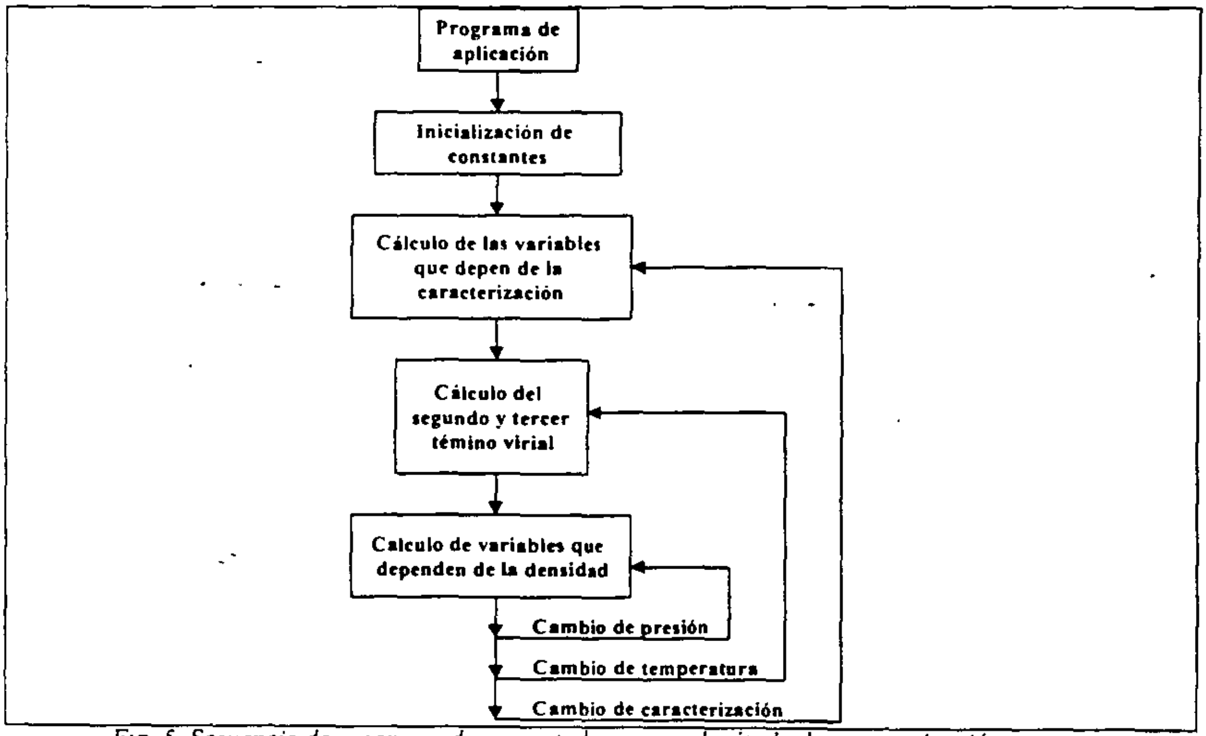


Fig. 5. Secuencia de programa de computadora para el método de caracterización grosso.

SECCION 14.5 CALCULO DE LA CAPACIDAD CALORIFICA BRUTA, DENSIDAD RELATIVA Y FACTOR DE COMPRESIBILIDAD PARA MEZCLAS DE GAS NATURAL A PARTIR DE UN ANALISIS COMPOSICIONAL.

1. RESUMEN.

Este estándar es publicado por la Gas Processors Association (GPA) como estándar GPA 2172. El estándar presenta el procedimiento para calcular, con base al análisis composicional, la capacidad calorífica bruta, la densidad relativa (real e ideal) y el factor de compresibilidad de una mezcla de gas natural. Para esto, es necesario incluir dentro del análisis practicado a la muestra, todos aquellos componentes (exceptuando el agua) que tengan fracciones molares mayores o igual a 0.0001. Algunas rutinas de análisis ignoran algunos componentes como lo son el Helio y el Acido Sulfhídrico, pero se hace notar que su consideración es importante para la exactitud de los cálculos. La aplicación de este estándar está orientada a las estaciones de transferencia de custodia.

La capacidad calorífica es una propiedad del gas evaluada sobre una base por unidad de masa Hm. Esta propiedad es técnicamente catalogada como una propiedad ideal Hm id. Desde un punto de vista práctico, la medición de flujo de masa no encuentra diferencia entre un gas ideal y un gas real. El valor es convertido a capacidad calorifica por pie cubico HV usando la siguiente relación El valor de HV se usa como un factor para calcular la razón de flujo de energía, o la energía total que pasa a través del medidor de flujo. HV es un parámetro que se emplea en las especificaciones del producto (gas natural)

2. ECUACIONES.

La Capacidad Calorífica Bruta por unidad de volumen de un gas seco se determina a partir de la expresión

$$Hv^{id}(dry) = x_1 Hv_1^{id} + x_2 Hv_2^{id} + \dots + x_N Hv_N^{id} = \sum_{i=1}^{N} x_i Hv_i^{id} \tag{1}$$

$$Hv^{id}(sat) = (1 - x_w) Hv^{id}(dry) \tag{2}$$

Donde:

Hv^{id} = *Capacidad Calorífica Bruta por unidad de Volumen a temperatura y presión base.*

x_i = *fracciones de moles por cada componente de la mezcla de gas.*

N = *Número total de componentes, excluyendo al agua.*

$x_w = \frac{P_w^{sat}}{P_b}$ = *fracción de moles de agua en el gas.*

P_w^{sat} = *presión de vapor del agua a la temperatura base.*

P_b = *Presión base.*

el superlativo (id) indica propiedad de un gas ideal, (sat) indica gas saturado con agua, (dry) indica gas seco..

En la ecuación (2) se presenta el caso de que el análisis composicional se hace considerando que el gas es seco pero en realidad el gas está saturado con agua, es necesario ajustar las fracciones en mol para tomar en cuenta el hecho de que el agua ha desplazado algo de gas disminuyendo por lo tanto su capacidad calorifica. En el caso de que el análisis composicional determine la fracción en moles del agua, entonces la expresión que se emplea para determinar la capacidad calorífica bruta es:

$$Hv^{id} = \sum_{i=1}^{N} x_i^{dry} Hv_i^{id} - x_w Hv_w^{id} \tag{3}$$

Es necesario remover el efecto del agua porque, aunque el agua tiene un determinado poder calorífico, éste sólo es un efecto de condensación.

En la siguiente tabla se dan algunos valores (dentro de USA) para el efecto de la presencia de agua en la mezcla de gas para algunas presiones base considerando una temperatura base de 60°F y una presión de vapor del agua de 0.25636 psia.

P_b (psia)	$1 - x_w$
14.50	0.9823
14.696	0.9826
14.73	0.9826
15.025	0.9829

En la siguiente tabla se dan algunos valores (fuera de USA) para el efecto de la presencia de agua en la mezcla de gas para algunas temperaturas base considerando una presión base de 1 atm.

T_b (°C)	$1 - x_w$
0	0.9940
15	0.9832
20	0.9769
25	0.9687

El cálculo de la densidad relativa a partir de la composición de la mezcla de gas se obtiene por la expresión:

$$G^{id} = x_1 G_1^{id} + x_2 G_2^{id} + \ldots + x_N G_N^{id} = \sum_{i=1}^{N} x_i G_i^{id} \qquad (4)$$

Donde.
G_i^{id} *es la densidad relativa de un gas ideal Datos de tabla de propiedades de componentes de gas natural a 60°F y 14.696 psia (Estándar GPA 2145)..*

FACTOR DE COMPRESIBILIDAD.

El factor de compresibilidad a ser utilizado en aplicaciones de transferencia de custodia, es el que se obtiene a partir de la metodología que se presenta en el estándar AGA Reporte No. 8 (API MPMS 14.2). Sin embargo, si el usuario desea obtener dicho factor de una manera simple y rápida, se recomienda emplear la siguiente fórmula

$$Z = 1 - P_b \left[\sum_{i=1}^{N} x_i b_i \right] \qquad (5)$$

Donde:
B_i *= Factores indicados por tabla de propiedades de componentes de gas natural a 60°F y 14.696 psia (Estándar GPA 2145)*

SECCION 14.4 CONVERSION DE MASA DE LIQUIDOS Y VAPORES DE GAS NATURAL A SU EQUIVALENTE EN VOLUMEN LIQUIDO.

1. RESUMEN.

Este estándar es técnicamente idéntico al estándar GPA 8173. Fue desarrollado en conjunto por el API y el GPA. El estándar describe un método para convertir la masa medida de gas natural a condiciones de operación, a su equivalente en volumen a temperatura estándar 15°C (60°F) y presión de equilibrio.

La determinación del volumen y de la densidad absoluta, y la toma de muestra y su análisis, deberán llevarse a cabo como se indica en el API MPMS 14.7. La densidad absoluta de un hidrocarburo puro en Kg/m^3 (pounds/gallon) se determina en el estándar GPA 4125.

2. PRECAUCIONES.

a. El equipo, instalación y operación del sistema de medición deberá cumplir estrictamente con lo especificado en el API MPMS 14.7.
b. El estándar solo aplica para fluidos de una fase, homogéneos y Newtonianos.
c. Para determinar con exactitud la masa de un fluido, se deberá determinar la densidad a la misma presión y temperatura con que se llevó a cabo la medición de volumen. La densidad puede ser medida directamente o calculada de acuerdo a lo que se especifica en el estándar API MPMS 14.7
d. El equipo de medición y de muestreo deberán ubicarse en un lugar que no sean afectados por pulsaciones del fluido.

3. METODO DE CALCULO.

3.1 CONVERSION DEL %MOL DE LA MEZCLA DE GAS, EN FRACCIONES DE PESO.

Dado el análisis composicional de la mezcla en %mol y el peso molecular que se muestra en el estándar GPA 2145 para cada componente.

a. Multiplicar el porcentaje en moles de cada componente por su respectivo peso molecular.
b. Dividir el producto de la multiplicación realizada a cada componente, entre la suma de los productos de todos los componentes, obteniéndose de esta forma la fracción de peso de cada uno de los componentes.

3.2 CALCULO DE LA MASA DE CADA UNO DE LOS COMPONENTES.

Dada la masa total en Kg (pounds) y la fracción de peso de cada componente.

a. Multiplicar la fracción de peso por el total de masa, obteniéndose así, la masa en pounds (Kg) por cada componente.
b. Sumar la masa de todos los componentes para asegurarse de que la suma es igual a la masa total.

3.3 CALCULAR EL VOLUMEN DE CADA COMPONENTE A 60°F (15°C) Y A LA PRESION DE EQUILIBRIO.

Dado la densidad absoluta de cada componente del estándar GPA 2145 y la masa de cada uno de los componentes.

a. Dividir la masa de cada componente entre su densidad absoluta para obtener su equivalente en volumen.
c. El equivalente en volumen total será igual a la suma de todos los equivelentes de volumen de cada componente.

4. EJEMPLO.

PASO 1

Componentes	Porcentaje Mol		Peso Molecular		Porcentaje Molecular X Peso Molecular		Suma de Porcentaje Molecular X Peso Molecular		Fracción de Peso
CO_2	0.11	X	44.010	=	4.84	/	4372.27	=	0.001107
C_1	2.14		16.043		34.33		4372.27		0.007852
C_2	38.97		30.070		1171.83		4372.27		0.268014
C_3	36.48		44.097		1608.66		4372.27		0.367923
IC_4	2.94		58.123		170.88		4372.27		0.039083
NC_4	8.77		58.123		509.74		4372.27		0.116585
IC_5	1.71		72.150		123.38		4372.27		0.028219
NC_5	1.82		72.150		131.31		4372.27		0.030032
C_6+	7.06		87.436		617.30		4372.27		0.141185
	100.00				4372.27				1.000000

PASO 2

Componentes	Fracción de Peso		Masa Total (Kilogramos)		Masa Composición (Kilogramos)
CO_2	0.001107	X	374,350	=	414
C_1	0.007852		374,350		2,939
C_2	0.268014		374,350		100,331
C_3	0.367923		374,350		137,732
IC_4	0.039083		374,350		14,631
NC_4	0.116585		374,350		43,644
IC_5	0.028219		374,350		10,564
NC_5	0.030032		374,350		11,242
C_6+	0.141185		374,350		52,853
	1.000000				374,350

PASO 3

Componentes	Masa Composición (Kilogramos)		Densidad (Kilogramos/m^3)		Metros Cubcos a 15 °C, EVP
CO_2	414	/	821.94	=	0.50
C_1	2,939		300.00		9.80
C_2	100,331		357.76		280.44
C_3	137,732		507.30		271.50
IC_4	14,631		562.98		25.99
NC_4	43,644		584.06		74.73
IC_5	10,564		624.35		16.92
NC_5	11,242		631.00		17.82
C_6+	52,853		713.10		74.12
	374,350				771.82

SECCION 14.1 RECOLECCION Y MANEJO DE MUESTRAS DE GAS NATURAL PARA TRANSFERENCIA DE CUSTODIA.

1. RESUMEN.

La medición, el muestreo y el análisis son las tres principales funciones críticas para determinar con exactitud el valor de un gas natural. En esta sección se describen el sistema de muestreo que conglomera los procedimientos de recolección, acondicionamiento y manejo de muestras de gas natural. El estándar considera el muestreo de gases dulces y amargos y la toma de muestras en líneas de baja y alta presión. No se incluye el muestreo de líquidos o de fluidos multifásicos. El estándar está orientado a sistemas de medición de transferencia de custodia.

2. SONDAS DE MUESTREO.

El objetivo de la sonda es recolectar una muestra del fluido que sea lo suficientemente representativa. El diseño de la sonda debe considerar la posible resonancia que se llega a inducir en ella debido a la alta velocidad del fluido.

Para seleccionar el tipo de sonda de muestreo, se debe definir el tipo de flujo que fluye en la línea. En general, el flujo turbulento es ventajoso para cualquier sistema de muestreo, ya que la misma turbulencia conduce a un fluido bien mezclado evitando la separación de los componentes del gas debido a la gravedad. La existencia de líquido en la línea puede provocar daños en el sistema de muestreo, además de que no se obtendrá una muestra representativa del gas. Cuando se llega a tomar una muestra de un fluido de dos fases, lo que se recomienda es separar el gas y el líquido y hacer el análisis por separado aunque esto conducirá a un análisis con poca exactitud, ya que se corre el riesgo de condensar parte del gas, o bien, de extraer el gas del separador a una temperatura diferente que la de la línea.

Las líneas de gas libres de líquidos y que se encuentren a condiciones de temperatura muy por arriba de su punto de condensación, pueden emplear cualquier tipo de sonda. Para líneas de gas que estén operando cerca del punto de condensación se deberán emplear diseños especiales de sondas las cuales puedan afrontar posibles problemas de condensación y/o de partículas de líquidos que fluyen con el gas. Básicamente, existen dos tipos de sonda que se emplean en el muestreo de gases, Sondas de Muestreo de Tubo Recto y Sondas Reguladas. En cualquiera de los dos casos, la sonda deberá estar instalada de tal forma que el extremo recolector esté ubicado en la parte central de una división en tres partes del tubo. La sonda puede estar opcionalmente fija al sistema o puede ser removible. Se recomienda que la sonda esté localizada como mínimo 5D aguas abajo de cualquier elemento que provoque disturbios en el flujo. El material de la sonda, debe ser el apropiado para usarse con las características del fluido considerando las impurezas y las condiciones ambientales. Las sondas pueden ser modificadas para alguna aplicación en específico, como lo es caso de proveerlas con aletas para incrementar la transferencia de calor entre la muestra de gas y el gas que está fluyendo (para que la muestra se mantenga a la misma temperatura del fluido), o bien, de proveerlas con dispositivos de calefacción para garantizar que la muestra se mantenga en estado gaseoso. Opcionalmente, se pueden adicionar filtros, que se colocan en el extremo recolector, para reducir la posibilidad de que partículas de líquidos entren a la sonda.

El extremo recolector de las Sondas de Muestreo de Tubo Recto puede ser inclinado o recto y su orientación no es importante. Las Sondas Reguladas se emplean comúnmente cuando existe un analizador continuo y deben estar diseñadas de tal forma que el gas que llegue al analizador sea a presión reducida. Se debe tener especial cuidado en el empleo de este tipo de sondas, ya que al regular la presión se puede dar el caso de la muestra que está dentro de la sonda se condense por el efecto del regulador de presión, por lo que muestra no será lo suficientemente representativa. Para evitar el problema de condensación, se puede emplear un regulador de presión que utilice un método de regulación por calentamiento.

3. TRANSMISION DE LA MUESTRA HACIA EL ANALIZADOR O CONTENEDOR. (CIRCUITO DEL SISTEMA DE MUESTREO).

El circuito del sistema de muestreo debe ser corto y debe estar diseñado de tal forma que permita que la razón de flujo de la muestra sea relativamente alta; esto para evitar que exista una disgregación de la mezcla del gas. Los circuitos del sistema de muestreo no deben purgar a la atmósfera ya que esto provoca la emisión de desechos de gas al medio ambiente y puede contraponerse a las regulaciones ambientales. Se debe tener cuidado de que no exista una caída de presión alta en el circuito ya que la muestra puede llegar a condensarse y redundar en la exactitud del análisis. En el caso de que se llegase a dar la condensación, se deberá asegurar que todos los gases condensados sean revaporizados antes de proceder a su análisis. Se recomienda equipar al sistema con un sensor que mida la presión diferencial entre los dos extremos del circuito para monitorear la pérdida de presión en el circuito. En el caso de que se requiera, puede incluirse dentro del circuito un sistema de bombeo. Deberá cuidarse de que el sistema de bombeo no provoque inestabilidad y/o pulsaciones en el flujo. En caso de ser necesario, se recomienda aislar térmicamente el circuito para evitar la condensación de la muestra.

4. VELOCIDAD DE MUESTREO.

La velocidad del intervalo de muestreo se determina en función de las variaciones que pueden sufrir la velocidad de flujo y la composición del fluido en la línea. Se recomienda que la velocidad de muestreo sea proporcional a las variaciones de flujo y de composición del fluido.

5. CONTENEDORES DE MUESTRAS.

Un contenedor de muestras es el dispositivo que se emplea para retener la muestra hasta que su composición haya sido determinada. El contenedor no deberá afectar por ningún motivo la composición del gas, por lo que su limpieza y manejo debe ser la adecuada para asegurar que la muestra del gas no sea contaminada. Como medida preventiva, los contenedores deberán etiquetarse con su ID y especificar su máxima presión de trabajo.

Se recomienda el empleo de contenedores de acero inoxidable y puede ser del tipo de una o de dos válvulas o bien, del tipo de pistón flotante. Para aplicaciones de gases amargos los contenedores deberán estar cubiertos de teflón o resina epoxídica, no obstante con esto, se recomienda que las muestras de este tipo de gases, sean analizados en sitio ya que el contenedor cubierto puede no eliminar totalmente la absorción o reacción de los contaminantes. El uso de metales suaves como cobre, aluminio o bronce deberán ser evitados debido a sus excesivas razones de corrosión. El factor corrosión siempre deberá ser considerado para el diseño de los sistemas de muestreo. Una descripción general de los contenedores de muestreo se encuentra en el estándar GPA 2166. Si el contenedor va a ser transportado deberá cubrir las regulaciones del US Department of Transportation (DOT).

Los contenedores deben ser purgados y limpiados antes de cada recolección de muestras. Deberán emplearse solventes que no dejen residuos después del secado, como lo es la acetona. El Nitrógeno y el Helio son un buen ejemplo de gases que pueden ser empleados para el secado o purga de los cilindros, ya que el cromatógrafo no cuantificará a estos gases como parte de la muestra a ser analizada. Por tal razón es común que los cilindros o contenedores estén precargados y que empleen como gas de arrastre al Nitrógeno o al Helio.

La limpieza con vapor solo se aceptará si el vapor es limpio y no contiene elementos que propicien la corrosión. Si la muestra contiene componentes de azufre, entonces no se deberá ocupar el vapor para limpieza de los contenedores por ninguna circunstancia.

Todo el sistema de muestreo, incluyendo cualquier separador que se encuentre dentro del sistema, deberá ser purgado y limpiado de contaminantes y líquidos acumulados antes de la recolección de la muestra.

6. METODOS DE MUESTREO ESPORADICOS.

Hay siete diferentes métodos que son aceptados por API. Para detalle de los métodos consultar GPA 2166.

a. MÉTODO DE CONTENEDOR EVACUADO. Las válvulas y fittings del contenedor de muestra deberán estar en buenas condiciones y libres de fuga. Si pudiese llegar a existir condensación en el contenedor (ya que la temperatura en el contenedor es menor que en la línea), se recomienda usar el método de presión reducida.
b. MÉTODO DE PRESIÓN REDUCIDA. Es método es similar a la del contenedor evacuado solo que en esté caso el contenedor es llenado lentamente hasta llegar aproximadamente a un tercio de la presión de línea. La presión reducida es necesaria para evitar la condensación de la muestra, ya que la temperatura de la muestra en el contenedor es menor a la de la línea.
c. MÉTODO DE HELIO COMPRIMIDO. Es método es similar a la del contenedor evacuado solo que la carga de helio se usa para mantener el contenedor libre de aire antes del muestreo.
d. MÉTODO DEL CILINDRO DE PISTÓN FLOTANTE. Es conocido que una muestra depositada en un cilindro de pistón flotante, a la presión de línea y con líneas de muestreo calentadas, proporcionará resultados de análisis muy cercanos a los que se obtienen con un analizador en línea. El cilindro de pistón flotante deberá calentarse en el laboratorio hasta alcanzar una temperatura necesaria para asegurar una completa vaporización de cualquier líquido.
e. MÉTODO DE PURGA. (LLENADO Y VACIADO). Es el más simple y el que requiere menor equipo. El número de ciclos de purga se describe en la Tabla 1.
f. MÉTODO DE DESPLAZAMIENTO DE AGUA. Precaución: El agua puede absorber o desprender CO_2, H_2S y/u otros componentes dependiendo de la cantidad de agua y del tiempo de contacto. Usando agua destilada se evitará el desprendimiento, pero no la absorción, de CO_2 o otros componentes. El desplazamiento del fluido puede contaminar los sistemas de muestra del cromatógrafo.
g. MÉTODO CONTROLADO DE PURGA. (SOLO PARA GAS SECO). Si el gas que se muestrea no es seco, el liquido puede acumularse en el tubing que se encuentra a la salida del contenedor de la muestra.

Tabla 1. Ciclos de Purga – Método de llenado y vaciado

Máxima Presión del gas en el contenedor (psig)	Número de ciclos de purga.
15 - 29	13
30 - 59	8
60 - 89	6
90 - 149	5
150 - 500	4
> 500	3

7. MUESTREO AUTOMATICO.

Las muestras son automáticamente tomadas por un largo periodo de tiempo y una determinada velocidad de muestreo. De los muestreadores comerciales se recomienda el de tipo desplazamiento, el cual bombea la muestra hacia el cilindro de pistón flotante con una presión de línea constante, además, se recomienda uno que tenga retroalimentación del computador de flujo para que este pueda ajustar el periodo de muestreo en función de la razón de flujo, o bien, en función de las variaciones de la composición del fluido. En caso de que la composición y la razón de flujo sean relativamente constantes, el ajuste del periodo de muestreo será por tiempo.

El sistema de muestreo puede incluir un regulador de presión que se encargará de elevar la presión de la muestra que está siendo recolectada en el contenedor, hasta un máximo de la presión de línea. Este regulador no se recomienda para líneas de baja presión, o para líneas donde las razones de flujo son muy variables.

A excepción de los gases muy secos, el circuito, el dispositivo de muestreo y el contenedor deben ser aislados para evitar una posible condensación de la muestra. En el caso de que el analizador sea de tipo continuo, tal como los cromatógrafos o los gravitómetros, se deberá cerrar el circuito de conducción de la muestra hacia un punto de retorno de más baja presión hacia la línea, por lo que el analizador deberá estar localizado lo más cerca posible de la toma de muestra para mantener las lineas del circuito lo más cortas posible. Se recomienda que las lineas del circuito sean de tubing de acero inoxidable de ¼ o de ½ pulgada. El circuito del sistema de muestra no deberá conformar un sistema de bypass para el elemento de medición primario.

8. ANALISIS DE LAS MUESTRAS.

Para evitar un análisis no representativo debido a la condensación durante el manejo de la muestra, éstas deberán ser calentadas uniformemente al menos por dos horas a una temperatura mínima de 140°F ó de 20 a 50°F por abajo de la temperatura de la línea, cualquiera que sea mayor. Baños de agua a temperatura controlada es un aceptable método para calentar los contenedores de muestras de gas natural. No siempre será necesario calentar los contenedores de muestras, aunque será indispensable si es necesario. Especial cuidado deberá tenerse para no sobrepresionar el contenedor y deberá considerarse el efecto del calor sobre los sellos y/o sobre cualquier otro material.

Las calibraciones de cromatógrafos que utilizan factores de respuesta publicados, no son adecuadas para aplicaciones de transferencia de custodia, ya que estos factores asumen que el cromatógrafo (columnas y detectores) trabajan exactamente en las mismas condiciones que con las que se obtuvieron los mencionados factores. Asimismo, asumen que el sistema de muestreo está libre de contaminación y/o de cualquier otra complicación. Los cromatógrafos deben ser calibrados con estándares gravimétricos preparados con tolerancias mínimas y con composiciones similares a las del gas natural que está siendo analizado. Los gases estándar deberán ser mantenidos al menos 20°F por arriba de su punto de condensación durante todo el tiempo que dure la calibración. Los factores de respuesta obtenidos por este tipo de calibración son los aceptados para aplicaciones de transferencia de custodia. Para saber si los factores de respuesta fueron determinados correctamente, es necesario graficar sobre una escala logarítmica los factores obtenidos contra el peso molecular de las fracciones; si la gráfica da como resultado una línea recta, entonces los factores fueron determinados correctamente; si no es así, quiere decir que las columnas del detector no están trabajando en óptimas condiciones. Es común que los analizadores de gas natural trabajen componente a componente hasta C_5 posteriormente agrupan los componentes más pesados en un solo valor que se denomina C_6+. Cuando es necesario llevar a cabo análisis de composiciones más allá del rango de C_6+, entonces es necesario utilizar columnas capilares en el cromatógrafo.

La composición del fluido, así como la presión y velocidad del fluido, deberán ser consideradas para especificar el hardware que conformará el sistema de muestreo.

SECCION 14.6 MEDICION CONTINUA DE DENSIDAD.

1. RESUMEN.

Este estándar provee criterios y procedimientos para el diseño, instalación y operación de un sistema de medición continua de densidad para fluidos newtonianos de la industria del petróleo y de gas natural. La aplicación de este estándar se limita a fluidos limpios, homogéneos y de una sola fase. Los fluidos criogénicos son excluidos del alcance de este estándar. El seguimiento de los lineamientos de este estándar, garantiza una alta exactitud en la medición de la densidad del fluido, pudiendo llegar a tener hasta un 0.10% de error. Los procedimientos y criterios que se especifican han sido aplicados a fluidos cuya densidad de flujo es mayor que 0.3 g/cm^3 a temperatura de operación por arriba de 60°F (15.6°C) y a presión de saturación.

2. ESPECIFICACIONES GENERALES.

Todo el equipo deberá ser diseñado para soportar la máxima presión de operación a la cual será expuesto. Todos los materiales deberán ser resistentes a la corrosión. Las instalaciones deberán estar adecuadas para ser provistas de aislamiento térmico, drenado, despresurización, purgado y calentamiento. Todo el equipo deberá ser inspeccionado y mantenido de forma regular.

Antes de que el sistema de medición de densidad sea diseñado, es necesario tener un amplio conocimiento del fluido y del equipo de medición para lograr el 0.10% de error que garantiza la aplicación de este estándar. Para un aprovechamiento sistemático del diseño se deberá considerar principalmente los aspectos siguientes:

a. Propiedades y comportamiento del fluido.
b. Sistema de muestreo para determinar la densidad.
c. Equipo de prueba del sistema de medición de la densidad.

Para determinar la densidad del fluido con exactitud es necesario aplicar correcciones a la medición de la densidad por los efectos de la temperatura y de la presión. De hecho, se recomienda aislar térmicamente el medidor de flujo, el medidor de densidad, el elemento de calibración del densitómetro y toda la tubería de interconexión; esto para minimizar las desviaciones de densidad debidas a la diferencia de temperaturas que existe entre estos elementos.

2.1 PROPIEDADES Y COMPORTAMIENTO DEL FLUIDO.

Si la composición del fluido es constante, entonces la densidad del fluido estará en función de su temperatura y presión. La sensibilidad de la densidad del fluido a las variaciones de temperatura y presión debe ser analizada mediante un diagrama de entalpia o curvas generalizadas de desviación de densidad. La temperatura y presión existente en el medidor de flujo, el medidor de densidad y el elemento de calibración del densitómetro deben ser lo más idénticas posible, de tal forma que los siguientes criterios se cumplan:

a. Durante la operación normal, la desviación de densidad entre el medidor de densidad, el elemento de calibración del densitómetro y el medidor de flujo no deberá exceder el 0.05%.
b. El error resultante por diferencias de presión no deberá exceder el 0.01% ó 1 psig, cualquiera que sea más grande.
c. El error resultante por diferencias en la temperatura no deberá exceder el 0.04% ó 0.2°F, cualquiera que sea mayor.

En el caso de que el sistema esté operando cerca del punto de equilibrio, los criterios de desviación son::

a. Durante la calibración (proving), la desviación de densidad entre el medidor de densidad, el picnómetro y el medidor de flujo no deberá exceder el 0.05%.
b. El densitómetro deberá instalarse tan cerca como sea posible del medidor de flujo para evitar desviaciones debidas a la presión.

c. Para evitar desviaciones debidas a la temperatura, el tubería principal que existe entre el medidor de flujo y el punto de muestreo deberá ser aislado térmicamente.

En la Fig. 1 se muestra un arreglo esquemático para la ubicación de los puntos de medición de presión y temperatura que permitan llevar a cabo la verificación de las desviaciones estipuladas.

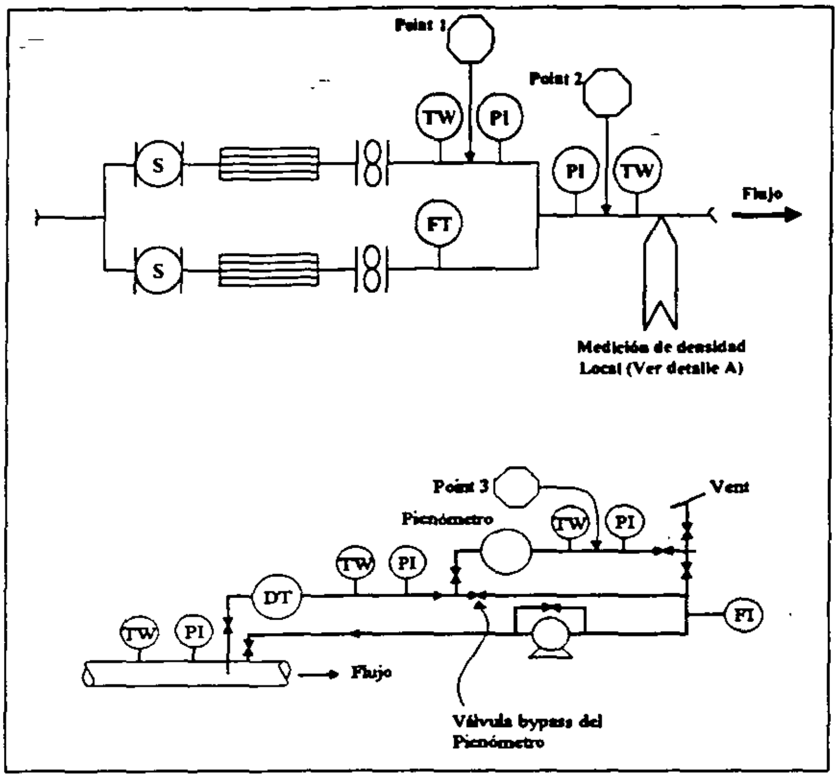


Fig. 1. Puntos de toma de lecturas de Presión y Temperatura para inferir las desviaciones de densidad.

Cuando se lleva a cabo la calibración del medidor de flujo, deberá cuidarse que las conexiones del prover lleguen a provocar una diferencia de densidad entre el flujómetro y el prover, porqué eso redundaría en un error que no es real. Asimismo, deberá cuidarse la no-existencia de dispositivos que no restrinjan el flujo entre el medidor de flujo, el medidor de densidad, el picnómetro y el prover, de tal forma que puedan resultar en diferencias en densidad.

2.2 SISTEMA DE MUESTREO PARA DETERMINAR LA DENSIDAD.

El densitómetro a ser instalado debe ser sometido a un análisis de sensibilidad a la razón de flujo del sistema de muestreo, a la velocidad del sonido en el fluido que está fluyendo, a las variaciones de temperatura y presión, a la rugosidad de la tubería, a la acumulación de líquidos o partículas, a la vibración mecánica y a las pulsaciones en el fluido.

Los densitómetros continuos son los más empleados para instalarse en los sistemas de medición de densidad. Esto porque permite conocer en todo momento las variaciones de densidad que pudiera llegar a tener el fluido. Entre los densitómetros continuos los más comunes son los de resonancia natural o de elemento vibratorio. Estos densitómetros se basan en le principio de que la densidad es inversamente proporcional a la frecuencia de vibración. Este tipo de densitómetros es sensible a los efectos de la velocidad del sonido y a los efectos provocados por las impurezas del fluido. Los densitómetros de tipo flotante y de pesado continuo normalmente son aplicados en aquellos sistemas cuyo fluido es de bajo o moderada viscosidad. Los dos tipos de densitómetros son sensibles a la vibración y a la posición horizontal. El densitómetro a ser instalado, deberá tener una exactitud mínima de 0.001 gr/cm^3 y una repetibilidad de 0 0005 gr/cm^3 sobre el rango sobre el cual vaya a operar.

El sistema de muestreo para la densidad deberá de:

- Instalarse en una localidad donde el fluido sea homogéneo y que no induzca la separación del fluido al proceso.
- Proveer los suficientes puntos de medición para determinar la temperatura y presión de cada dispositivo.
- Proveer el suficiente flujo para minimizar el retardo de la respuesta entre el densitómetro y el picnómetro.
- Ser instalado de tal forma que minimice la pulsación y cavitación del fluido.
- Ser instalado de tal forma que permita su limpieza sin llegar a impactar en la medición de la densidad.
- Proveer conexiones para uno o más elementos de calibración (picnómetros), que esté lo más cerca posible del elemento de flujo (sin llegar a afectar su desempeño por variaciones en el perfil de velocidad).
- Contemplar la instalación de la sonda de muestreo tal y como se especifica en el estándar API MPMS 14.1.

Los errores en la medición de densidad generalmente se deben a:

- Cambios en la temperatura y presión del fluido.
- Variaciones de la temperatura ambiente.
- Cambios en la composición del fluido.

Para minimizar el efecto de las diferencias de temperatura, el sistema de muestreo para el densitómetro deberá incluir enlaces térmicos, los cuales pueden ser provistos por aislamiento térmico o bien por su instalación cerca de una fuente de calor.

Hay dos tipos de sistemas de muestreo, los cuales se clasifican según el tipo de montaje del densitómetro. Los sistemas de inserción y los sistemas de slipstream. Los sistemas de inserción son aquellos donde el densitómetro se inserta directamente en la línea pero el arreglo para la calibración del densitómetro sigue montándose en modo slipstream. En la Fig. 2 se muestra un arreglo típico de muestreo continuo tipo inserción.

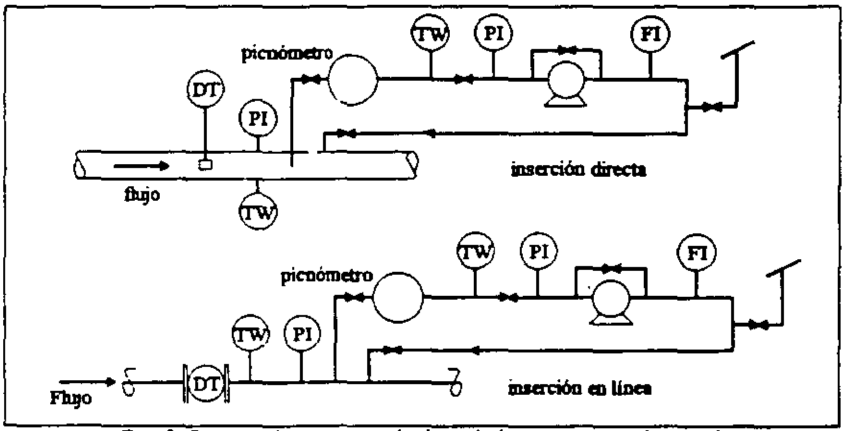
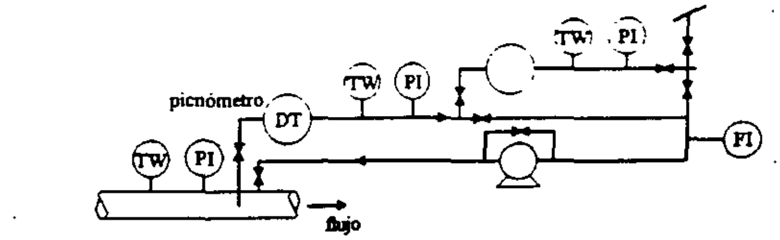
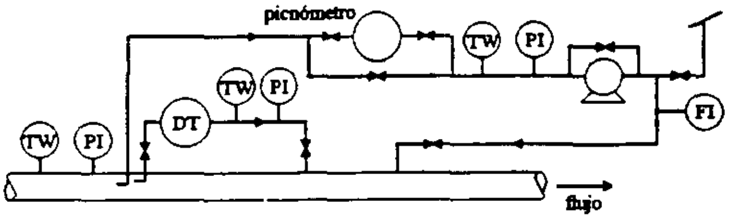


Fig. 2. Sistema de muestreo de densidad continua tipo Inserción.

Los sistemas de muestreo tipo slipstream son los más empleados y son aquellos que desvían parte del fluido hacia un circuito donde se mide la densidad. El circuito debe proveer lo necesario para llevar a cabo la calibración del densitómetro. En la Fig. 3 se muestra un arreglo típico de muestreo continuo tipo slipstream.



picnómetro en serie con un contador de densidad



picnómetro en paralelo con un contador de densidad

Fig. 3. Sistema de muestreo de densidad continua tipo Slipstream.

Para la gran mayoría de las aplicaciones el densitómetro es instalado en serie con el picnómetro. Deberá asegurarse que la muestra que toman ambos dispositivos tengan la misma homogeneidad.

2.3 EQUIPO DE PRUEBA DEL SISTEMA DE MEDICIÓN DE LA DENSIDAD.

Se recomienda llevar a cabo la calibración del densitómetro In-situ, con está acción se eliminará la necesidad de introducir correcciones por la fuerza gravitacional. El equipo de calibración o prueba consiste en un picnómetro, un dispositivo para pesar las muestras, un conjunto de pesos muertos certificados, un instrumento de temperatura y un instrumento de presión. El instrumento de temperatura deberá tener una exactitud de 0.2°F (0.1°C) y la exactitud del instrumento de presión deberá ser de 1 psi (6.9 kPa) ambos trazables a un patrón primario.

El picnómetro es el dispositivo más exacto y por lo tanto recomendado para llevar a cabo la calibración de un densitómetro bajo condiciones de flujo. El picnómetro es una vasija de tipo flow-through que atrapa una muestra representativa del fluido a condiciones de operación, permitiendo el manejo de fluidos a alta presión durante el muestreo y el transporte y permiten determinar la densidad del fluido con una precisión del 0.02%. El picnómetro deberá someterse a un análisis de sensibilidad a la razón del flujo del sistema de muestreo, a la acumulación de líquidos y partículas y a la condensación de agua atmosférica.

Antes de llevar a cabo una prueba o calibración del densitómetro, se deberán llevar a cabo las siguientes acciones.

- Lavar y secar con aire seco el picnómetro.
- Calibrar el dispositivo de pesado de las muestras con los pesos muertos certificados.
- Verificar el desempeño de los instrumentos de presión y temperatura.
- Verificar el peso del picnómetro totalmente evacuado. (W_0). Para esto hay que tomar de referencia el valor especificado en el certificado de calibración del picnómetro. El peso obtenido en W_0 no deberá diferir más allá del 0.02%.
- Obtener el valor del peso del picnómetro lleno de aire. (W_a).
- Instalar el picnómetro y ventear el aire del picnómetro.
- Llenar el picnómetro con el fluido y cerrar (parcialmente o totalmente) la válvula para desviar el flujo hacia el sistema de muestreo.
- Verificar la desviación de densidad y estabilidad.
- Cuando se haya estabilizado las condiciones de temperatura y presión en el picnómetro tomar las lecturas del densitómetro, temperatura y presión del densitómetro y temperatura y presión del picnómetro

- Abrir la válvula de bypass y quitar el picnómetro del sistema de muestreo.
- Pesar el picnómetro lleno y registrar la lectura.
- Calcular el factor de corrección del densitómetro. (DMF)
- Repetir la operación completa para verificar la repetibilidad del densitómetro.
- Calcular la repetibilidad y el promedio de los factores de corrección del densitómetro.
- En caso de que se haga un ajuste a la salida del densitómetro repetir al menos dos veces el procedimiento para verificar el desempeño del densitómetro ya ajustado.
- Vaciar el picnómetro y limpiarlo perfectamente .
- Verificar nuevamente el peso del picnómetro evacuado (W_o). Si el peso del picnómetro evacuado difiere del valor estipulado en el certificado de calibración más allá del 0.02% los resultados de la prueba serán invalidados.

Los requerimientos de repetibilidad son que dos pruebas consecutivas tengan una tolerancia de repetibilidad no mayor que el 0.05% Si la variación de la densidad en el intervalo de dos muestreos es mayor que 0.05%, entonces la condición de repetibilidad es prácticamente inalcanzable por lo que será necesario aumentar la tolerancia requerida.

SECCION 14.7 ESTANDAR PARA LA MEDICION DE MASA DE LIQUIDOS DE GAS NATURAL.

1. RESUMEN.

El estándar fue desarrollado en conjunto por la GPA y la API. La publicación sirve como referencia para la selección, diseño, instalación, operación y mantenimiento de sistemas de medición de masa de líquido de gas natural, de una sola fase, los cuales operan en el rango de densidad de 300 a 700 kg/m^3.

La medición de masa es utilizada donde las condiciones de temperatura, presión y composición de la mezcla del fluido presentan dificultad para convertir el volumen de condiciones de flujo a condiciones estándar. Ejemplo de este tipo de fluidos es el etano, los líquidos de gas natural (NGL) y/o mezclas de etano y propano. Dentro del estándar se considera que las condiciones estándar de temperatura y presión son 15°C y presión de vapor en equilibrio.

2. MEDICION DE MASA.

La medición de la masa puede ser llevada a cabo por medidores tipo turbina, de desplazamiento positivo o de orificio. En el caso de los dos primeros, la determinación de la masa se lleva a cabo mediante la expresión:

Volumen medido a condiciones de operación X Factor de Medición a condiciones de operación X Densidad en masa por unidad de volumen a condiciones de operación X Factor de corrección del densitómetro a condiciones de operación

Para el caso de placas de orificio, la determinación de la masa es a partir de la expresión que se indica en el estándar API MPMS 14.3 Parte 1.

3. DETERMINACION DE DENSIDAD.

La medición de densidad será mediante el empleo de densitómetros instalados y calibrados tal y como se especifica en los lineamientos establecidos el estándar API MPMS 14.6. En el caso de que el uso de densitómetros no sea práctico, la densidad del líquido a condiciones de flujo puede ser calculada como una función de la composición, temperatura y presión. Es recomendable que la densidad ya sea calculada o medida sea aplicada en tiempo real a la medición de flujo de masa. Sin embargo, por el tiempo que tarda en llevarse a cabo el análisis composicional del fluido, comúnmente se emplea el promedio de temperatura y presión que se registra entre cada análisis composicional.

El empleo de correlaciones empíricas y/o ecuaciones de estado generalizadas adiciona un determinado valor de incertidumbre a la medición total de flujo. El nivel de incertidumbre que incorpora dependerá del método o ecuación de estado empleada.

4. MEDICION VOLUMETRICA.

La medición volumétrica podrá ser llevada cabo por medidores de desplazamiento positivo, de tipo turbina o de orificio. El medidor de desplazamiento positivo deberá cumplir con las recomendaciones del estándar API MPMS 5.2 y los accesorios relacionados deberán cumplir con el estándar API MPMS 5.4. Los medidores tipo turbina deberán cumplir con las recomendaciones del estándar API MPMS 5.3 y los accesorios relacionados deberán cumplir con el estándar API MPMS 5.4. Estos medidores deberán ser probados de acuerdo a los lineamientos estipulados en los estándares API MPMS 4 y API MPMS 5. Si las presiones y temperaturas existentes en el medidor de flujo y el probador varían, entonces se deben de aplicar las correcciones que se especifican en los estándares API MPMS 11 y API MPMS 12.

Si la medición volumétrica se lleva a cabo por un medidor de orificio, éste deberá cumplir con las recomendaciones del estándar API MPMS 14.3. El cálculo del volumen a condiciones estándar puede ser llevado a cabo mediante el empleo de los procedimientos especificados en el estándar GPA 8173 (API MPMS 14.4).

5. MUESTREO.

El muestreo deberá ser llevado a cabo de acuerdo a los lineamientos establecidos en el estándar API MPMS 14.1 además de los puntos que se exponen a continuación.

La sonda de muestreo deberá instalarse al centro del flujo de corriente. Una línea de bypass alrededor de un dispositivo que provoque una presión diferencial deberá ser provisto para suministrar producto a las válvulas de inyección de la muestra. El bypass no deberá ser sobre el medidor de flujo.

Precauciones deberán ser tomadas para evitar la vaporización en el circuito del sistema de muestreo, sobre todo cuando la operación se lleva a cabo cerca de la presión de vapor del producto. En algunos casos es necesario controlar la presión o temperatura de los contenedores de la muestra para evitar su vaporización.

El circuito del sistema de muestreo deberá ser corto y de diámetro pequeño. El circuito deberá ser purgado completamente antes de la toma de la siguiente muestra. La obtención de una muestra representativa deberá llevarse a cabo de acuerdo a los lineamientos establecidos en el estándar 14.1.

El sistema de recolección de la muestra deberá ser diseñado para mantener la muestra en estado líquido. Esto se logra si se emplea un cilindro de pistón flotante como contenedor, el cual emplea un gas inerte que se opone a la inyección del líquido y mantiene el nivel de presión por arriba de la presión de vapor de la muestra. La transferencia de la muestra hacia un cilindro portátil para su análisis en el laboratorio, deberá llevarse a cabo de acuerdo a los procedimientos recomendados por los estándares GPA.

6. ANALISIS DE LA MUESTRA.

Dependiendo de la composición de la corriente, el análisis de una muestra líquida deberá seguir los procedimientos cromatográficos descritos en los estándares GPA 2165, 2177 y 2186. Donde sea aplicable, puede ser requerido un análisis extendido para determinar el peso molecular y la densidad de la fracción del C_6+.

7. CONVERSION DE LA MASA MEDIDA A VOLUMEN.

La conversión de masa a su volumen equivalente deberá ser llevada a cabo de acuerdo a los procedimientos que se especifican en el estándar GPA 8173 (API MPMS 14.4). Para este efecto, un análisis cromatográfico es usado para determinar la masa de cada uno de los componentes que conforman la masa total.

SECCION 14.8 MEDICION DE LPG.

1. RESUMEN.

Este estándar describe los sistemas de medición estáticos y dinámicos usados para medir LPG en un rango de densidad relativa de 0.350 a 0.637. El estándar sirve como una guía para la selección, instalación, operación y mantenimiento de los sistemas de medición de LPG. El estándar no especifica tolerancias o límites de exactitud.

2. CARACTERISTICAS DEL FLUIDO.

Ciertas características físicas del LPG requieren especial atención para lograr mediciones con un nivel aceptable de exactitud. El LPG permanecerá en estado líquido solo si una presión suficientemente más grande que la presión de equilibrio es mantenida. En los sistemas de medición de líquidos una adecuada presión deberá ser mantenida para prevenir la vaporización causada por pérdidas de presión atribuibles a la tubería y válvulas.

El LPG es más compresible y tiene un coeficiente más grande de expansión térmica que hidrocarburos más pesados. La aplicación de los factores de compresibilidad y de corrección de temperatura son requeridos para determinar la medición a condiciones estándar.

La prueba o calibración de los medidores empleados en la determinación del flujo deberá cumplir con los lineamientos establecidos en las normas API MPMS 4 y API MPMS 5.

3. REQUERIMIENTOS PARA LA MEDICION DE FLUJO.

Provisiones deberán ser tomadas para asegurar que el LPG sea mantenido totalmente en fase liquida. Para esto, la presión a la entrada del medidor deberá ser como mínimo 1.25 veces la presión de equilibrio a la temperatura en que se esté llevando la medición, mas dos veces la caída de presión a través del medidor a máxima razón de flujo, o bien, a una presión de 125 psi más grande que la presión de vapor a la máxima temperatura de operación. Cualquiera que sea más baja. Los eliminadores de aire deben ser usados con mucha precaución particularmente porque pueden provocar la vaporización del fluido. Se recomienda tener una medición continua de temperatura para una mayor exactitud en la medición de flujo.

La determinación de densidad del fluido deberá llevarse a cabo tal como se describe en los estándares API MPMS 9.2 y 14.6. El equipo de muestreo deberá estar localizado como es requerido en el estándar API MPMS 8. Muestras representativas deberán ser obtenidas como se especifica en el estándar GPA 2166.

La instalación de las estaciones de medición, el cálculo de la razón de flujo volumétrico, la prueba o calibración de los medidores, la recolección, manejo y análisis de las muestras, la determinación de la densidad, la determinación de la masa y la conversión de la masa medida a unidades de volumen a condiciones estándar se lleva a cabo tal y como se especifica en el estándar API MPMS 14.7.

Manual of Petroleum Measurement Standards

Chapter 14—Natural Gas Fluids Measurement

Section 3—Concentric, Square-Edged Orifice Meters

Part 1—General Equations and Uncertainty Guidelines

Measurement Coordination Department

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Chapter 14—Natural Gas Fluids Measurement

SECTION 3—CONCENTRIC, SQUARE-EDGED ORIFICE METERS

PART 1—GENERAL EQUATIONS AND UNCERTAINTY GUIDELINES

1.1 Introduction

1.1.1 SCOPE

This standard provides a single reference for engineering equations, uncertainty estimations, construction and installation requirements, and standardized implementation recommendations for the calculation of flow rate through concentric, square-edged, flange-tapped orifice meters. Both U.S. customary (IP) and International System of Units (SI) units are included.

1.1.2 ORGANIZATION OF STANDARD

The standard is organized into four parts. Parts 1, 2, and 4 apply to the measurement of any Newtonian fluid in the petroleum and chemical industries. Part 3 focuses on the application of Parts 1, 2, and 4 to the measurement of natural gas.

1.1.2.1 Part 1—General Equations and Uncertainty Guidelines

The mass flow rate and base (or standard) volumetric flow rate equations are discussed, along with the terms required for solution of the flow equation.

The empirical equations for the coefficient of discharge and expansion factor are presented. However, the bases for the empirical equations are contained in other sections of this standard or the appropriate reference document.

For the proper use of this standard, a discussion is presented on the prediction (or determination) of the fluid's properties at flowing conditions. The fluid's physical properties shall be determined by direct measurements, appropriate technical standards, or equations of state.

Uncertainty guidelines are presented for determining the possible error associated with the use of this standard for any fluid application. User-defined uncertainties for the fluid's physical properties and auxiliary (secondary) devices are required to solve the practical working formula for the estimated uncertainty.

1.1.2.2 Part 2—Specifications and Installation Requirements

Specifications are presented for orifice meters, in particular, orifice plates, orifice plate holders, sensing taps, meter tubes, and flow conditioners.

Installation requirements for orifice plates, meter tubes, thermometer wells, flow conditioners, and upstream/downstream meter tube lengths are presented.

1.1.2.3 Part 3—Natural Gas Applications

The application of this standard to natural gas is presented, along with practical guidelines. Mass flow rate and base (or standard) volumetric flow rate methods are presented in conformance with North American industry practices.

1.1.2.4 Part 4—Background, Development, and Implementation Procedure and Subroutine Documentation for Empirical Flange-Tapped Discharge Coefficient Equation

The coefficient of discharge data base for flange-tapped orifice meters and its background, development, and limitations are presented.

Implementation procedures for flange-tapped orifice meters are presented, along with a set of example calculations. The examples are designed to aid in checkout procedures for any routines that are developed using the implementation procedures.

1.1.3 REFERENCED PUBLICATIONS

Several documents served as references for the revision of this standard. In particular, previous editions of Chapter 14.3 (ANSI[1]/API 2530; A.G.A.[2] Report No. 3) provided a wealth of information. The laboratory reports for the experimental data bases also provided valuable information concerning the control of independent variables, both qualitatively and quantitatively. Other publications, symposium proceedings, trade journals, textbooks, and society papers were consulted for the revision of this standard.

A complete bibliography is available upon request from the American Petroleum Institute. A reduced list, referencing the major experimental research, is contained in Appendix 1-A.

1.2 Field of Application

1.2.1 APPLICABLE FLUIDS

This standard applies to steady-state mass flow conditions for fluids that, for all practical purposes, are considered to be clean, single phase, homogeneous, and Newtonian and have pipe Reynolds numbers of 4000 or greater. All gases, most liquids, and most dense phase fluids associated with the petroleum, petrochemical, and natural gas industries are usually considered Newtonian fluids.

1.2.2 TYPES OF METERS

This standard provides design, construction, and installation specifications for flange-tapped, concentric, square-edged orifice meters of nominal 2-inch Schedule 160 and larger pipe diameters.

An orifice meter is a fluid flow measuring device that produces a differential pressure to infer flow rate. The meter consists of the following elements (see Figure 1-1):

a. A thin, concentric, square-edged orifice plate.
b. An orifice plate holder consisting of a set of orifice flanges (or an orifice fitting) equipped with the appropriate differential pressure sensing taps.
c. A meter tube consisting of the adjacent piping sections (with or without flow conditioners).

The auxiliary (secondary) devices necessary for the precise determination of flow rate are not included in the scope of this standard. These devices are usually instruments that sense the differential and static pressure, fluid temperature, and fluid density and/or relative density (specific gravity), and either mechanical recording devices or electronic calculators. Publications of the A.G.A., API, GPA,[3] and others should be used to specify and install these auxiliary (secondary) devices.

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[1] American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103.
[2] American Gas Association, 1515 Wilson Boulevard, Arlington, Virginia 22209.
[3] Gas Processors Association, 6526 East 60th Street, Tulsa, Oklahoma 74145.

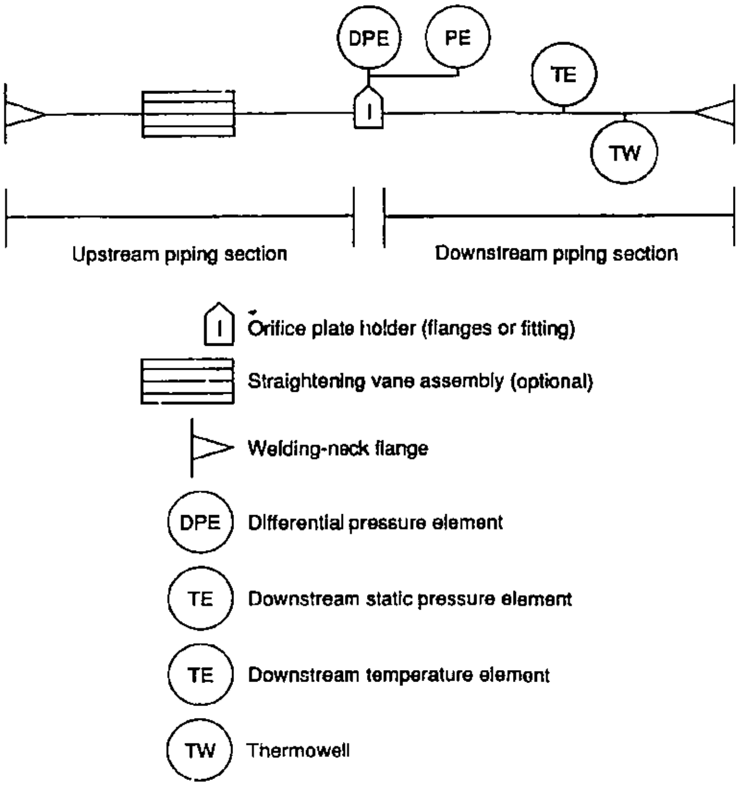


Figure 1-1—Orifice Meter

1.2.3 UNCERTAINTY OF MEASUREMENT

Many factors influence the overall measurement uncertainty associated with a metering application. Major contributors include construction tolerances in the meter components, tolerances of empirical coefficient of discharge data bases or in-situ flow calibrations, predictability of and variations in the fluid's physical properties, and uncertainties associated with the auxiliary (secondary) devices.

Using the guidelines contained in this standard in combination with the associated uncertainty tolerances for the fluid's physical properties, in-situ calibrations, or coefficient of discharge data bases, and the appropriate auxiliary (secondary) devices, the user can estimate the overall measurement uncertainty associated with a properly designed, installed, and maintained thin plate, concentric, square-edged orifice metering application.

1.3 Method of Calculation

This standard provides recommended standardized calculation implementation methods for the quantification of fluid flow under defined conditions, regardless of the point of origin or destination or the units of measure required by governmental customs or statute. The recommended implementation procedures provided in Chapter 14.3, Part 4, allow different entities using various computer languages on different computing hardware to arrive at nearly identical results using the same standardized input data.

The following two recommended implementation procedures have been prepared to illustrate the standardized set of mathematical expressions and sequencing, including iteration/rounding techniques:

Date of Issue: July 1991

Affected Publication: *Manual of Petroleum Measurement Standards*, Chapter 14, "Natural Gas Fluids Measurement," Section 3, "Concentric, Square-Edged Orifice Meters," Part 1, "General Equations and Uncertainty Guidelines," Third Edition, September 1990

ERRATA

On page 2, Footnote 1 should read as follows:

[1] American National Standards Institute, 11 West 42nd Street, New York, New York 10036

On page 3, Figure 1-1 should appear as follows (that is, the letters PE *should be used to represent the downstream static pressure element):*

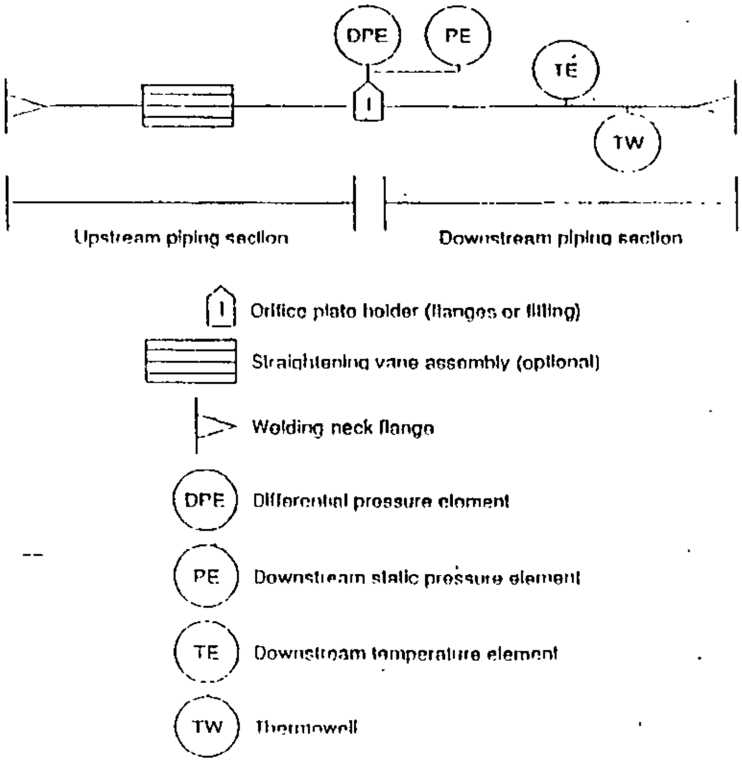


Figure 1-1—Orifice Meter

On page 13, the first paragraph should read as follows (that is, the word Ohio *should replace the word* Oklahoma*):*

Although it does not mean that other data are of inferior quality, it is known that insufficient information exists to determine whether the independent variables were controlled and quantified. Some examples of comparison quality data are the Ohio State University Data Base (303 flange-tapped points); the 1983 NBS Boulder Experiments, the Foxboro Columbus–Daniel 1000 Point Data Base, and the Japanese Water Data Base.

7-(

a. Mass flow rate.
b. Standard volumetric flow rate.

The procedures presented address only the solution of the flow rate equation and require specific inputs (fixed and variable). Typical fixed inputs include meter tube internal diameter, orifice plate bore diameter, and linear coefficient of expansion for steels (pipe and orifice plate). Typical variable inputs may include differential and static pressure, temperature, fluid density, isentropic exponent for compressible fluids, and fluid viscosity.

The fluid's physical properties shall be determined by direct measurements, appropriate technical standards, or equations of state. If multiple parties are involved in the measurement, the appropriate technical method selected for determining the fluid's physical properties shall be mutually agreed upon.

1.4 Symbols

This standard reflects orifice meter application to fluid flow measurement with symbols in general technical use.

Symbol	Represented Quantity
C_d	Orifice plate coefficient of discharge.
C_d(FT)	Coefficient of discharge at a specified pipe Reynolds number for flange-tapped orifice meter.
C_i	Coefficient of discharge at infinite pipe Reynolds number.
C_i(CT)	Coefficient of discharge at infinite pipe Reynolds number for corner-tapped orifice meter.
C_i(FT)	Coefficient of discharge at infinite pipe Reynolds number for flange-tapped orifice meter.
c_p	Specific heat at constant pressure.
c_v	Specific heat at constant volume.
d	Orifice plate bore diameter calculated at flowing temperature, T_f.
d_m	Orifice plate bore diameter measured at T_m.
d_r	Orifice plate bore diameter at reference temperature, T_r.
D	Meter tube internal diameter calculated at flowing temperature, T_f.
D_m	Meter tube internal diameter measured at T_m.
D_r	Meter tube internal diameter at reference temperature, T_r.
ΔP	Orifice differential pressure.
°C	Temperature, in degrees Celsius.
°F	Temperature, in degrees Fahrenheit.
K	Temperature, in kelvins.
°R	Temperature, in degrees Rankine.
E_v	Velocity of approach factor.
g_c	Dimensional conversion constant.
G_i	Ideal gas relative density (specific gravity).
k	Isentropic exponent.
k_i	Ideal gas isentropic exponent.
k_p	Perfect gas isentropic exponent.
k_r	Real gas isentropic exponent.
MF	In-situ calibration meter factor.
Mr_{air}	Molar mass of air.
Mr_{gas}	Molar mass of gas.
N_1	Unit conversion factor (orifice flow).
N_2	Unit conversion factor (Reynolds number).
N_3	Unit conversion factor (expansion factor).
N_4	Unit conversion factor (discharge coefficient).
P_b	Base (reference or standard) pressure.

P_f	Static pressure of fluid at the pressure tap.
P_{f_1}	Absolute static pressure at the orifice upstream differential pressure tap.
P_{f_2}	Absolute static pressure at the orifice downstream differential pressure tap.
q_m	Mass flow rate.
q_{m_i}	Mass flow rate indicated by the orifice meter being calibrated.
q_{m_p}	Mass flow rate determined by the primary mass flow system (or master meter).
q_v	Volume flow rate at flowing (actual) conditions.
q_{v_i}	Volume flow rate indicated by the orifice meter being calibrated.
Q_v	Volume flow rate at base (standard) conditions.
R	Universal gas constant.
R_a	Roughness average value from continuously averaging meter readings.
Re_D	Pipe Reynolds number.
T	Temperature.
T_b	Base (reference or standard) temperature.
T_f	Temperature of fluid at flowing conditions.
T_m	Temperature of the orifice plate or meter tube at time of diameter measurements.
T_r	Reference temperature of orifice plate bore diameter and/or meter tube inside diameter.
x	Ratio of differential pressure to absolute static pressure.
x_1	Ratio of differential pressure to absolute static pressure at the upstream pressure tap.
S( )	Sensitivity coefficient (influence coefficient).
Y	Expansion factor.
Y_1	Expansion factor based on upstream absolute static pressure.
Y_2	Expansion factor based on downstream absolute static pressure.
Z	Fluid compressibility.
Z_f	Fluid compressibility at flowing conditions.
Z_{f_1}	Compressibility of the fluid flowing at the upstream pressure tap location.
Z_{f_2}	Compressibility of the fluid flowing at the downstream pressure tap location.
α	Linear coefficient of thermal expansion.
α_1	Linear coefficient of thermal expansion of the orifice plate material.
α_2	Linear coefficient of thermal expansion of the meter tube material.
β	Ratio of orifice diameter to meter tube diameter calculated at flowing conditions.
μ	Absolute viscosity of fluid flowing.
π	Universal constant.
ρ	Density of the fluid.
ρ_b	Density of the fluid at base conditions (P_b, T_b).
$\rho_{t,p}$	Density of the fluid at flowing conditions (P_f, T_f).

1.5 Definitions

This standard reflects orifice meter application to fluid flow measurement. The definitions are given to emphasize the particular meaning of the terms as used in this standard.

1.5.1 PRIMARY ELEMENT

The primary element is defined as the orifice plate, the orifice plate holder with its associated differential pressure sensing taps, and the meter tube.

1.5.1.1 Orifice Plate

The orifice plate is defined as a thin plate in which a circular concentric aperture (bore) has been machined. The orifice plate is described as a thin plate with sharp, square edge because the thickness of the plate material is small, compared with the internal diameter of the measuring aperture (bore), and because the upstream edge of the measuring aperture is sharp and square.

1.5.1.2 Orifice Plate Bore Diameter (d, d_m, d_r)

The calculated orifice plate bore diameter (d) is the internal diameter of the orifice plate measuring aperture (bore) computed at flowing temperature (T_f), as specified in 1.6.2. The calculated orifice plate bore diameter (d) is used in the flow equation for the determination of flow rate.

The measured orifice plate bore diameter (d_m) is the measured internal diameter of the orifice plate measuring aperture at the temperature of the orifice plate (T_m) at the time of bore diameter measurements, determined as specified in Chapter 14.3, Part 2.

The reference orifice plate bore diameter (d_r) is the internal diameter of the orifice plate measuring aperture at reference temperature (T_r), calculated as specified in Chapter 14.3, Part 2. The reference orifice plate bore diameter is the certified or stamped orifice plate bore diameter.

1.5.1.3 Orifice Plate Holder

The orifice plate holder is defined as a pressure-containing piping element, such as a set of orifice flanges or an orifice fitting, used to contain and position the orifice plate in the piping system.

1.5.1.4 Meter Tube

The meter tube is defined as the straight sections of pipe, including all segments that are integral to the orifice plate holder, upstream and downstream of the orifice plate, as specified in Chapter 14.3, Part 2.

1.5.1.5 Meter Tube Internal Diameter (D, D_m, D_r)

The calculated meter tube internal diameter (D) is the inside diameter of the upstream section of the meter tube computed at flowing temperature (T_f), as specified in 1.6.3. The calculated meter tube internal diameter (D) is used in the diameter ratio and Reynolds number equations.

The measured meter tube internal diameter (D_m) is the inside diameter of the upstream section of the meter tube at the temperature of the meter tube (T_m) at the time of internal diameter measurements, determined as specified in Chapter 14.3, Part 2.

The reference meter tube internal diameter (D_r) is the inside diameter of the upstream section of the meter tube at the reference temperature (T_r), calculated as specified in Chapter 14.3, Part 2. The reference meter tube internal diameter is the certified or stamped meter tube internal diameter.

1.5.1.6 Diameter Ratio (β)

The diameter ratio (β) is defined as the calculated orifice plate bore diameter (d) divided by the calculated meter tube internal diameter (D).

1.5.2 PRESSURE MEASUREMENT

1.5.2.1 Tap Hole

A tap hole is a hole drilled radially in the wall of the meter tube or orifice plate holder, the inside edge of which is flush and without any burrs.

1.5.2.2 Flange Taps

Flange taps are a pair of tap holes positioned as follows (see Figure 1-2):

a. The upstream tap center is located 1 inch (25.4 millimeters) upstream of the nearest plate face.
b. The downstream tap center is located 1 inch (25.4 millimeters) downstream of the nearest plate face.

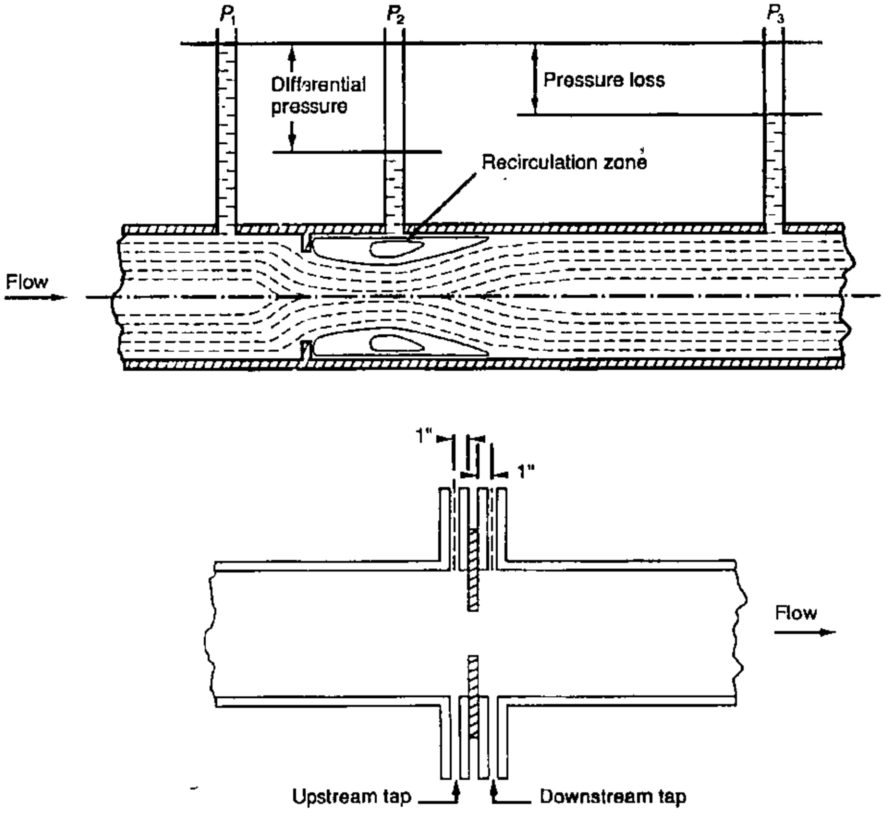
1.5.2.3 Differential Pressure (ΔP)

The differential pressure (ΔP) is the static pressure difference measured between the upstream and downstream flange taps.

1.5.2.4 Static Pressure (P_f)

The static pressure (P_f) is the absolute flowing fluid pressure measured at one of the flange tap holes. The absolute pressure may be measured directly or can be obtained by adding local barometric pressure to measured gauge pressure:

Absolute static pressure = Gauge static pressure + Local barometric pressure



FLANGE–TAPPED ORIFICE METER

Figure 1-2—Orifice Tapping Location

1.5.3 TEMPERATURE MEASUREMENT (T_f)

The temperature is the flowing fluid temperature (T_f) measured at the designated upstream or downstream location, as specified in Chapter 14.3, Part 2.

In flow measurement applications where the fluid velocity is well below sonic, it is common practice to insert a temperature sensing device in the middle of the flowing stream to obtain the flowing temperature. For practical applications, the sensed temperature is assumed to be the static temperature of the flowing fluid.

The use of flowing temperature in this part of the standard requires the temperature to be measured in degrees Fahrenheit or degrees Celsius. However, if the flowing temperature is used in an equation of state to determine the density of the flowing fluid, it may require that the Fahrenheit or Celsius values be converted to absolute temperature values of degrees Rankine or kelvins through the following relationships:

$$°R = °F + 459.67$$

$$K = °C + 273.15$$

1.5.4 FLOW RATE DETERMINATION

1.5.4.1 Orifice Flow Rate (q_m, q_v, Q_v)

The orifice flow rate is the mass or volume flow through an orifice meter per unit of time.

1.5.4.2 Orifice Plate Coefficient of Discharge (C_d)

The orifice plate coefficient of discharge (C_d) is the ratio of the true flow to the theoretical flow and is applied to the theoretical flow equation to obtain the actual (true) flow.

1.5.4.3 Velocity of Approach (E_v)

The velocity of approach factor (E_v) is a mathematical expression that relates the velocity of the flowing fluid in the orifice meter approach section (upstream meter tube) to the fluid velocity in the orifice plate bore.

1.5.4.4 Expansion Factor (Y)

The expansion factor (Y) is an empirical expression used to correct the flow rate for the reduction in fluid density that a compressible fluid experiences when it passes through the orifice plate bore.

1.5.4.5 Pipe Reynolds Number (Re_D)

The pipe Reynolds number is a dimensionless ratio of forces used to correlate the variations in the orifice plate coefficient of discharge (C_d) with changes in the fluid's properties, flow rate, and orifice meter geometry.

1.5.5 FLUID PHYSICAL PROPERTIES

1.5.5.1 Density ($\rho_{t,p}$, ρ_b)

The flowing fluid density ($\rho_{t,p}$) is the mass per unit volume of the fluid being measured at flowing conditions (T_f, P_f).

The base fluid density (ρ_b) is the mass per unit volume of the fluid being measured at base conditions (T_b, P_b).

1.5.5.2 Absolute Viscosity (μ)

The absolute viscosity (μ) is the measure of a fluid's intermolecular cohesive force's resistance to shear per unit of time.

1.5.5.3 Compressibility (*Z*)

The compressibility (Z) is an adjustment factor used to account for the deviation from the ideal gas law.

1.5.5.4 Isentropic Exponent (*k*)

The isentropic exponent (*k*) is a thermodynamic state property that establishes the relationship between an expanding fluid's pressure and density as the fluid flows through the orifice plate bore.

1.5.6 BASE CONDITIONS (P_b, T_b)

Historically, the flow measurement of some fluids, such as custody transfer and process control, have been stated in volume units at base (reference or standard) conditions of pressure and temperature.

The base conditions for the flow measurement of fluids, such as crude petroleum and its liquid products, whose vapor pressure is equal to or less than atmospheric at base temperature are defined in the United States as a pressure of 14.696 pounds per square inch absolute (101.325 kilopascals) at a temperature of 60.0°F (15.56°C). According to the International Standards Organization, base conditions are defined as a pressure of 14.696 pounds per square inch absolute (101.325 kilopascals) at a temperature of 59.00°F (15.00°C)

For fluids, such as liquid hydrocarbons, whose vapor pressure is greater than atmospheric pressure at base temperature, the base pressure is customarily designated as the equilibrium vapor pressure at base temperature.

The base conditions for the flow measurement of natural gases are defined in the United States as a pressure of 14.73 pounds per square inch absolute (101.560 kilopascals) at a temperature of 60.0°F (15.56°C). According to the International Standards Organization, base conditions are defined as a pressure of 14.696 pounds per square inch absolute (101.325 kilopascals) at a temperature of 59.00°F (15.00°C).

For both liquid and gas applications, these base conditions can change from one country to the next, one state to the next, or one industry to the next. Therefore, it is necessary that the base conditions be identified for standard volumetric flow measurement.

1.5.7 SENSITIVITY COEFFICIENT (S)

In estimating the uncertainty associated with the metering facility, a number of variables must be combined. The mathematical relationships among the variables establish the sensitivity of the metered quantities to each of these variables. As such, each variable that may influence the flow equation has a specific sensitivity coefficient. The derivation of this coefficient is based on a mathematical relationship or estimated from calculations, tables, or curves.

1.5.8 METER FACTOR (MF)

The meter factor (MF) is a number obtained by dividing the quantity of fluid measured by the primary mass flow system by the quantity indicated by the orifice meter during calibration.

1.6 Orifice Flow Equation

The accepted one-dimensional equation for mass flow through a concentric, square-edged orifice meter is stated in Equation 1-1 or 1-2. The derivation is based on conservation of mass and energy, one-dimensional fluid dynamics, and empirical functions such as equations of state and thermodynamic process statements. Any derivation is accurate when all the assumptions used to develop it are valid. As a result, an empirical orifice plate coefficient of discharge is applied to the theoretical equation to adjust for multidimensional viscous fluid dynamic effects. In addition, an empirical expansion factor is applied to the theoretical equation to adjust for the reduction in fluid density that a compressible fluid experiences when it passes through an orifice plate.

The fundamental orifice meter mass flow equation is as follows:

$$q_m = C_d E_v Y(\pi/4) d^2 \sqrt{2 g_c \rho_{t,p} \Delta P} \tag{1-1}$$

Where:

C_d = orifice plate coefficient of discharge.
d = orifice plate bore diameter calculated at flowing temperature (T_f).
ΔP = orifice differential pressure.
E_v = velocity of approach factor.
g_c = dimensional conversion constant.
π = universal constant
= 3.14159.
q_m = mass flow rate.
$\rho_{t,p}$ = density of the fluid at flowing conditions (P_f, T_f).
Y = expansion factor.

The practical orifice meter flow equation used in this standard is a simplified form that combines the numerical constants and unit conversion constants in a unit conversion factor (N_1):

$$q_m = N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P} \tag{1-2}$$

Where:

C_d = orifice plate coefficient of discharge.
d = orifice plate bore diameter calculated at flowing temperature (T_f).
ΔP = orifice differential pressure.
E_v = velocity of approach factor.
N_1 = unit conversion factor.
q_m = mass flow rate.
$\rho_{t,p}$ = density of the fluid at flowing conditions (P_f, T_f).
Y = expansion factor.

The expansion factor, Y, is included in Equations 1-1 and 1-2 because it is applicable to all single-phase, homogeneous Newtonian fluids. For incompressible fluids, such as water at 60°F (15.56°C) and atmospheric pressure, the empirical expansion factor is defined as 1.0000.

The orifice plate coefficient of discharge, C_d, and the expansion factor, Y, are empirical functions derived from experimental data.

The orifice meter is a mass meter from which a differential pressure signal is developed as a function of the velocity of the fluid as it passes through the orifice plate bore. Manipulation of the density variable in the equation permits calculation of flow rate in either mass or volume units. The volumetric flow rate at flowing (actual) conditions can be calculated using the following equation:

$$q_v = q_m / \rho_{t,p} \tag{1-3}$$

The volumetric flow rate at base (standard) conditions can be calculated using the following equation:

$$Q_v = q_m / \rho_b \tag{1-4}$$

The mass flow rate (q_m) can be converted to a volumetric flow rate at base (standard) conditions (Q_v) if the fluid density at the base conditions (ρ_b) can be determined or is specified.

The unit conversion factor, N_1, is defined and presented in 1.11.

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D_r = reference meter tube internal diameter at T_r.
T_f = temperature of the fluid at flowing conditions.
T_r = reference temperature of the meter tube internal diameter.

Note: α, T_f, and T_r must be in consistent units. For the purpose of this standard, T_r is assumed to be 68°F (20°C).

The meter tube internal diameter, D_r, calculated at T_r is the diameter determined in accordance with the requirements contained in Chapter 14.3, Part 2.

1.7 Empirical Coefficient of Discharge

Empirical coefficients of discharge for flange-tapped orifice meters have been determined from experimental data by comparing the measured and theoretical flow rates. A major factor in the definition of the experimental patterns for this orifice research was dynamic similarity. Using Reynolds' Law of Similarity, experimental correlations can be applied to dynamically similar meters.

To accurately predict the coefficient of discharge, C_d(FT), for a flange-tapped orifice meter manufactured to the specifications of this standard, certain parameters concerning the orifice meter and the fluid must be known. The relationships between these functions can be simplified for application to commercial use. In fact, the coefficient of discharge can be shown to depend on a number of parameters, the major ones being the Reynolds number (Re_D), sensing tap location, meter tube diameter (D), and β ratio:

$$C_d = f(Re_D, \text{Sensing tap location}, D, \beta)$$

In 1978, Jean Stolz presented an equation form that correlates the near vicinity taps for orifice meters based on the near field static wall pressure gradient. A complete discussion of the bases of the equation is beyond the scope of this standard. However, the bibliography contained in Appendix 1-A will allow the reader to further explore this technical discussion.

1.7.1 REGRESSION DATA BASE

Working jointly, a group of technical experts from the United States, Europe, Canada, Norway, and Japan have developed an equation using the Stolz linkage form that fits the Regression Data Set more accurately than have previously published equations. The new equation was developed from a significantly larger data base than was previously used for discharge coefficient equation development.

The Regression Data Set consists of data taken on four fluids (oil, water, natural gas, and air) from different sources, 11 different laboratories, on 12 different meter tubes of differing origins and more than 100 orifice plates of differing origins. The data provided a pipe Reynolds number range from accepted turbulent flow of 4000 to 36,000,000 on which to select the best model. The orifice configurations included flange, corner, and radius taps. Nominal pipe sizes investigated were 2, 3, 4, 6, and 10 inches, in compliance with ANSI/API 2530 specifications. Nominal β ratios used in the equation determination were 0.100, 0.200, 0.375, 0.500, 0.575, 0.660, and 0.750.

The bivariate data (C_d, Re_D) were measured in a manner appropriate for the test fluid and laboratory. The method of determining mass flow rate, expansion factor, fluid density, and fluid viscosity varied with the laboratory apparatus and test fluid.

Rather than including possibly erroneous data in the equation regression, the API/GPA/A.G.A. technical experts envisioned two classes of data sets for orifice research—regression and comparison. At a meeting of interested international orifice metering experts in November 1988, it was mutually agreed that the Regression Data Set be defined as follows:

> The Regression Data Set shall consist of those data points contained in the API/GPA and EC discharge coefficient experiments which were performed on orifice plates whose diameter was greater than 0.45 inch (11.4mm) and if the pipe Reynolds number was equal to or greater than 4000 (turbulent flow regime).
>
> Data which does not satisfy these criteria shall be included in the Comparison Data Set.

Although it does not mean that other data are of inferior quality, it is known that insufficient information exists to determine whether the independent variables were controlled and quantified. Some examples of comparison quality data are the Oklahoma State University Data Base (303 flange-tapped points), the 1983 NBS Boulder Experiments, the Foxboro–Columbus–Daniel 1000-Point Data Base, and the Japanese Water Data Base.

The exclusion for orifice bore diameters less than 0.45 inch (11.4 millimeters) was due to the increased uncertainty associated with the relative sharpness of the orifice plate upstream edge.

The Regression Data Set, as defined above, consists of data generated on orifice meters equipped with corner, radius, and flange tappings. The number of regression data points are summarized as follows:

Tapping	No. of points
Flange	5,734
Corner	2,298
Radius	2,160
Total	10,192

The empirical data associated with the API/GPA Data Base and the EC Data Base are the highest quality and largest quantity available today.

Detailed information on the experiments, regression data, statistical fit, and other pertinent information may be found in Chapter 14.3, Part 4, or the references contained in Appendix 1-A.

1.7.2 EMPIRICAL COEFFICIENT OF DISCHARGE EQUATION FOR FLANGE–TAPPED ORIFICE METERS

The concentric, square-edged, flange-tapped orifice meter coefficient of discharge, C_d(FT), equation, developed by Reader-Harris/Gallagher (RG), is structured into distinct linkage terms and is considered to best represent the current regression data base. The equation is applicable to nominal pipe sizes of 2 inches (50 millimeters) and larger; diameter ratios (β) of 0.1–0.75, provided the orifice plate bore diameter, d_r, is greater than 0.45 inch (11.4 millimeters); and pipe Reynolds numbers (Re_D) greater than or equal to 4000. For diameter ratios and pipe Reynolds numbers below the limit stated, refer to 1.12.4.1. The RG coefficient of discharge equation for an orifice meter equipped with flange taps is defined as follows:

$$C_d(\mathrm{FT}) = C_i(\mathrm{FT}) + 0.000511\left[\frac{10^6\beta}{Re_D}\right]^{0.7} + (0.0210 + 0.0049A)\beta^4 C \tag{1-9}$$

$$C_i(\mathrm{FT}) = C_i(\mathrm{CT}) + \mathit{Tap\ Term} \tag{1-10}$$

$$C_i(\mathrm{CT}) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1 - \beta)M_1 \tag{1-11}$$

$$\mathit{Tap\ Term} = \mathit{Upstrm} + \mathit{Dnstrm} \tag{1-12}$$

$$\mathit{Upstrm} = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \tag{1-13}$$

$$\mathit{Dnstrm} = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \tag{1-14}$$

Also,

$$B = \frac{\beta^4}{1 - \beta^4} \tag{1-15}$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4},\ 0.0\right) \tag{1-16}$$

$$M_2 = \frac{2L_2}{1 - \beta} \tag{1-17}$$

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Although it does not mean that other data are of inferior quality, it is known that insufficient information exists to determine whether the independent variables were controlled and quantified. Some examples of comparison quality data are the Oklahoma State University Data Base (303 flange-tapped points), the 1983 NBS Boulder Experiments, the Foxboro–Columbus–Daniel 1000-Point Data Base, and the Japanese Water Data Base.

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The empirical data associated with the API/GPA Data Base and the EC Data Base are the highest quality and largest quantity available today.

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$$C_d(\mathrm{FT}) = C_i(\mathrm{FT}) + 0.000511\left[\frac{10^6\beta}{Re_D}\right]^{0.7} + (0.0210 + 0.0049A)\beta^4 C \qquad (1\text{-}9)$$

$$C_i(\mathrm{FT}) = C_i(\mathrm{CT}) + \mathit{Tap\ Term} \qquad (1\text{-}10)$$

$$C_i(\mathrm{CT}) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1-\beta)M_1 \qquad (1\text{-}11)$$

$$\mathit{Tap\ Term} = \mathit{Upstrm} + \mathit{Dnstrm} \qquad (1\text{-}12)$$

$$\mathit{Upstrm} = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \qquad (1\text{-}13)$$

$$\mathit{Dnstrm} = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \qquad (1\text{-}14)$$

Also,

$$B = \frac{\beta^4}{1-\beta^4} \qquad (1\text{-}15)$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4},\ 0.0\right) \qquad (1\text{-}16)$$

$$M_2 = \frac{2L_2}{1-\beta} \qquad (1\text{-}17)$$

$$A = \left[\frac{19{,}000\beta}{Re_D}\right]^{0.8} \tag{1-18}$$

$$C = \left[\frac{10^6\beta}{Re_D}\right]^{0.35} \tag{1-19}$$

Where:

β = diameter ratio
= d/D.
C_d(FT) = coefficient of discharge at a specified pipe Reynolds number for flange-tapped orifice meter.
C_i(FT) = coefficient of discharge at infinite pipe Reynolds number for flange-tapped orifice meter.
C_i(CT) = coefficient of discharge at infinite pipe Reynolds number for corner-tapped orifice meter.
d = orifice plate bore diameter calculated at T_f.
D = meter tube internal diameter calculated at T_f.
e = Napierian constant
= 2.71828.
L_1 = dimensionless correction for the tap location
= L_2
= N_4/D for flange taps.
N_4 = 1.0 when D is in inches
= 25.4 when D is in millimeters.
Re_D = pipe Reynolds number.

1.7.3 REYNOLDS NUMBER *(Re_D)*

The RG equation uses pipe Reynolds number as the correlating parameter to represent the change in the orifice plate coefficient of discharge, C_d, with reference to the fluid's mass flow rate (its velocity through the orifice), the fluid density, and the fluid viscosity.

The pipe Reynolds number can be calculated using the following equation:

$$Re_D = \frac{4\,q_m}{\pi\,\mu\,D} \tag{1-20}$$

The pipe Reynolds number equation used in this standard is in a simplified form that combines the numerical constants and unit conversion constants:

$$Re_D = \frac{N_2 q_m}{\mu D} \tag{1-21}$$

For the Reynolds number equations presented above, the symbols are described as follows:

D = meter tube internal diameter calculated at flowing temperature (T_f).
μ = absolute viscosity of fluid.
N_2 = unit conversion factor.
π = universal constant
= 3.14159.
q_m = mass flow rate.
Re_D = pipe Reynolds number.

The unit conversion factor, N_2, for the Reynolds number equations is defined and presented in 1.11.

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ERRATA

On page 1, the last sentence of 1.1.1 should read as follows:

U.S. customary [Inch-Pound (IP)] and International System of Units (SI) units are included.

On page 13, Equations 1-16 and 1-17 should read as follows:

$$M_1 = \max\left(2.8 - \frac{D_r}{N_4},\ 0.0\right) \qquad (1\text{-}16)$$

$$M_2 = \frac{2L_2}{1 - \beta} \qquad (1\text{-}17)$$

On page 14, the nomenclature should read as follows (that is, D_r should be inserted in the list):

Where:

β = diameter ratio
= d/D.
$C_d(FT)$ = coefficient of discharge at a specified pipe Reynolds number for flange-tapped orifice meter.
$C_i(FT)$ = coefficient of discharge at infinite pipe Reynolds number for flange-tapped orifice meter.
$C_i(CT)$ = coefficient of discharge at infinite pipe Reynolds number for corner-tapped orifice meter.
d = orifice plate bore diameter calculated at T_f.
D = meter tube internal diameter calculated at T_f.
D_r = meter tube internal diameter at reference temperature, T_r.
e = Napierian constant = 2.71828.
$L_1 = L_2$ = dimensionless correction for the tap location
= N_4/D, for flange taps.
N_4 = 1.0 when D_r is in inches
= 25.4 when D_r is in millimeters.
Re_D = pipe Reynolds number.

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1.7.4 FLOW CONDITIONS

1.7.4.1 General

The condition of the meter tube, the mating of the piping sections, the ΔP sensing tap holes, the straight lengths of pipe preceding and following the primary element, and so forth, are factors that influence the flowing conditions. Although some factors may be considered insignificant for commercial purposes, flowing conditions can influence field accuracy.

To assure accuracy within the uncertainty stated, certain flow condition limitations must be followed:

a. The flow shall approach steady-state mass flow conditions on fluids that are considered clean, single phase, homogeneous, and Newtonian.
b. The fluid shall not undergo any change of phase as it passes through the orifice.
c. The flow shall be subsonic through the orifice and the meter tube.
d. The Reynolds number shall be within the specified limitations of the empirical coefficients.
e. No bypass of flow around the orifice shall occur at any time.

1.7.4.2 Law of Similarity

The empirical coefficients calculated from the equations in this standard are valid if dynamic similarity exists between the metering installation and the experimental data base. Technically, this approach is termed the Law of Similarity.

Dynamic similarity is the underlying principle for present-day theoretical and experimental fluid mechanics. The principle states that two geometrically similar meters with identical initial flow directions shall display geometrically similar streamlines.

The mechanical specifications for the meter tube, the orifice plate, the orifice flanges or fitting, the differential pressure sensing taps, the upstream and downstream piping requirements, the flow straightener (if applicable), and the thermowell must be adhered to, as stated in the standard, to assure geometric similarity.

Geometric similarity requires that the experimental flow system be a scale model of the field installations. The experimental pattern's design identifies sensitive dimensional regions to explore, measure, and empirically fit. A proper experimental pattern for orifice meters allows the user to extrapolate to larger meter tube diameters without increasing the uncertainty.

Dynamic similarity implies a correspondence of fluid forces between the two metering systems. The Reynolds number is a measure of the ratio of the inertial to viscous forces. For the orifice meter, the inertial to viscous forces are the forces considered significant within the application limitations of this standard. As a result, the Reynolds number is the term that correlates dynamic similarity in all empirical coefficient of discharge equations. In fact, the Reynolds number correlation provides a rational basis for extrapolation of the empirical equation, provided the physics of the fluid does not change. For instance, the physics associated with subsonic flow is not similar to that associated with sonic flow.

For the empirical data base, undisturbed flow conditions (flow pattern and fully developed velocity profile) were achieved through the use of straight lengths of meter tube both upstream and downstream from the orifice and the use of flow straighteners. For both the API/GPA and EC experiments, an undisturbed flow condition was defined as the equivalent of a symmetrical, approximately swirl-free velocity profile located approximately 45 pipe diameters downstream of a Sprenkle flow conditioner, in circular pipes with an average internal surface wall roughness, R_a, of approximately 150 microinches.

1.7.5 PULSATING FLOW

Reliable measurements of flow cannot be obtained with an orifice meter when appreciable pulsations are present at the point of measurement. Currently, no satisfactory theoretical or empirical adjustment for orifice measurement in pulsating flow applications exists that, when applied to custody transfer measurement, will maintain the measurement accuracy predicted by this standard.

1.7.5.1 Sources

Pulsations in a pipeline, originating from a reciprocating device, a rotary device, valve actions, piping configuration, or another similar source, consist of sudden changes in the velocity, pressure, and density of the fluid flowing. The most common sources of pulsation are the following:

a. Reciprocating compressors, engines, or impeller-type boosters.
b. Pumping or improperly sized pressure regulators and loose or worn valves.
c. Irregular movement of quantities of water or oil condensates in the line.
d. Intermitters on wells, automatic drips, or separator dumps.
e. Dead-ended piping tee junctions and similar cavities.

1.7.5.2 Pulsation Reduction

To obtain reliable measurements, it is necessary to suppress pulsation. In general, the following practices have been effective in diminishing pulsation and/or its effect on orifice flow measurement:

a. Locating the meter tube in a more favorable location with regard to the source of the pulsation, such as the inlet side of regulators, or increasing the distance from the source of the pulsation.
b. Inserting capacity tanks (volume), flow restrictions, or specially designed filters in the line between the source of pulsation and the meter tube to reduce the amplitude of the pulsation.
c. Using short-coupled impulse tubing and/or manifolds of approximately the same size as the pressure taps to the differential pressure measurement instrument.
d. Operating at differentials as high as is practicable by replacing the orifice plate in use with a smaller orifice bore plate or by concentrating flow in a multiple meter tube installation through a limited number of tubes.
e. Using smaller sized meter tubes and keeping essentially the same orifice diameter while maintaining the highest practical limit of the differential pressure.

Considerable study and experimentation have been conducted to evaluate the requirements and methods necessary to achieve pulsation reduction. This material is outside the scope of this standard and may be found in many publications that are readily available.

1.7.5.3 Pulsation Instruments

Instruments, both mechanical and electronic, have been developed that indicate the presence of pulsation. These devices are used to determine the effectiveness of pulsation suppression practices.

1.8 Empirical Expansion Factor (Y) for Flange–Tapped Orifice Meters

Expansibility research on water, air, steam, and natural gas using orifice meters equipped with various sensing taps is the basis for the present expansion factor equation. The empirical research compared the flow for an incompressible fluid with that of several compressible fluids.

The expansion factor, Y, was defined as follows:

$$Y = \frac{C_{d_1}}{C_{d_2}} \qquad (1\text{-}22)$$

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Where:

C_{d_1} = coefficient of discharge from compressible fluids tests.
C_{d_2} = coefficient of discharge from incompressible fluids tests.

Buckingham derived the empirical expansion factor equations for orifice meters equipped with various sensing taps based on the following correlation:

$$Y = f(\beta, k, x) \tag{1-23}$$

Where:

β = diameter ratio (d/D).
k = isentropic exponent.
x = ratio of differential pressure to absolute static pressure.

Compressible fluids expand as they flow through a square-edged orifice. For practical applications, it is assumed that the expansion follows a polytropic, ideal, one-dimensional path.

This assumption defines the expansion as reversible and adiabatic (no heat gain or loss). Within practical operating ranges of differential pressure, flowing pressure, and temperature, the expansion factor equation is insensitive to the value of the isentropic exponent. As a result, the assumption of a perfect or ideal isentropic exponent is reasonable for field applications. This approach was adopted by Buckingham and Bean in their correlation. They empirically developed the upstream expansion factor (Y_1) using the downstream temperature and upstream pressure.

Within the limits of this standard's application, it is assumed that the temperatures of the fluid at the upstream and downstream differential sensing taps are identical for the expansion factor calculation.

The application of the expansion factor is valid as long as the following dimensionless pressure ratio criteria are followed:

$$0 < \frac{\Delta P}{N_3 P_{f_1}} < 0.20$$

Or,

$$0.8 < \frac{P_{f_2}}{P_{f_1}} < 1.0$$

Where:

ΔP = orifice differential pressure.
N_3 = unit conversion factor.
P_f = absolute static pressure at the pressure tap.
P_{f_1} = absolute static pressure at the upstream pressure tap.
P_{f_2} = absolute static pressure at the downstream pressure tap.

Although use of the upstream or downstream expansion factor equation is a matter of choice, the upstream expansion factor is recommended because of its simplicity. If the upstream expansion factor is chosen, then the determination of the flowing fluid compressibility should be based on the upstream absolute static pressure, P_{f_1}. Likewise, if the downstream expansion factor is selected, then the determination of the flowing fluid compressibility should be based on the downstream absolute static pressure, P_{f_2}.

The expansion factor equation for flange taps is applicable over a β range of 0.10–0.75.

1.8.1 UPSTREAM EXPANSION FACTOR (Y_1)

The upstream expansion factor requires determination of the upstream static pressure, the diameter ratio, and the isentropic exponent.

On page 14, Equation 1-19 should read as follows:

$$C = \left[\frac{10^6}{Re_D}\right]^{0.35}$$

On page 17, the second equation for the dimensionless pressure ratio should read as follows:

$$0.8 < \frac{P_{f_2}}{P_{f_1}} < 1.0$$

On page 26, Equation 1-40 should read as follows:

$$\delta C_d(\mathrm{FT}) / \delta C_i(\mathrm{FT}) = 1 + 0.7895\left(\frac{4000}{Re_D}\right)^{0.8}$$

On page 30, the first two paragraphs under 1.12.4.5 should read as follows (that is, the words meter tube *should replace the word* plate*):*

The meter tube diameter uncertainty may be determined from dimensional measurements or, alternatively, from the roundness specifications presented in Chapter 14.3, Part 2.

If the dimensional measurements are available, the meter tube diameter uncertainty is equated to the root mean square (rms) of the differences between each reading and the mean value.

NOTICE TO USERS OF PART 1

Chapter 14.3, Part 4, "Background, Development, Implementation Procedure, and Subroutine Documentation for Empirical Flange-Tapped Discharge Coefficient Equation" will provide the calculation procedure necessary to obtain uniform answers. Users of Part 1 may find it desirable to obtain Part 4 before attempting to program the equations contained in Part 1.

If the absolute static pressure is taken at the upstream differential pressure tap, then the value of the expansion factor, Y_1, shall be calculated as follows:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\frac{x_1}{k} \tag{1-24}$$

When the upstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_1}} \tag{1-25}$$

When the downstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_2} + \Delta P} \tag{1-26}$$

Where:

ΔP = orifice differential pressure.
k = isentropic exponent.
N_3 = unit conversion factor.
P_{f_1} = absolute static pressure at the upstream pressure tap.
P_{f_2} = absolute static pressure at the downstream pressure tap.
x_1 = ratio of differential pressure to absolute static pressure at the upstream tap.
x_1/k = upstream acoustic ratio.
Y_1 = expansion factor based on the absolute static pressure measured at the upstream tap.

1.8.2 DOWNSTREAM EXPANSION FACTOR (Y_2)

The downstream expansion factor requires determination of the downstream static pressure, the upstream static pressure, the downstream compressibility factor, the upstream compressibility factor, the diameter ratio, and the isentropic exponent. The value of the downstream expansion factor, Y_2, shall be calculated using the following equation:

$$Y_2 = Y_1\sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \tag{1-27}$$

Or,

$$Y_2 = \left[1 - (0.41 + 0.35\beta^4)\frac{x_1}{k}\right]\sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \tag{1-28}$$

When the upstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_1}} \tag{1-29}$$

When the downstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_2} + \Delta P} \tag{1-30}$$

Where:

ΔP = orifice differential pressure.
k = isentropic exponent.
N_3 = unit conversion factor.
P_{f_1} = absolute static pressure at the upstream pressure tap.
P_{f_2} = absolute static pressure at the downstream pressure tap.

x_1 = ratio of differential pressure to absolute static pressure at the upstream tap.
x_1/k = upstream acoustic ratio.
Y_1 = expansion factor based on the absolute static pressure measured at the upstream tap.
Y_2 = expansion factor based on the absolute static pressure measured at the downstream tap.
Z_{f_1} = fluid compressibility at the upstream pressure tap.
Z_{f_2} = fluid compressibility at the downstream pressure tap.

1.9 In-Situ Calibration

1.9.1 GENERAL

The statement of the uncertainty of the empirical coefficient of discharge for concentric, square-edged orifice meters, C_d, is predicated on compliance with the requirements of this standard.

For accurate measurement applications, the flowmeter and adjacent piping should meet the requirements of the relevant, preferably the most stringent, specification of the standard. Deviations from the standard's specifications (for example, eccentricity, steps between adjacent sections of pipe, prerun lengths with or without a flow conditioner, post-run lengths, and pipe wall roughness) will invalidate the uncertainty statement.

To assure the accuracy of such flow measurements, the user may wish to calibrate the meter in situ. This is particularly suggested for orifice meters under 2 inches (50 millimeters) nominal pipe size. *In situ* is defined as being under normal operating conditions, with the actual approach piping configuration, using the actual fluid with the actual orifice plate and recording system in place.

Calibration of an orifice meter in situ requires the use of a primary mass flow system. This primary mass flow system may be portable or permanently installed. A master meter that has been calibrated with a primary mass flow standard can also be used for in-situ calibration.

The in-situ calibration should be performed with a primary mass flow system (or master meter) with an overall uncertainty less than the overall uncertainty of q_{m_i} of the meter being calibrated. Refer to the working uncertainty equation given in 1.12.

To perform an in-situ calibration, the primary mass flow system (or master meter) should be installed either upstream or downstream of the pipe fitting nearest to the meter tube or meter tube manifold so that it provides a calibration of the meter in its normal flowing configuration (that is, velocity profile). In-situ calibration should be performed at the normal flow rate, temperature, and pressure of the meter station. Additionally, in-situ calibration may be performed over the range of flow rates, temperatures, and pressures to assure a higher confidence level over the complete range of flowing conditions.

1.9.2 METER CORRECTION FACTOR

The in-situ calibration can provide a meter factor (MF) that may be used to correct the calculated mass flow rate as determined by Equation 1-1, if agreed upon by the parties. The MF is defined as follows:

$$\mathrm{MF} = \frac{q_{m_p}}{q_{m_i}} = \frac{q_{m_p}}{q_{v_i}\rho_{t,p}} \tag{1-31}$$

Where:

q_{m_p} = mass flow rate determined by the primary mass flow system (or master meter).
q_{m_i} = mass flow rate indicated by the orifice meter being calibrated.
q_{v_i} = volumetric flow rate indicated by the orifice meter being calibrated.
$\rho_{t,p}$ = density (mass) of fluid at the meter at flowing conditions.

Alternatively, the results may be used to identify installations that exceed the uncertainty estimated using 1.12. If the MF falls outside the $0.9 \leq MF \leq 1.1$ limits, the system should be investigated until the physical cause for the deviation has been identified and corrected.

When the meter factors are determined over a range of operating conditions, several values of MF may result. A plot of MF versus pipe Reynolds number (Re_D) should provide a single curve that may be used for determining MF corrections.

If the MF is applied to the metered quantities for custody transfer purposes, then in-situ calibration should be periodically repeated to ensure accurate measurement. Additional in-situ calibrations should be performed when physical changes to the metering system or significantly different operating conditions are encountered.

1.10 Fluid Physical Properties

Certain fluid physical properties are required to solve the orifice flow equation.

For the mass flow equation, the following fluid properties are required:

a. The viscosity at flowing conditions, μ.
b. The fluid density at flowing conditions, $\rho_{t,p}$.
c. The isentropic exponent, k, for compressible fluids.

For the standard volumetric flow equation, the density at base conditions, ρ_b, is required for solution.

1.10.1 VISCOSITY (μ)

The absolute (or dynamic) viscosity of the fluid at flowing conditions is required to compute the pipe Reynolds number. Fluid viscosities may be measured experimentally or computed from empirical equations.

For high Reynolds number applications, viscosity variations are usually ignored, since a sensitivity analysis indicates negligible effect in the flow computation. For low Reynolds number applications, accurate viscosity values and their variation with composition, temperature, and pressure may have a significant affect on the flow computation.

1.10.2 DENSITY ($\rho_{t,p}$, ρ_b)

Appropriate values for the density of the fluid, $\rho_{t,p}$ and ρ_b, can be obtained using one of two methods:

a. Empirical density correlation. The empirical density value may be calculated by an equation of state or another technically qualified expression.
b. On-line density meters. An on-line density meter can measure the fluid density at operating conditions (or base conditions).

For on-line density meter applications where the density at flowing conditions (or base conditions) is greater than 0.30 gram per cubic centimeter, refer to Chapter 14.6 for the installation, operation, and calibration of these devices.

For on-line density meter applications where the density at flowing conditions (or base conditions) is less than 0.30 gram per cubic centimeter, refer to the manufacturers' recommendations for the installation, operation, and calibration of these devices. The manufacturer should be able to demonstrate that operation of the on-line density measurement device will not interfere with the basic operation of the orifice meter.

From a practical standpoint, the fluid temperature differences between the upstream sensing tap, the downstream sensing tap, and the temperature sensing device are assumed to be insignificant when the temperature device is installed as required in Chapter 14.3, Part 2. For fluids whose density changes rapidly with changes in flowing temperature, for low fluid velocities, and/or to minimize ambient temperature and heat transfer effects, the user may wish to thermally insulate the meter tube between the primary element and the temperature device.

1.10.3 ISENTROPIC EXPONENT (*k*)

The isentropic exponent, k, is required in the solution of the empirical expansion factor (Y) equation.

As a compressible fluid flows through the reduced area of an orifice plate bore, it undergoes a contraction and then an expansion. The expansion, which results in a change in the static pressure, is assumed to follow a polytropic path expressed by the following relationship:

$$\frac{P_f}{[\rho_{t,p}]^n} = \text{Constant} \qquad (1\text{-}32)$$

Where:

P_f = absolute static pressure.
$\rho_{t,p}$ = density of the fluid at flowing conditions (P_f, T_f).
n = polytropic exponent.

However, if the expansion is assumed to be relatively rapid (that is, short in length) and the pressure change relatively small in magnitude, the polytropic relationship can be replaced by an idealized (reversible and adiabatic) one-dimensional isentropic expansion relationship of the following form:

$$\frac{P_f}{[\rho_{t,p}]^k} = \text{Constant} \qquad (1\text{-}33)$$

Where:

P_f = absolute static pressure.
$\rho_{t,p}$ = density of the fluid at flowing conditions (P_f, T_f).
k = isentropic exponent.

The real compressible fluid isentropic exponent, k_r, is a function of the fluid and the pressure and temperature. For an ideal gas, the isentropic exponent, k_i, is equal to the ratio of its specific heats (c_p/c_v) and is independent of pressure. A perfect gas is an ideal gas that has constant specific heats. The perfect gas isentropic exponent, k_p, is equal to k_i evaluated at base conditions. It has been found that for many applications, the value of k_r, is nearly identical to the value of k_i, which is nearly identical to k_p. From a practical standpoint, the flow equation is not particularly sensitive to small variations in the isentropic exponent. Therefore, the perfect gas isentropic exponent, k_p, is often used in the flow equations. This greatly simplifies the calculations. This approach was adopted by Buckingham in his correlation for the expansion factor.

1.11 Unit Conversion Factors

1.11.1 ORIFICE FLOW EQUATION

The values for the unit conversion factor, N_1, for the orifice flow rate equation are summarized in Table 1-2. The table contains common engineering units, along with their corresponding conversion factor value.

1.11.2 REYNOLDS NUMBER EQUATION

The values for the unit conversion factor, N_2, for the Reynolds number equation are summarized in Table 1-3. The table contains common engineering units, along with their corresponding conversion factor value.

1.11.3 EXPANSION FACTOR EQUATION

The values for the unit conversion factor, N_3, for the expansion factor equation are summarized in Table 1-4. The table contains common engineering units, along with their corresponding conversion factor value.

1.11.4 FLOW RATE PER UNIT OF TIME CONVERSION

To convert the mass or volume flow rate per unit of time to another unit of time, the following multiplication factors are applicable:

From	To	Multiplying Factor
Units per second	Units per minute	60
Units per second	Units per hour	3,600
Units per second	Units per day	86,400

Table 1-2—Orifice Flow Rate Equation: Unit Conversion Factor (N_1)

Mass Rate

$$q_m = N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P}$$

Volumetric Rate at Flowing (Actual) Conditions

$$q_v = \frac{q_m}{\rho_{t,p}} = \frac{N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P}}{\rho_{t,p}}$$

Volumetric Rate at Base Conditions

$$Q_v = \frac{q_m}{\rho_b} = \frac{N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P}}{\rho_b}$$

Where:

	IP Units	SI Units	
π	3.141593	3.141593	Universal constant
g_c	32.1740	NA	lbm-ft/(lbf-sec²)
g_c	NA	1.0000	kg·m/(N·sec²)
d	Feet	Meters	
ΔP	lbf/ft²	Pa	
$\rho_{t,p}$	lbm/ft³	kg/m³	
ρ_b	lbm/ft³	kg/m³	
q_m	lbm/sec	kg/sec	
q_v	ft³/sec	m³/sec	
Q_v	Sft³/sec	Nm³/sec	
N_1	6.30025 E+00 6.30025	1.11072 E+00 1.11072	

	U.S. Units	U.S. Units	U.S. Units	Metric Units	Metric Units	
π	3.14159	3.14159	3.14159	3.14159	3.14159	Universal constant
g_c	32.1740	32.1740	32.1740	NA	NA	lbm-ft/ (lbf-sec²)
g_c	NA	NA	NA	1.0000	1.0000	kg·m/ (N·sec²)
d	Inches	Inches	Inches	Millimeters	Millimeters	
ΔP	lbf/in²	in H_2O_{60}	in H_2O_{68}	Millibar	kPa	
$\rho_{t,p}$	lbm/ft³	lbm/ft³	lbm/ft³	kg/m³	kg/m³	
ρ_b	lbm/ft³	lbm/ft³	lbm/ft³	kg/m³	kg/m³	
q_m	lbm/sec	lbm/sec	lbm/sec	kg/sec	kg/sec	
q_v	ft³/sec	ft³/sec	ft³/sec	m³/sec	m³/sec	
Q_v	Sft³/sec	Sft³/sec	Sft³/sec	Nm³/sec	Nm³/sec	
N_1	5.25021 E–01 0.525021	9.97424 E–02 0.0997424	9.97019 E–02 0.0997019	3.51241 E–04 0.000351241	3.51241 E–05 0.0000351241	

Table 1-3—Reynolds Number Equation: Unit Conversion Factor (N_2)

$$Re_D = \frac{4q_m}{\pi\mu D} \quad \text{or} \quad Re_D = \frac{N_2 q_m}{\mu D}$$

Where:

	IP Units	SI Units	
q_m	lbm/sec	kg/sec	
π	3.14159	3.14159	Universal constant
μ	lbm/ft-sec	kg/m·sec	SI Unit equal to Pa·sec
D	Feet	Meters	
N_2	1.27324 E+00 1.27324	1.27324 E+00 1.27324	

	U.S. Units	U.S. Units	Metric Units	Metric Units	
q_m	lbm/sec	lbm/sec	kg/sec	kg/sec	
π	3.14159	3.14159	3.14159	3.14159	Universal constant
μ	Centipoise	Poise	Centipoise	Poise	
D	Inches	Inches	Millimeters	Millimeters	
N_2	2.27375 E+04 22,737.5	22.7375 E+01 227.375	1.27324 E+06 127,324	1.27324 E+04 12,732.4	

1.12 Practical Uncertainty Guidelines

The most important assumption underlying the calculation of the orifice discharge coefficient equation is that laboratories' systematic equipment biases are randomized within the data base. This means that there is no bias in the equation's ability to represent reality due to equipment variety in the various laboratories. Such an assumption of randomization has precedent in ISO 5168, established in 1978, and a 1939 paper by Rossini and Deming. This allows the use of results from the world's finest laboratories without requiring that experimental equipment be identical.

Table 1-4—Empirical Expansion Factor Equation: Unit Conversion Factor (N_3)

$$x = \frac{\Delta P}{N_3 P}$$

	IP Units	SI Units
ΔP	lbf/ft^2	Pascals
P	lbf/ft^2	Pascals
N_3	1.00000 E+00 1.00000	1.00000 E+00 1.00000

	U.S. Units	U.S. Units	U.S. Units
ΔP	lbs/in^2	in H_2O_{60}	in H_2O_{68}
P	lbs/in^2	lbs/in^2	lbs/in^2
N_3	1.00000 E+00 1.00000	2.77070 E+01 27.7070	2.77300 E+01 27.7300

	Metric Units	Metric Units	Metric Units
ΔP	Kilopascals	Millibar	Millibar
P	Megapascals	Bar	Megapascals
N_3	1.00000 E+03 1000.00	1.00000 E+03 1000.00	1.00000 E-02 0.0100000

Every effort has been made to remove residual bias from the representation of the experimental data by the equation for mass flow. Consequently, the subsequent precision statements are valid for an individual orifice meter installation for which physical characteristics and measurements of these characteristics are maintained within the precision that is used to determine the contributions to imprecision in mass flow measurement caused by various factors.

In accordance with prudent statistical and engineering practice, the estimated orifice flow rate uncertainty shall be calculated at the 95-percent confidence level.

1.12.1 GENERAL

Many factors associated with an orifice installation influence the overall error in flow measurement. These errors are due to uncertainties about the following:

a. Representation of reality by the mass flow equation.
b. Uncertainty about actual physical properties of the fluid being measured.
c. Imprecision in the measurement of important installation parameters (such as orifice diameter and β ratio)

Examples of the calculations of the overall uncertainty as it depends on these major categories are given below. For ease of understanding, graphical summaries are presented where feasible.

1.12.2 UNCERTAINTY OVER A FLOW RANGE

From a practical standpoint, the accuracy envelope for an orifice meter is usually estimated using the uncertainty assigned to the differential pressure sensing device. This technique realistically estimates the uncertainty associated with the designer's flow range.

An accuracy envelope incorporates the influence quantities associated with the ΔP sensing device. The significant quantities include ambient temperature effects, static pressure effects, long-term drift, hysteresis, linearity, repeatability, and the calibration standard's uncertainty.

For some applications, parallel orifice meters are required to meet the user's desired uncertainty and rangeability. In addition, the designer may choose to install stacked ΔP devices calibrated for different ranges to minimize uncertainty while maximizing rangeability for a given orifice plate, as shown in Figure 1-3.

1.12.3 UNCERTAINTY OF FLOW RATE

The overall uncertainty is the quadrature sum (square root of the sum of the squares) of the uncertainties associated with the pertinent variables:

$$q_m = f(C_d, Y, \Delta P, d, D, \rho_{t,p})$$

For practical considerations, the pertinent variables are assumed to be independent to provide a simpler uncertainty calculation. In fact, no significant change in the uncertainty estimate will occur if the user applies the simplified uncertainty equations presented below.

The total uncertainty of the flow rate through an orifice meter may be calculated by one of two methods:

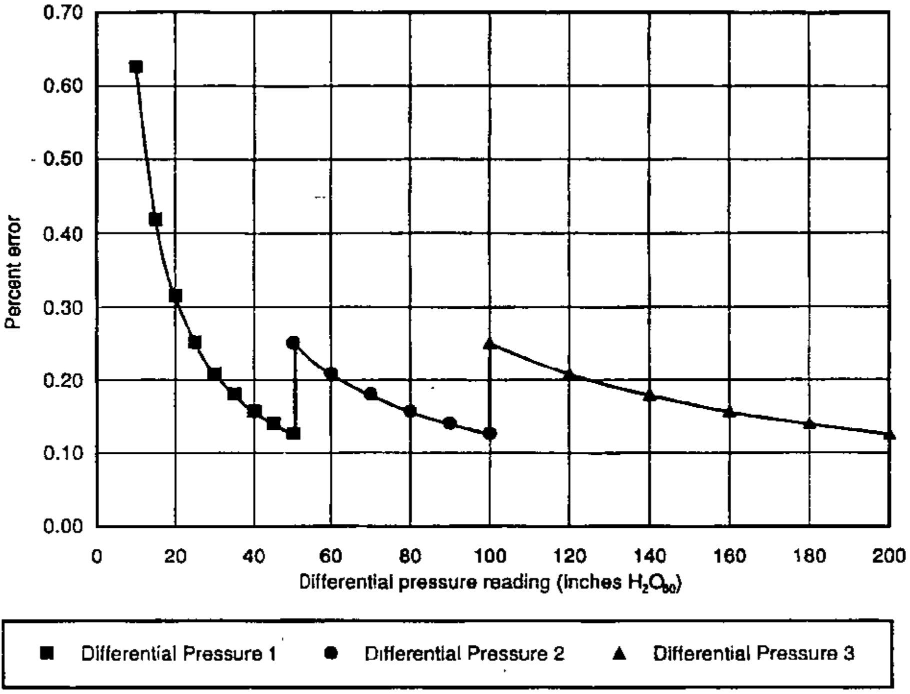
a. Empirical coefficient of discharge using flange-tapped orifice meters.
b. In-situ calibration using orifice meters.

1.12.3.1 Uncertainty Using Empirical Coefficient of Discharge for Flange-Tapped Orifice Meter

The basic flow equation used is as follows:

$$q_m = C_d E_v Y (\pi / 4) d^2 \sqrt{2 g_c \rho_{t,p} \Delta P}$$

100



Note: The precision of the differential pressure device used in this example is ±0.25 percent of full scale.

Figure 1-3—Contribution to Flow Error due to Differential Pressure Instrumentation

Where:

E_v = velocity of approach factor

$$= \frac{1}{\sqrt{1-\beta^4}}.$$

β = diameter ratio (d/D).

Using differentiation, one can show that

$$(\delta q_m/q_m) = S_{C_d}(\delta C_d/C_d) + S_{E_v}(\delta E_v/E_v) + S_Y(\delta Y/Y) + S_d(\delta d/d) \\ + S_{\rho_{t,p}}(\delta\rho_{t,p}/\rho_{t,p}) + S_{\Delta P}(\delta\Delta P/\Delta P) \quad (1\text{-}34)$$

Where:

S = sensitivity coefficient of the particular variable.

Therefore,

$$S_{C_d} \text{ and } S_Y = 1.0$$

And,

$$S_d = 2$$
$$S_{\rho_{t,p}} = \tfrac{1}{2}$$
$$S_{\Delta P} = \tfrac{1}{2}$$

By continuing this process to put $\delta E_v/E_v$ in terms of $\delta d/d$ and $\delta D/D$, it can be shown that

$$(\delta E_v / E_v) = \frac{2\beta^4}{1 - \beta^4}[(\delta d / d) - (\delta D / D)] \tag{1-35}$$

Assuming that independent estimates are available for $\delta C_d/C_d$, $\delta Y/Y$, $\delta d/d$, and $\delta D/D$ and substituting for $\delta E_v/E_v$ gives us the following working equation for the uncertainty of the mass flow rate:

$$(\delta q_m / q_m) = \left\{(\delta C_d / C_d)^2 + (\delta Y / Y)^2 + \left[\frac{2}{1 - \beta^4}\right]^2 (\delta d / d)^2 \right.$$
$$\left. + \left[\frac{-2\beta^4}{1 - \beta^4}\right]^2 (\delta D / D)^2 + \tfrac{1}{4}(\delta \rho_{t,p} / \rho_{t,p})^2 + \tfrac{1}{4}(\delta \Delta P / \Delta P)^2 \right\}^{0.5} \tag{1-36}$$

1.12.3.2 Uncertainty Using an In–Situ Calibration

When the orifice meter has been calibrated in situ, the practical working formula for the uncertainty of the mass flow rate can be expressed as follows:

$$(\delta q_m / q_m) = \left[(\delta \mathrm{MF} / \mathrm{MF})^2 + \tfrac{1}{4}(\delta \Delta P / \Delta P)^2 + \tfrac{1}{4}(\delta \rho_{t,p} / \rho_{t,p})^2\right]^{0.5} \tag{1-37}$$

The meter factor (MF) term is estimated from the combination of the primary mass flow uncertainty, the master meter uncertainty, and the precision of the orifice meter calibration. Note that the meter factor (MF) determined for the orifice plate and tube is a combination of several possible errors. No additional uncertainty is necessary for installation conditions or expansion factor.

1.12.4 TYPICAL UNCERTAINTIES

For precise metering applications, such as custody transfer, the flowmeter and adjacent piping should meet the requirements of the relevant, preferably the most stringent, specification of the standard. In the following sections, the typical uncertainties expressed can be obtained only through compliance with the specifications of the standard.

1.12.4.1 Empirical Coefficient of Discharge

The estimated uncertainty of the empirical coefficient of discharge for concentric, square-edged, flange-tapped orifice meters that are in compliance with this standard is a function of the Reynolds number and the diameter ratio (β). At very high Reynolds numbers the uncertainty is only a function of the diameter ratio (β). This uncertainty estimate is shown graphically in Figure 1-4. As the Reynolds number decreases, the uncertainty of the orifice plate coefficient of discharge increases. The ratio of the uncertainty at a given Reynolds number to the uncertainty at infinite Reynolds number is shown graphically in Figure 1-5. The overall uncertainty of the empirical coefficient of discharge is the product of the value read from Figure 1-4 and the value read from Figure 1-5. The values for Figure 1-4 may be approximated by the following:

For $\beta > 0.175$,

$$\delta C_i(\mathrm{FT}) / C_d(\mathrm{FT}) = 0.5600 - 0.2550\beta + 1.9316\beta^8 \tag{1-38}$$

For $\beta \leq 0.175$,

$$\delta C_i(\mathrm{FT}) / C_d(\mathrm{FT}) = 0.7000 - 1.0550\beta \tag{1-39}$$

The values for Figure 1-5 may be approximated by the following:

$$\delta C_d(\mathrm{FT}) / \delta C_i(\mathrm{FT}) = 1 + 1.7895\left(\frac{4000}{Re_D}\right)^{0.8} \tag{1-40}$$

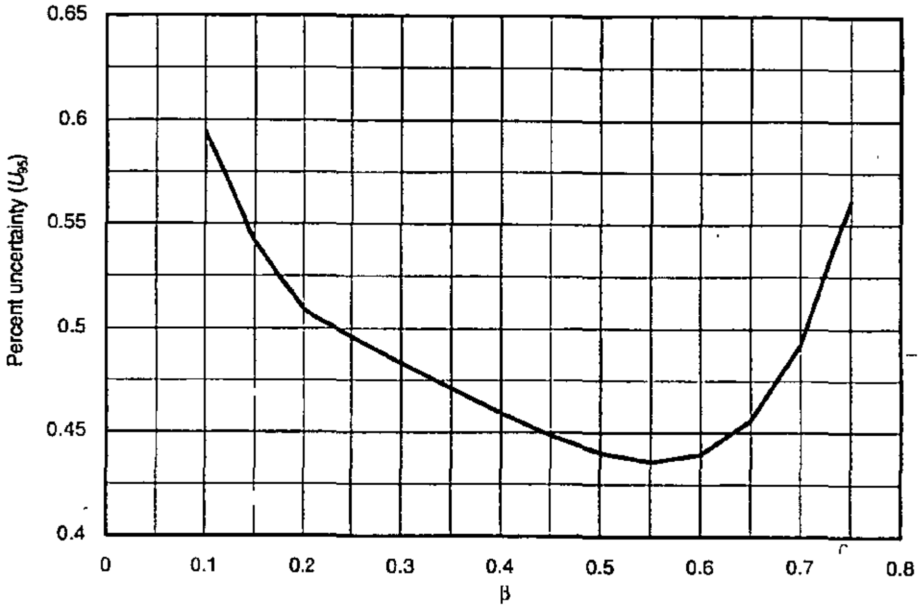


Figure 1-4—Empirical Coefficient of Discharge: Uncertainty at Infinite Reynolds Number

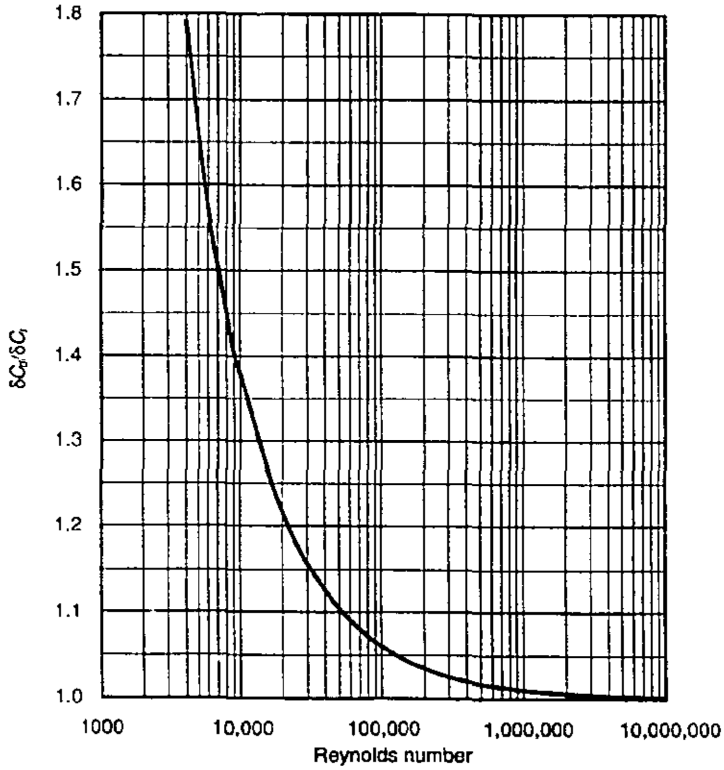


Figure 1-5—Relative Change in Uncertainty: Dependence on Reynolds Number

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These estimates for the uncertainty were developed using the regression data base discussed in 1.7.1. Orifice plates with bore diameters less than 0.45 inch (11.4 millimeters), installed according to Chapter 14.3, Part 2, may have coefficient of discharge [C_d(FT)] uncertainties as great as 3.0 percent. This large uncertainty is due to problems with edge sharpness. These types of problems are discussed further in Chapter 14.3, Part 2. Deviations from the installation specifications in Chapter 14.3, Part 2, will invalidate this uncertainty statement.

1.12.4.2 Empirical Expansion Factor for Flange-Tapped Orifice Meters

The values of Y computed by the empirical equations are subject to a tolerance varying from 0, when $x = 0$, to ±0.5 percent, when $x = 0.2$. For larger values of x, a somewhat larger uncertainty may be expected.

An alternative approach for determining the uncertainty for the expansion factor, which has been proposed in the international community, stipulates that when β, ΔP, P_f, and k are assumed to be known without error, the percentage uncertainty of the value of Y is estimated by

$$\pm 4\left[\frac{\Delta P}{N_3 P_f}\right] \text{ when } \beta \leq 0.750$$

The expansion factor uncertainty is presented in Table 1-5. For fluids that are not compressible, the expansion factor equals 1.000 by definition, and the estimated uncertainty is zero.

Table 1-5—Uncertainty Statement for Empirical Expansion Factor

Common U.S. Units

ΔP (inches H_2O_{60})	psid	Expansion Factor Uncertainty (%) When P_f (psia) Equals							
		50	100	250	500	750	1000	1250	1500
10	0.36	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
50	1.80	0.14	0.07	0.03	0.01	0.01	0.01	0.01	0.00
100	3.61	0.29	0.14	0.06	0.03	0.02	0.01	0.01	0.01
150	5.41	0.43	0.22	0.09	0.04	0.03	0.02	0.02	0.01
200	7.22	0.58	0.29	0.12	0.06	0.04	0.03	0.02	0.02
250	9.02	0.72	0.36	0.14	0.07	0.05	0.04	0.03	0.02
300	10.83	0.87	0.43	0.17	0.09	0.06	0.04	0.03	0.03

Common SI Units

ΔP (inches H_2O_{60})	kPa	Expansion Factor Uncertainty (%) When P_f (MPa) Equals							
		0.3	0.7	1.7	3.4	5.2	6.9	8.6	10.3
10	2.49	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
50	12.44	0.14	0.07	0.03	0.01	0.01	0.01	0.01	0.00
100	24.88	0.29	0.14	0.06	0.03	0.02	0.01	0.01	0.01
150	37.33	0.43	0.22	0.09	0.04	0.03	0.02	0.02	0.01
200	49.77	0.58	0.29	0.12	0.06	0.04	0.03	0.02	0.02
250	62.21	0.72	0.36	0.14	0.07	0.05	0.04	0.03	0.02
300	74.65	0.87	0.43	0.17	0.09	0.06	0.04	0.03	0.03

Notes:

1. Orifice plates having bore diameters less than 0.45 inch (11.4 millimeters), installed according to Chapter 14.3, Part 2, may have coefficient of discharge (C_d) uncertainties as great as 3.0 percent. This large uncertainty is due to problems with edge sharpness
2. The relative uncertainty level depicted in Figure 1-6 assumes a swirl-free inlet velocity profile.

1.12.4.3 Installation Conditions

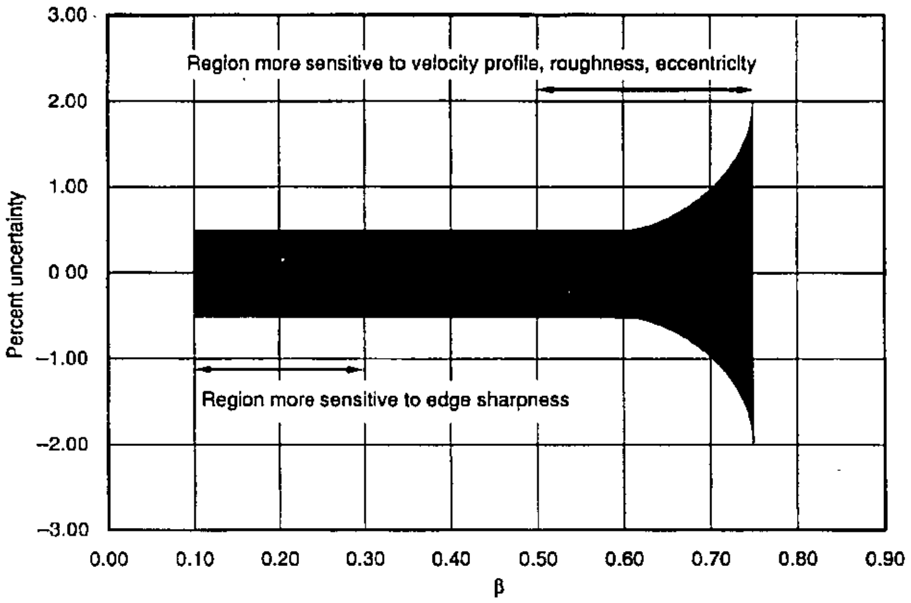
To assure accurate flow measurement, the fluid should enter the orifice plate with a fully developed flow profile, free from swirl or vortices. Such a condition is best achieved through the use of flow conditioners and adequate lengths of straight pipe preceding and following the orifice plate.

For various technical reasons, the uncertainty associated with installation conditions is difficult to quantify. Therefore, Figure 1-6 has been provided as a general guide. This figure represents a combined practical uncertainty level attributed to the following parameters:

a. Empirical coefficient of discharge.
b. Installation conditions, such as velocity profile and swirl.
c. Mechanical specifications, such as pipe wall roughness, plate eccentricity, and orifice plate bore edge sharpness.

Figure 1-6 depicts the prospective combined uncertainty level as a function of diameter ratio (β). It is apparent from the figure that the lowest relative combined uncertainty levels occur over a diameter ratio range of 0.10–0.60.

The approach length (upstream meter tube), piping configuration, and flow conditioning recommendations presented in Chapter 14.3, Part 2, are essentially unchanged from the second (1985) edition of the standard. Substantial research programs in these areas are currently under way by the API, the EC,[4] and the GRI.[5] A restatement of the orifice meter



Notes:
1. Orifice plates whose bore diameters are less than 0.45 inch (11.4 millimeters), installed according to Chapter 14, Section 3, Part 2, may have coefficient of discharge uncertainties as great as 3.0 percent. This large uncertainty is due to problems with edge sharpness.
2. The relative uncertainty level shown in the figure assumes a swirl-free inlet velocity profile.

Figure 1-6—Practical Uncertainty Levels

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[4] Commission of the European Communities, rue de la Loi 200, B-1049, Brussels, Belgium.
[5] Gas Research Institute, 8600 West Bryn Mawr Avenue, Chicago, Illinois 60631.

uncertainty will naturally follow the conclusion of the current research and may offer a basis for future changes in this standard.

1.12.4.4 Orifice Plate Bore Diameter

The plate diameter uncertainty may be determined from dimensional measurements or, alternatively, from the roundness specifications presented in Chapter 14.3, Part 2.

If the dimensional measurements are available, the plate diameter uncertainty is equated to the root mean square (rms) of the differences between each reading and the mean value.

For example, if the four measurements for d_m are 20.005, 20.002, 19.995, and 19.9980, then the mean value is 20.000.

The deviations from the mean are +0.005, +0.002, –0.005, and –0.002, so

$$\delta d_m = \left[\frac{\sum_{i=1}^{n}\left(\delta d_{m_i}\right)^2}{n-1}\right]^{0.5}$$

$$= \pm\left[\frac{(0.005)^2 + (0.002)^2 + (-0.005)^2 + (-0.002)^2}{3}\right]^{0.5}$$

$$= \pm 0.0044$$

$$\frac{\delta d_m}{d_m} = \pm\frac{0.0044}{20.00}$$

$$= \pm 0.00022 \times 100$$

$$= \pm 0.022 \text{ percent} \qquad (1\text{-}41)$$

1.12.4.5 Meter Tube Internal Diameter

The plate diameter uncertainty may be determined from dimensional measurements or, alternatively, from the roundness specifications presented in Chapter 14.3, Part 2.

If the dimensional measurements are available, the plate diameter uncertainty is equated to the root mean square (rms) of the differences between each reading and the mean value.

For example, if the four measurements for D_m are 20.050, 20.020, 19.950, and 19.980, then the mean value is 20.000.

The deviations from the mean are +0.05, +0.02, –0.05, and –0.02, so

$$\delta D_m = \left[\frac{\sum_{i=1}^{n}\left(\delta D_{m_i}\right)^2}{n-1}\right]^{0.5}$$

$$= \pm\left[\frac{(0.05)^2 + (0.02)^2 + (-0.05)^2 + (-0.02)^2}{3}\right]^{0.5}$$

$$= \pm 0.044$$

$$\frac{\delta D_m}{D_m} = \pm\frac{0.044}{20.00}$$

$$= \pm 0.0022 \times 100$$

$$= \pm 0.22 \text{ percent} \qquad (1\text{-}42)$$

1.12.4.6 Differential Pressure Device

Performance specifications for the differential pressure device must be provided by the manufacturer. The user selects a device based on its performance specifications and the desired uncertainty associated with the application.

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When considering the uncertainty, care should be taken to take into account the effects of ambient temperature, humidity, static pressure, driving mechanism, and response time on the user-selected device.

1.12.4.7 Fluid Density

When an empirical correlation is used to predict a liquid density, the uncertainty should be estimated based on the stated uncertainty of the correlation and the estimated uncertainty of the variables required to calculate the density. The following example for proplyene, calculated using the method of Chapter 11.3.3.2, demonstrates this procedure.

Proplyene is being metered at 60°F and 800 pounds per square inch absolute. The stated uncertainty of the Chapter 11.3.3.2 method for calculating the density of proplyene is ±0.24 percent. The stated uncertainty of the temperature measurement is ±0.5°F. The stated uncertainty of the pressure measurement is ±4 pounds per square inch absolute. The uncertainty in the density is calculated according to the following formula:

$$(\delta\rho_{t,p}/\rho_{t,p}) = \left\{(\delta\rho_{t,p}/\rho_{t,p})^2 + \left[\frac{\partial\rho_{t,p}}{\partial T_f}\right]^2_{P_f}(\delta T_f/\rho_{t,p})^2 + \left[\frac{\partial\rho_{t,p}}{\partial P_f}\right]^2_{T_f}(\delta P_f/\rho_{t,p})^2\right\}^{0.5} \quad (1\text{-}43)$$

Using this method, the following calculated values can be used to estimate $(\partial\rho_{t,p}/\partial T_f)_{P_f}$ and $(\partial\rho_{t,p}/\partial P_f)_{T_f}$:

T_f (°F)	P_f (psia)	Density (lb/ft³)
60	800	33.3413
60	780	33.3215
60	820	33.3611
58	800	33.4445
62	800	33.2376

$$\left[\frac{\partial\rho_{t,p}}{\partial T_f}\right]_{P_f} \cong (33.2376 - 33.4445)/4 = -0.052$$

$$\left[\frac{\partial\rho_{t,p}}{\partial P_f}\right]_{T_f} \cong (33.3611 - 33.3215)/40 = -0.00099$$

Then,

$$\begin{aligned}\delta\rho_{t,p}/\rho_{t,p} &\cong \pm\left[(0.0024)^2 + (-0.052)^2\left(\frac{0.5}{33.3413}\right)^2 + (0.00099)^2\left(\frac{4}{33.3413}\right)^2\right]^{0.5}\\ &= \pm\left[0.0024^2 + 0.0008^2 + 0.0001^2\right]^{0.5}\\ &= \pm 0.0025 \text{ or } \pm 0.25 \text{ percent}\end{aligned}$$

Therefore, the estimated overall uncertainty in the proplyene density is ±0.25 percent.

When on-line density meters are used, the uncertainty should be estimated based on the calibration technique, density differences between the orifice and density meter locations, and the density meter manufacturer's recommendations.

1.12.5 EXAMPLE UNCERTAINTY CALCULATIONS

Example uncertainty calculations for liquid and gas flows are presented in 1.12.5.1 and 1.12.5.2.

1.12.5.1 Example Uncertainty Estimate for Liquid Flow Calculation

An example of the effect of uncertainties is provided in Table 1-6, using the following flow equation:

Table 1-6—Example Uncertainty Estimate for Liquid Flow Calculation

		Uncertainty, U_{95} (%)	Sensitivity Coefficient, S	$(U_{95}S)^2$
C_d	Basic discharge coefficient	0.45	1.0	0.2025
d	Orifice diameter (Table 2-1)	0.05	$2/(1 - \beta^4)$	0.0114
D	Pipe diameter (2.5.1.3)	0.25	$-2\beta^4/(1 - \beta^4)$	0.0011
ΔP	Differential pressure	0.50	0.5	0.0625
ρ	Density	0.45	0.5	0.0506
Sum of squares				0.3281
Square root of sum of squares				0.5728

Note: As the table shows, the overall liquid flow measurement uncertainty at a 95-percent confidence level is ±0.57 percent.

$$q_m = C_d E_v Y(\pi/4) d^2 \sqrt{2 g_c \rho_{t,p} \Delta P}$$

The following assumptions and conditions were selected for the calculation:

a. The fluid flowing is proplyene. The liquid density will be calculated using the Chapter 11.3.3.2 method. The viscosity will be estimated using Procedure 11A5.1 from the API *Technical Data Book—Petroleum Refining*. The expansion factor will be assumed to be 1.0.

b. A 4-inch meter with a β ratio of 0.5, a static pressure of 800 pounds per square inch absolute, a flowing temperature of 60°F, and a differential pressure of 50 inches of water (60°F) is selected for the calculation.

c. For each variable, the uncertainty listed represents random error only.

As a result of the first two assumptions, the estimated values of the required physical properties are as follows:

$\rho_{t,p}$ = 33.3413 lbm/ft^3.
$\delta\rho_{t,p}/\rho_{t,p}$ = 0.25 percent (as shown in liquid density sensitivity section).
μ = 0.0956 centipoise = 0.0000643 lbm/ft-sec.

As a result of the calculations for the flow rate,

$C_d(\text{FT})$ = 0.603659.
q_m = 10.148 lbm/sec.
Re_D = 603,400.
$\delta C_i(\text{FT})/C_d(\text{FT})$ = ±0.44 percent (from Figure 1-4).
$\delta C_d(\text{FT})/\delta C_i(\text{FT})$ = 1.02 (from Figure 1-5).

This gives

$\delta C_d(\text{FT})/C_d(\text{FT})$ = 1.02 × ±0.44 = ±0.45 percent.

1.12.5.2 Example Uncertainty Estimate for Natural Gas Flow Calculation

For natural gas flow, fluid density is defined as follows:

$$\rho_{t,p} = \frac{G_i Mr_{air} P_f}{Z_f R T_f} \tag{1-44}$$

Where:

G_i = ideal gas relative density (specific gravity) of the gas (Mr_{gas}/Mr_{air}).
Mr_{air} = molar mass of air.
Mr_{gas} = molar mass of the gas.
P_f = static pressure of fluid.

R = universal gas constant.
T_f = temperature of the fluid at flowing conditions.
Z_f = fluid compressibility at flowing conditions.

The fluid density uncertainty term, $\frac{1}{4}(\delta\rho_{t,p}/\rho_{t,p})^2$ in 1:12.3.1 is replaced by the following terms for natural gas application:

$$\left[\tfrac{1}{2}(\delta G_i/G_i)\right]^2 + \left[\tfrac{1}{2}(\delta P_f/P_f)\right]^2 + \left[-\tfrac{1}{2}(\delta Z_f/Z_f)\right]^2 + \left[-\tfrac{1}{2}(\delta T_f/T_f)\right]^2$$

An example of the effect of uncertainties is provided in Table 1-7, using the following gas flow equation:

$$q_m = C_d E_v Y(\pi/4)d^2\sqrt{2g_c\frac{G_i Mr_{air} P_f}{Z_f R T_f}\Delta P} \tag{1-45}$$

The following assumptions and conditions were selected for the calculation:

a. For each variable, the uncertainty listed represents random error only.
b. A 4-inch meter with a β ratio of 0.5 and static and differential pressures equal to 250 pounds per square inch absolute and 50 inches of water, respectively, was selected for the calculation.

Note: The precision of the ΔP device used in this example was ±0.25 percent of full scale.

Table 1-7—Example Uncertainty Estimate for Natural Gas Flow Calculation

		Uncertainty, U_{95} (%)	Sensitivity Coefficient, S	$(U_{95}S)^2$
C_d	Basic discharge coefficient (Figure 1-4)	0.44	1	0.1936
Y	Expansion factor (Table 1-5)	0.03	1	0.0009
d	Orifice diameter (Table 2-1)	0.05	$2/(1-\beta^4)$	0.0114
D	Pipe diameter (2.5.1.3)	0.25	$-2\beta^4/(1-\beta^4)$	0.0110
ΔP	Differential pressure	0.50	0.5	0.0625
P	Static pressure	0.50	0.5	0.0625
Z	Compressibility factor (A.G.A. 8)	0.1	−0.5	0.0025
T	Flowing temperature	0.25	−0.5	0.0156
G	Relative density	0.60	0.5	0.0900
Sum of squares				0.4500
Square root of sum of squares				0.6700

Note: As the table shows, the overall gas flow measurement uncertainty at a 95-percent confidence level is ±0.67 percent.

On page 23, the last line of Table 1-3 should read as follows:

22,737.5 227.375 1,273,240 12,732.4

On page 25, S_{E_v} *should be added to the following line:*

Therefore,

$$S_{E_v}, S_{C_d}, \text{ and } S_Y = 1.0$$

On page 26, Equations 1-38 and 1-39 should read as follows:

$$100\,[\delta C_i(\mathrm{FT}) / C_d(\mathrm{FT})] = 0.5600 - 0.2550\beta + 1.9316\beta^8 \quad (1\text{-}38)$$

$$100\,[\delta C_i(\mathrm{FT}) / C_d(\mathrm{FT})] = 0.7000 - 1.0550\beta \quad (1\text{-}39)$$

On page 33, Table 1-7 should read as follows:

Table 1-7—Example Uncertainty Estimate for Natural Gas Flow Calculation

		Uncertainty, U_{95} (%)	Sensitivity Coefficient, S	$(U_{95}S)^2$
C_d	Basic discharge coefficient (Figure 1-4)	0.44	1	0 1936
Y	Expansion factor (Table 1-5)	0.03	1	0.0009
d	Orifice diameter (Table 2-1)	0.05	$2/(1 - \beta^4)$	0 0114
D	Pipe diameter (2.5.1.3)	0.25	$-2\beta^4/(1 - \beta^4)$	0.0011
ΔP	Differential pressure	0.50	0.5	0 0625
P	Static pressure	0.50	0.5	0 0625
Z	Compressibility factor (A.G.A. 8)	0.1	−0.5	0 0025
T	Flowing temperature	0 25	−0.5	0 0156
G	Relative density	0.60	0.5	0.0900
Sum of squares				0.4401
Square root of sum of squares				0.6634

Note: As the table shows, the overall gas flow measurement uncertainty at a 95-percent confidence level is ±0.67 percent.

APPENDIX 1-A—REFERENCES

Note: This appendix is not a part of this standard but is included for informational purposes only.

The following references are pertinent to the discussions contained in Part 1.

1-A.1 Discharge Coefficient Studies

1-A.1.1 API/GPA EXPERIMENTAL PROGRAM

Britton, C. L., Caldwell, S., and Seidl, W., "Measurements of Coefficients of Discharge for Concentric, Flange-Tapped, Square-Edged Orifice Meters in White Mineral Oil Over a Low Reynolds Number Range," American Petroleum Institute, Washington, D.C., 1988.

"Coefficients of Discharge for Concentric, Square-Edged, Flange-Tapped Orifice Meters: Equation Data Set—Supporting Documentation for Floppy Diskettes," American Petroleum Institute, Washington, D.C., 1988.

Whetstone, J. R., Cleveland, W. G., Baumgarten, G. P., and Woo, S., "Measurements of Coefficients of Discharge for Concentric, Flange-Tapped, Square-Edged Orifice Meters in Water Over a Reynolds Number Range of 600 to 2,700,000" (Technical Note 1264), National Institute of Standards and Technology, Washington, D.C., 1989.

1-A.1.2 EC EXPERIMENTAL PROGRAM

Hobbs, J. M., "Experimental Data for the Determination of Basic 100mm Orifice Meter Discharge Coefficients" (Report EUR 10027), Commission of the European Communities, Brussels, 1985.

Hobbs, J. M., "The EEC Orifice Plate Project: Part I. Traceabilities of Facilities Used and Calculation Methods Employed" (Report PR5:EUEC/17), Commission of the European Communities, Brussels, 1987.

Hobbs, J. M., "The EEC Orifice Plate Project: Part II. Critical Evaluation of Data Obtained During EEC Orifice Plate Tests" (Report EUEC/17), Commission of the European Communities, Brussels, 1987.

Hobbs, J. M., "The EEC Orifice Plate Project: Tables of Valid Data for EEC Orifice Analysis" (Report EUEC/17), Commission of the European Communities, Brussels, 1987.

Hobbs, J. M., Sattary, J. A., and Maxwell, A. D., "Experimental Data for the Determination of Basic 250mm Orifice Meter Discharge Coefficients" (Report EUR 10979), Commission of the European Communities, Brussels, 1987.

1-A.1.3 OSU EXPERIMENTAL PROGRAM

Beitler, S. R., "The Flow of Water Through Orifices" (Bulletin 89), Engineering Experiment Station, Ohio State University, Columbus, 1935.

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1-A.1.4 EMPIRICAL COEFFICIENT EQUATIONS

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APPENDIX 1-B—DISCHARGE COEFFICIENTS FOR FLANGE-TAPPED ORIFICE METERS

Note: This appendix is not a part of this standard but is included for informational purposes only.

Table 1-B-1—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 2-Inch (50-Millimeter) Meter [D = 1.939 Inches (49.25 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.60014	0.59940	0.59883	0.59873	0.59862	0.59860	0.59858	0.59857	0.59857	0.59857
0.04	0.60102	0.59981	0.59890	0.59873	0.59854	0.59851	0.59847	0.59847	0.59846	0.59846
0.06	0.60178	0.60016	0.59895	0.59872	0.59848	0.59844	0.59839	0.59838	0.59837	0.59837
0.08	0.60248	0.60050	0.59901	0.59873	0.59843	0.59838	0.59832	0.59831	0.59830	0.59829
0.10	0.60315	0.60083	0.59908	0.59875	0.59840	0.59834	0.59827	0.59826	0.59824	0.59824
0.12	0.60381	0.60116	0.59916	0.59879	0.59839	0.59832	0.59824	0.59823	0.59821	0.59821
0.14	0.60448	0.60150	0.59927	0.59886	0.59841	0.59832	0.59823	0.59821	0.59820	0.59819
0.16	0.60515	0.60187	0.59940	0.59894	0.59844	0.59835	0.59825	0.59823	0.59820	0.59820
0.18	0.60586	0.60226	0.59955	0.59905	0.59850	0.59840	0.59828	0.59826	0.59824	0.59823
0.20	0.60660	0.60269	0.59974	0.59919	0.59859	0.59848	0.59835	0.59832	0.59829	0.59829
0.22	0.60738	0.60315	0.59996	0.59936	0.59871	0.59858	0.59844	0.59841	0.59838	0.59837
0.24	0.60823	0.60367	0.60022	0.59957	0.59886	0.59872	0.59856	0.59853	0.59849	0.59848
0.26	0.60914	0.60423	0.60052	0.59982	0.59904	0.59889	0.59871	0.59867	0.59863	0.59862
0.28	0.61014	0.60487	0.60087	0.60011	0.59926	0.59909	0.59889	0.59885	0.59880	0.59878
0.30	0.61123	0.60557	0.60127	0.60045	0.59952	0.59933	0.59911	0.59906	0.59900	0.59898
0.32	0.61243	0.60635	0.60173	0.60084	0.59982	0.59962	0.59936	0.59931	0.59923	0.59921
0.34	0.61375	0.60722	0.60224	0.60128	0.60017	0.59994	0.59965	0.59959	0.59950	0.59948
0.36	0.61522	0.60818	0.60282	0.60178	0.60056	0.60030	0.59998	0.59990	0.59980	0.59978
0.38	0.61683	0.60926	0.60347	0.60234	0.60100	0.60071	0.60034	0.60026	0.60014	0.60011
0.40	0.61862	0.61044	0.60419	0.60296	0.60149	0.60117	0.60075	0.60065	0.60051	0.60047
0.42	0.62059	0.61175	0.60499	0.60365	0.60202	0.60167	0.60119	0.60108	0.60091	0.60087
0.44	0.62276	0.61319	0.60586	0.60440	0.60261	0.60221	0.60167	0.60154	0.60134	0.60129
0.46	0.62515	0.61476	0.60682	0.60522	0.60324	0.60279	0.60218	0.60203	0.60180	0.60174
0.48	0.62777	0.61647	0.60784	0.60610	0.60391	0.60341	0.60271	0.60254	0.60228	0.60221
0.50	0.63063	0.61833	0.60895	0.60703	0.60462	0.60406	0.60327	0.60307	0.60278	0.60270
0.52	0.63374	0.62034	0.61012	0.60803	0.60536	0.60473	0.60384	0.60361	0.60327	0.60318
0.54	0.63712	0.62249	0.61136	0.60906	0.60612	0.60541	0.60441	0.60415	0.60376	0.60366
0.56	0.64077	0.62479	0.61265	0.61014	0.60688	0.60609	0.60497	0.60467	0.60423	0.60411
0.58	0.64470	0.62722	0.61399	0.61123	0.60763	0.60675	0.60549	0.60516	0.60465	0.60451
0.60	0.64890	0.62979	0.61535	0.61233	0.60836	0.60738	0.60596	0.60558	0.60501	0.60486
0.62	0.65337	0.63246	0.61671	0.61341	0.60903	0.60794	0.60636	0.60593	0.60529	0.60511
0.64	0.65811	0.63524	0.61806	0.61445	0.60963	0.60842	0.60665	0.60617	0.60545	0.60525
0.66	0.66309	0.63809	0.61937	0.61542	0.61012	0.60878	0.60681	0.60628	0.60546	0.60523
0.68	0.66829	0.64098	0.62061	0.61629	0.61047	0.60899	0.60680	0.60621	0.60529	0.60504
0.70	0.67369	0.64389	0.62174	0.61703	0.61066	0.60902	0.60660	0.60593	0.60491	0.60463
0.72	0.67925	0.64679	0.62274	0.61762	0.61064	0.60884	0.60615	0.60542	0.60428	0.60396
0.74	0.68494	0.64964	0.62358	0.61802	0.61040	0.60842	0.60546	0.60464	0.60338	0.60303
0.75	0.68781	0.65103	0.62394	0.61815	0.61019	0.60812	0.60501	0.60415	0.60282	0.60245

Table 1-B-2—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 3-Inch (75-Millimeter) Meter [D = 2.900 Inches (73.66 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59763	0.59688	0.59632	0.59622	0.59611	0.59609	0.59606	0.59606	0.59606	0.59605
0.04	0.59859	0.59737	0.59646	0.59629	0.59611	0.59607	0.59604	0.59603	0.59602	0.59602
0.06	0.59942	0.59780	0.59659	0.59636	0.59612	0.59607	0.59603	0.59602	0.59601	0.59601
0.08	0.60019	0.59821	0.59672	0.59645	0.59615	0.59609	0.59603	0.59602	0.59601	0.59601
0.10	0.60094	0.59861	0.59687	0.59655	0.59620	0.59613	0.59606	0.59605	0.59603	0.59603
0.12	0.60167	0.59902	0.59703	0.59666	0.59626	0.59619	0.59611	0.59609	0.59608	0.59608
0.14	0.60241	0.59944	0.59721	0.59680	0.59635	0.59627	0.59618	0.59616	0.59614	0.59614
0.16	0.60316	0.59989	0.59742	0.59697	0.59647	0.59638	0.59627	0.59625	0.59623	0.59623
0.18	0.60394	0.60036	0.59766	0.59716	0.59661	0.59650	0.59639	0.59637	0.59634	0.59634
0.20	0.60475	0.60086	0.59792	0.59737	0.59677	0.59666	0.59653	0.59651	0.59648	0.59647
0.22	0.60561	0.60140	0.59822	0.59763	0.59697	0.59684	0.59670	0.59667	0.59664	0.59663
0.24	0.60652	0.60199	0.59855	0.59791	0.59720	0.59706	0.59690	0.59687	0.59683	0.59682
0.26	0.60751	0.60263	0.59893	0.59824	0.59746	0.59730	0.59713	0.59709	0.59704	0.59703
0.28	0.60857	0.60333	0.59935	0.59860	0.59775	0.59758	0.59738	0.59734	0.59729	0.59728
0.30	0.60973	0.60410	0.59983	0.59901	0.59808	0.59790	0.59767	0.59762	0.59756	0.59755
0.32	0.61099	0.60495	0.60035	0.59947	0.59846	0.59825	0.59800	0.59794	0.59787	0.59785
0.34	0.61238	0.60589	0.60093	0.59998	0.59887	0.59864	0.59835	0.59829	0.59820	0.59818
0.36	0.61391	0.60691	0.60158	0.60054	0.59933	0.59907	0.59874	0.59867	0.59857	0.59854
0.38	0.61558	0.60804	0.60229	0.60116	0.59982	0.59954	0.59917	0.59908	0.59896	0.59893
0.40	0.61742	0.60929	0.60306	0.60184	0.60037	0.60005	0.59963	0.59953	0.59939	0.59935
0.42	0.61945	0.61064	0.60391	0.60257	0.60095	0.60059	0.60012	0.60001	0.59984	0.59980
0.44	0.62167	0.61213	0.60483	0.60337	0.60158	0.60118	0.60064	0.60051	0.60032	0.60027
0.46	0.62410	0.61374	0.60581	0.60422	0.60224	0.60179	0.60118	0.60103	0.60081	0.60075
0.48	0.62676	0.61548	0.60687	0.60512	0.60294	0.60244	0.60175	0.60157	0.60131	0.60125
0.50	0.62966	0.61737	0.60799	0.60608	0.60366	0.60310	0.60232	0.60212	0.60182	0.60174
0.52	0.63280	0.61939	0.60917	0.60707	0.60440	0.60377	0.60289	0.60266	0.60232	0.60223
0.54	0.63620	0.62155	0.61040	0.60810	0.60515	0.60444	0.60344	0.60318	0.60279	0.60269
0.56	0.63987	0.62383	0.61166	0.60914	0.60588	0.60509	0.60397	0.60367	0.60323	0.60311
0.58	0.64380	0.62625	0.61295	0.61019	0.60658	0.60570	0.60444	0.60410	0.60360	0.60346
0.60	0.64800	0.62877	0.61425	0.61121	0.60723	0.60625	0.60483	0.60445	0.60388	0.60373
0.62	0.65246	0.63138	0.61552	0.61219	0.60780	0.60671	0.60512	0.60470	0.60405	0.60387
0.64	0.65716	0.63406	0.61674	0.61310	0.60826	0.60704	0.60527	0.60479	0.60407	0.60386
0.66	0.66209	0.63679	0.61788	0.61389	0.60856	0.60722	0.60524	0.60471	0.60389	0.60366
0.68	0.66723	0.63953	0.61889	0.61453	0.60868	0.60719	0.60499	0.60439	0.60348	0.60322
0.70	0.67253	0.64223	0.61974	0.61498	0.60855	0.60691	0.60447	0.60381	0.60279	0.60250
0.72	0.67797	0.64486	0.62038	0.61519	0.60814	0.60633	0.60363	0.60289	0.60176	0.60144
0.74	0.68348	0.64736	0.62075	0.61510	0.60740	0.60541	0.60243	0.60161	0.60035	0.59999
0.75	0.68624	0.64855	0.62083	0.61494	0.60689	0.60480	0.60167	0.60081	0.59948	0.59911

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Table 1-B-3—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 4-Inch (100-Millimeter) Meter [*D* = 3.826 Inches (97.18 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59764	0.59689	0.59633	0.59623	0.59612	0.59610	0.59607	0.59607	0.59607	0.59607
0.04	0.59861	0.59739	0.59648	0.59631	0.59613	0.59610	0.59606	0.59605	0.59605	0.59605
0.06	0.59945	0.59784	0.59662	0.59640	0.59616	0.59611	0.59606	0.59605	0.59605	0.59604
0.08	0.60024	0.59826	0.59677	0.59650	0.59620	0.59615	0.59609	0.59608	0.59606	0.59606
0.10	0.60100	0.59868	0.59693	0.59661	0.59626	0.59620	0.59613	0.59612	0.59610	0.59610
0.12	0.60175	0.59910	0.59711	0.59675	0.59635	0.59627	0.59619	0.59618	0.59616	0.59616
0.14	0.60250	0.59954	0.59731	0.59690	0.59645	0.59637	0.59628	0.59626	0.59624	0.59624
0.16	0.60326	0.60000	0.59754	0.59708	0.59658	0.59649	0.59639	0.59637	0.59635	0.59634
0.18	0.60405	0.60048	0.59779	0.59729	0.59674	0.59664	0.59652	0.59650	0.59647	0.59647
0.20	0.60488	0.60099	0.59807	0.59752	0.59692	0.59681	0.59668	0.59666	0.59663	0.59662
0.22	0.60575	0.60155	0.59838	0.59779	0.59713	0.59701	0.59686	0.59684	0.59680	0.59680
0.24	0.60667	0.60215	0.59873	0.59809	0.59737	0.59723	0.59708	0.59704	0.59701	0.59700
0.26	0.60767	0.60280	0.59912	0.59842	0.59765	0.59749	0.59732	0.59728	0.59723	0.59722
0.28	0.60874	0.60352	0.59955	0.59880	0.59795	0.59779	0.59759	0.59755	0.59749	0.59748
0.30	0.60991	0.60430	0.60004	0.59922	0.59830	0.59811	0.59789	0.59784	0.59778	0.59776
0.32	0.61118	0.60516	0.60057	0.59969	0.59868	0.59847	0.59822	0.59816	0.59809	0.59807
0.34	0.61258	0.60610	0.60116	0.60021	0.59910	0.59887	0.59858	0.59852	0.59843	0.59841
0.36	0.61410	0.60713	0.60181	0.60078	0.59956	0.59930	0.59898	0.59891	0.59880	0.59878
0.38	0.61578	0.60827	0.60252	0.60140	0.60006	0.59978	0.59941	0.59932	0.59920	0.59917
0.40	0.61763	0.60951	0.60330	0.60207	0.60060	0.60028	0.59987	0.59977	0.59963	0.59959
0.42	0.61965	0.61086	0.60414	0.60280	0.60118	0.60082	0.60035	0.60023	0.60007	0.60003
0.44	0.62187	0.61233	0.60504	0.60358	0.60180	0.60140	0.60086	0.60073	0.60054	0.60048
0.46	0.62429	0.61393	0.60601	0.60442	0.60245	0.60200	0.60139	0.60123	0.60101	0.60095
0.48	0.62694	0.61567	0.60705	0.60530	0.60312	0.60262	0.60192	0.60175	0.60149	0.60142
0.50	0.62983	0.61753	0.60814	0.60623	0.60381	0.60325	0.60246	0.60226	0.60197	0.60189
0.52	0.63296	0.61952	0.60928	0.60719	0.60451	0.60388	0.60300	0.60277	0.60243	0.60234
0.54	0.63634	0.62164	0.61047	0.60817	0.60521	0.60450	0.60350	0.60324	0.60285	0.60275
0.56	0.63999	0.62389	0.61168	0.60915	0.60588	0.60509	0.60396	0.60367	0.60323	0.60310
0.58	0.64389	0.62625	0.61290	0.61013	0.60651	0.60563	0.60436	0.60403	0.60352	0.60338
0.60	0.64806	0.62871	0.61411	0.61106	0.60707	0.60609	0.60467	0.60429	0.60372	0.60356
0.62	0.65247	0.63124	0.61528	0.61194	0.60753	0.60643	0.60484	0.60442	0.60377	0.60359
0.64	0.65713	0.63384	0.61638	0.61272	0.60785	0.60664	0.60486	0.60438	0.60365	0.60345
0.66	0.66201	0.63645	0.61737	0.61335	0.60800	0.60665	0.60467	0.60413	0.60332	0.60309
0.68	0.66708	0.63905	0.61820	0.61381	0.60792	0.60643	0.60422	0.60362	0.60271	0.60245
0.70	0.67230	0.64160	0.61884	0.61403	0.60756	0.60591	0.60347	0.60280	0.60178	0.60149
0.72	0.67764	0.64403	0.61921	0.61396	0.60686	0.60504	0.60234	0.60160	0.60046	0.60014
0.74	0.68303	0.64629	0.61926	0.61354	0.60577	0.60377	0.60078	0.59996	0.59869	0.59834
0.75	0.68573	0.64733	0.61915	0.61318	0.60505	0.60295	0.59981	0.59895	0.59762	0.59725

Table 1-B-4—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 6-Inch (150-Millimeter) Meter [*D* = 5.761 Inches (146.33 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59765	0.59691	0.59635	0.59624	0.59613	0.59611	0.59609	0.59608	0.59608	0.59608
0.04	0.59864	0.59742	0.59651	0.59634	0.59616	0.59613	0.59609	0.59608	0.59608	0.59607
0.06	0.59950	0.59788	0.59667	0.59644	0.59620	0.59616	0.59611	0.59610	0.59609	0.59609
0.08	0.60030	0.59832	0.59683	0.59656	0.59626	0.59621	0.59615	0.59614	0.59613	0.59612
0.10	0.60107	0.59876	0.59701	0.59669	0.59635	0.59628	0.59621	0.59620	0.59618	0.59618
0.12	0.60184	0.59920	0.59721	0.59685	0.59645	0.59637	0.59629	0.59628	0.59626	0.59626
0.14	0.60260	0.59965	0.59743	0.59702	0.59657	0.59649	0.59640	0.59638	0.59636	0.59636
0.16	0.60339	0.60013	0.59767	0.59722	0.59672	0.59663	0.59653	0.59651	0.59649	0.59648
0.18	0.60419	0.60063	0.59794	0.59744	0.59690	0.59679	0.59668	0.59666	0.59663	0.59663
0.20	0.60503	0.60116	0.59824	0.59770	0.59710	0.59698	0.59686	0.59683	0.59680	0.59680
0.22	0.60592	0.60173	0.59857	0.59798	0.59733	0.59720	0.59706	0.59703	0.59700	0.59699
0.24	0.60686	0.60235	0.59894	0.59830	0.59758	0.59745	0.59729	0.59726	0.59722	0.59721
0.26	0.60786	0.60302	0.59934	0.59865	0.59787	0.59772	0.59755	0.59751	0.59746	0.59745
0.28	0.60895	0.60374	0.59979	0.59904	0.59820	0.59803	0.59783	0.59779	0.59773	0.59772
0.30	0.61013	0.60454	0.60029	0.59948	0.59855	0.59837	0.59814	0.59810	0.59803	0.59802
0.32	0.61141	0.60540	0.60083	0.59995	0.59894	0.59874	0.59849	0.59843	0.59836	0.59834
0.34	0.61281	0.60635	0.60143	0.60048	0.59937	0.59914	0.59886	0.59879	0.59871	0.59868
0.36	0.61434	0.60739	0.60208	0.60105	0.59984	0.59958	0.59926	0.59918	0.59908	0.59905
0.38	0.61602	0.60852	0.60279	0.60167	0.60034	0.60005	0.59968	0.59960	0.59948	0.59945
0.40	0.61786	0.60976	0.60356	0.60234	0.60087	0.60055	0.60014	0.60004	0.59990	0.59986
0.42	0.61988	0.61111	0.60439	0.60306	0.60144	0.60108	0.60061	0.60049	0.60033	0.60029
0.44	0.62210	0.61257	0.60528	0.60382	0.60204	0.60164	0.60110	0.60097	0.60078	0.60073
0.46	0.62452	0.61415	0.60623	0.60464	0.60266	0.60221	0.60160	0.60145	0.60123	0.60117
0.48	0.62715	0.61586	0.60723	0.60549	0.60330	0.60280	0.60211	0.60193	0.60167	0.60161
0.50	0.63002	0.61769	0.60829	0.60637	0.60395	0.60339	0.60260	0.60240	0.60211	0.60203
0.52	0.63313	0.61965	0.60938	0.60727	0.60460	0.60396	0.60308	0.60285	0.60251	0.60242
0.54	0.63649	0.62172	0.61050	0.60819	0.60523	0.60452	0.60352	0.60326	0.60287	0.60276
0.56	0.64011	0.62391	0.61163	0.60910	0.60582	0.60502	0.60390	0.60360	0.60316	0.60303
0.58	0.64398	0.62620	0.61276	0.60997	0.60634	0.60546	0.60419	0.60385	0.60335	0.60321
0.60	0.64810	0.62858	0.61386	0.61079	0.60678	0.60579	0.60437	0.60399	0.60342	0.60326
0.62	0.65247	0.63101	0.61489	0.61153	0.60709	0.60600	0.60440	0.60398	0.60333	0.60315
0.64	0.65707	0.63349	0.61583	0.61214	0.60724	0.60602	0.60424	0.60376	0.60303	0.60283
0.66	0.66188	0.63596	0.61663	0.61258	0.60718	0.60582	0.60384	0.60330	0.60248	0.60226
0.68	0.66688	0.63839	0.61723	0.61279	0.60685	0.60535	0.60314	0.60254	0.60162	0.60137
0.70	0.67201	0.64073	0.61758	0.61272	0.60618	0.60453	0.60207	0.60140	0.60038	0.60010
0.72	0.67724	0.64291	0.61762	0.61230	0.60512	0.60329	0.60057	0.59983	0.59869	0.59837
0.74	0.68250	0.64487	0.61726	0.61144	0.60358	0.60156	0.59856	0.59773	0.59647	0.59611
0.75	0.68512	0.64575	0.61690	0.61083	0.60260	0.60048	0.59733	0.59646	0.59513	0.59476

Table 1-B-5—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 8-Inch (200-Millimeter) Meter [*D* = 7.625 Inches (193.68 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59766	0.59691	0.59635	0.59625	0.59614	0.59612	0.59610	0.59609	0.59609	0.59609
0.04	0.59865	0.59744	0.59652	0.59636	0.59617	0.59614	0.59610	0.59610	0.59609	0.59609
0.06	0.59952	0.59791	0.59669	0.59647	0.59623	0.59618	0.59613	0.59612	0.59612	0.59611
0.08	0.60033	0.59835	0.59687	0.59659	0.59630	0.59624	0.59618	0.59617	0.59616	0.59616
0.10	0.60111	0.59880	0.59706	0.59674	0.59639	0.59632	0.59625	0.59624	0.59623	0.59622
0.12	0.60189	0.59925	0.59727	0.59690	0.59650	0.59643	0.59635	0.59633	0.59632	0.59631
0.14	0.60266	0.59971	0.59749	0.59708	0.59664	0.59655	0.59646	0.59645	0.59643	0.59642
0.16	0.60345	0.60020	0.59775	0.59729	0.59680	0.59670	0.59660	0.59658	0.59656	0.59656
0.18	0.60427	0.60071	0.59803	0.59753	0.59698	0.59688	0.59677	0.59674	0.59672	0.59671
0.20	0.60511	0.60125	0.59833	0.59779	0.59719	0.59708	0.59695	0.59693	0.59690	0.59689
0.22	0.60601	0.60183	0.59867	0.59808	0.59743	0.59731	0.59717	0.59714	0.59710	0.59710
0.24	0.60695	0.60246	0.59905	0.59841	0.59770	0.59756	0.59740	0.59737	0.59733	0.59733
0.26	0.60797	0.60313	0.59947	0.59877	0.59800	0.59785	0.59767	0.59763	0.59759	0.59758
0.28	0.60906	0.60387	0.59992	0.59917	0.59833	0.59816	0.59796	0.59792	0.59787	0.59786
0.30	0.61024	0.60467	0.60042	0.59961	0.59869	0.59851	0.59828	0.59823	0.59817	0.59816
0.32	0.61153	0.60554	0.60097	0.60010	0.59909	0.59888	0.59863	0.59857	0.59850	0.59848
0.34	0.61293	0.60649	0.60157	0.60062	0.59952	0.59929	0.59901	0.59894	0.59885	0.59883
0.36	0.61447	0.60753	0.60223	0.60120	0.59999	0.59973	0.59941	0.59933	0.59923	0.59920
0.38	0.61615	0.60866	0.60294	0.60182	0.60049	0.60020	0.59983	0.59975	0.59963	0.59960
0.40	0.61799	0.60990	0.60371	0.60248	0.60102	0.60070	0.60028	0.60018	0.60004	0.60001
0.42	0.62001	0.61124	0.60453	0.60320	0.60158	0.60122	0.60075	0.60063	0.60047	0.60043
0.44	0.62222	0.61270	0.60541	0.60395	0.60217	0.60177	0.60123	0.60110	0.60091	0.60086
0.46	0.62464	0.61427	0.60635	0.60475	0.60278	0.60233	0.60172	0.60157	0.60134	0.60128
0.48	0.62727	0.61597	0.60734	0.60559	0.60340	0.60290	0.60220	0.60203	0.60177	0.60170
0.50	0.63013	0.61778	0.60837	0.60645	0.60403	0.60346	0.60268	0.60248	0.60218	0.60210
0.52	0.63323	0.61972	0.60943	0.60732	0.60464	0.60401	0.60312	0.60289	0.60255	0.60246
0.54	0.63658	0.62177	0.61052	0.60820	0.60523	0.60452	0.60352	0.60326	0.60287	0.60277
0.56	0.64018	0.62393	0.61161	0.60906	0.60578	0.60498	0.60386	0.60356	0.60312	0.60299
0.58	0.64403	0.62618	0.61269	0.60989	0.60625	0.60536	0.60410	0.60376	0.60325	0.60312
0.60	0.64814	0.62851	0.61372	0.61065	0.60662	0.60563	0.60421	0.60383	0.60326	0.60310
0.62	0.65248	0.63089	0.61468	0.61131	0.60686	0.60576	0.60416	0.60373	0.60309	0.60291
0.64	0.65706	0.63330	0.61554	0.61182	0.60691	0.60569	0.60390	0.60342	0.60270	0.60249
0.66	0.66183	0.63570	0.61623	0.61215	0.60673	0.60538	0.60339	0.60285	0.60203	0.60180
0.68	0.66679	0.63804	0.61671	0.61224	0.60627	0.60476	0.60255	0.60195	0.60103	0.60078
0.70	0.67188	0.64027	0.61691	0.61201	0.60544	0.60378	0.60132	0.60065	0.59963	0.59934
0.72	0.67705	0.64233	0.61676	0.61140	0.60418	0.60234	0.59962	0.59888	0.59774	0.59742
0.74	0.68225	0.64413	0.61619	0.61032	0.60240	0.60037	0.59736	0.59654	0.59527	0.59492
0.75	0.68484	0.64491	0.61571	0.60957	0.60128	0.59916	0.59599	0.59513	0.59379	0.59342

Table 1-B-6—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 10-Inch (250-Millimeter) Meter [D = 9.562 Inches (242.87 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59767	0.59692	0.59636	0.59625	0.59614	0.59612	0.59610	0.59610	0.59609	0.59609
0.04	0.59866	0.59745	0.59653	0.59637	0.59618	0.59615	0.59611	0.59611	0.59610	0.59610
0.06	0.59953	0.59792	0.59671	0.59649	0.59624	0.59620	0.59615	0.59614	0.59613	0.59613
0.08	0.60035	0.59838	0.59689	0.59662	0.59632	0.59627	0.59621	0.59620	0.59618	0.59618
0.10	0.60114	0.59883	0.59709	0.59677	0.59642	0.59635	0.59628	0.59627	0.59626	0.59625
0.12	0.60192	0.59928	0.59730	0.59694	0.59654	0.59646	0.59638	0.59637	0.59635	0.59635
0.14	0.60270	0.59976	0.59754	0.59713	0.59668	0.59660	0.59651	0.59649	0.59647	0.59647
0.16	0.60350	0.60025	0.59780	0.59734	0.59685	0.59676	0.59665	0.59663	0.59661	0.59661
0.18	0.60432	0.60076	0.59808	0.59758	0.59704	0.59694	0.59682	0.59680	0.59678	0.59677
0.20	0.60517	0.60131	0.59840	0.59785	0.59726	0.59714	0.59702	0.59699	0.59696	0.59696
0.22	0.60607	0.60190	0.59874	0.59816	0.59750	0.59738	0.59724	0.59721	0.59718	0.59717
0.24	0.60702	0.60253	0.59913	0.59849	0.59778	0.59764	0.59748	0.59745	0.59741	0.59740
0.26	0.60804	0.60321	0.59955	0.59886	0.59808	0.59793	0.59775	0.59772	0.59767	0.59766
0.28	0.60914	0.60395	0.60001	0.59926	0.59842	0.59825	0.59805	0.59801	0.59796	0.59795
0.30	0.61032	0.60475	0.60052	0.59971	0.59879	0.59860	0.59838	0.59833	0.59827	0.59825
0.32	0.61161	0.60563	0.60107	0.60019	0.59919	0.59898	0.59873	0.59867	0.59860	0.59858
0.34	0.61302	0.60658	0.60167	0.60072	0.59962	0.59939	0.59911	0.59904	0.59896	0.59893
0.36	0.61456	0.60763	0.60233	0.60130	0.60009	0.59983	0.59951	0.59944	0.59933	0.59931
0.38	0.61624	0.60876	0.60304	0.60192	0.60059	0.60030	0.59994	0.59985	0.59973	0.59970
0.40	0.61809	0.61000	0.60381	0.60259	0.60112	0.60080	0.60038	0.60028	0.60014	0.60011
0.42	0.62010	0.61134	0.60463	0.60330	0.60168	0.60132	0.60085	0.60073	0.60057	0.60053
0.44	0.62231	0.61279	0.60551	0.60405	0.60226	0.60186	0.60132	0.60119	0.60100	0.60095
0.46	0.62473	0.61436	0.60643	0.60484	0.60286	0.60241	0.60180	0.60165	0.60143	0.60137
0.48	0.62735	0.61605	0.60741	0.60566	0.60347	0.60297	0.60228	0.60210	0.60185	0.60178
0.50	0.63021	0.61785	0.60843	0.60651	0.60409	0.60352	0.60274	0.60253	0.60224	0.60216
0.52	0.63331	0.61977	0.60947	0.60737	0.60468	0.60405	0.60316	0.60293	0.60259	0.60250
0.54	0.63665	0.62181	0.61054	0.60822	0.60525	0.60454	0.60354	0.60328	0.60289	0.60278
0.56	0.64024	0.62395	0.61161	0.60906	0.60577	0.60497	0.60384	0.60355	0.60310	0.60298
0.58	0.64408	0.62618	0.61265	0.60985	0.60621	0.60532	0.60405	0.60371	0.60321	0.60307
0.60	0.64817	0.62848	0.61365	0.61057	0.60654	0.60555	0.60412	0.60374	0.60317	0.60301
0.62	0.65250	0.63083	0.61457	0.61118	0.60672	0.60562	0.60402	0.60360	0.60295	0.60277
0.64	0.65706	0.63320	0.61536	0.61164	0.60672	0.60549	0.60371	0.60323	0.60250	0.60229
0.66	0.66182	0.63555	0.61599	0.61190	0.60647	0.60511	0.60312	0.60258	0.60176	0.60153
0.68	0.66675	0.63784	0.61639	0.51190	0.60592	0.60441	0.60219	0.60159	0.60067	0.60042
0.70	0.67181	0.64000	0.61650	0.61158	0.60499	0.60332	0.60086	0.60019	0.59916	0.59888
0.72	0.67696	0.64198	0.61624	0.61085	0.60361	0.60176	0.59903	0.59829	0.59715	0.59683
0.74	0.68212	0.64369	0.61553	0.60963	0.60167	0.59964	0.59663	0.59580	0.59453	0.59418
0.75	0.68468	0.64441	0.61497	0.60880	0.60047	0.59834	0.59517	0.59430	0.59297	0.59259

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Table 1-B-7—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 12-Inch (300-Millimeter) Meter [D = 11.374 Inches (288.90 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59767	0.59692	0.59636	0.59626	0.59615	0.59613	0.59610	0.59610	0.59609	0.59609
0.04	0.59867	0.59745	0.59654	0.59637	0.59619	0.59616	0.59612	0.59611	0.59611	0.59611
0.06	0.59954	0.59793	0.59672	0.59650	0.59625	0.59621	0.59616	0.59615	0.59614	0.59614
0.08	0.60037	0.59839	0.59691	0.59663	0.59634	0.59628	0.59622	0.59621	0.59620	0.59620
0.10	0.60116	0.59885	0.59711	0.59679	0.59644	0.59637	0.59630	0.59629	0.59628	0.59627
0.12	0.60194	0.59931	0.59733	0.59696	0.59656	0.59649	0.59641	0.59639	0.59638	0.59637
0.14	0.60273	0.59978	0.59757	0.59716	0.59671	0.59663	0.59654	0.59652	0.59650	0.59650
0.16	0.60353	0.60028	0.59783	0.59738	0.59688	0.59679	0.59669	0.59667	0.59665	0.59664
0.18	0.60435	0.60080	0.59812	0.59762	0.59708	0.59698	0.59686	0.59684	0.59681	0.59681
0.20	0.60521	0.60135	0.59844	0.59790	0.59730	0.59719	0.59706	0.59704	0.59701	0.59700
0.22	0.60611	0.60194	0.59879	0.59820	0.59755	0.59743	0.59728	0.59726	0.59722	0.59722
0.24	0.60707	0.60258	0.59918	0.59854	0.59783	0.59769	0.59753	0.59750	0.59746	0.59746
0.26	0.60809	0.60326	0.59960	0.59891	0.59814	0.59799	0.59781	0.59777	0.59773	0.59772
0.28	0.60919	0.60401	0.60007	0.59932	0.59848	0.59831	0.59811	0.59807	0.59802	0.59800
0.30	0.61038	0.60481	0.60058	0.59977	0.59885	0.59866	0.59844	0.59839	0.59833	0.59832
0.32	0.61167	0.60569	0.60113	0.60026	0.59925	0.59905	0.59880	0.59874	0.59867	0.59865
0.34	0.61308	0.60665	0.60174	0.60079	0.59969	0.59946	0.59918	0.59911	0.59902	0.59900
0.36	0.61462	0.60769	0.60240	0.60137	0.60016	0.59990	0.59958	0.59951	0.59940	0.59938
0.38	0.61630	0.60883	0.60311	0.60199	0.60066	0.60037	0.60001	0.59992	0.59980	0.59977
0.40	0.61815	0.61006	0.60388	0.60265	0.60119	0.60087	0.60045	0.60035	0.60021	0.60018
0.42	0.62017	0.61140	0.60470	0.60336	0.60175	0.60139	0.60092	0.60080	0.60064	0.60059
0.44	0.62237	0.61285	0.60557	0.60411	0.60233	0.60193	0.60139	0.60126	0.60107	0.60101
0.46	0.62479	0.61442	0.60649	0.60490	0.60292	0.60247	0.60186	0.60171	0.60149	0.60143
0.48	0.62741	0.61610	0.60747	0.60572	0.60353	0.60302	0.60233	0.60216	0.60190	0.60183
0.50	0.63027	0.61790	0.60847	0.60655	0.60413	0.60357	0.60278	0.60258	0.60229	0.60221
0.52	0.63336	0.61982	0.60951	0.60740	0.60472	0.60408	0.60320	0.60297	0.60263	0.60254
0.54	0.63670	0.62184	0.61056	0.60825	0.60527	0.60456	0.60356	0.60330	0.60291	0.60280
0.56	0.64028	0.62397	0.61162	0.60907	0.60577	0.60498	0.60385	0.60355	0.60311	0.60299
0.58	0.64412	0.62619	0.61264	0.60984	0.60619	0.60530	0.60403	0.60370	0.60319	0.60305
0.60	0.64821	0.62847	0.61362	0.61053	0.60650	0.60551	0.60408	0.60370	0.60313	0.60297
0.62	0.65253	0.63080	0.61451	0.61111	0.60665	0.60555	0.60395	0.60352	0.60288	0.60270
0.64	0.65708	0.63315	0.61527	0.61154	0.60661	0.60538	0.60360	0.60312	0.60239	0.60219
0.66	0.66182	0.63548	0.61586	0.61176	0.60632	0.60496	0.60296	0.60243	0.60161	0.60138
0.68	0.66674	0.63773	0.61621	0.61171	0.60572	0.60421	0.60199	0.60139	0.60047	0.60021
0.70	0.67179	0.63985	0.61627	0.61133	0.60473	0.60306	0.60059	0.59992	0.59890	0.59861
0.72	0.67692	0.64178	0.61594	0.61053	0.60327	0.60142	0.59869	0.59795	0.59680	0.59649
0.74	0.68206	0.64343	0.61514	0.60922	0.60124	0.59921	0.59619	0.59536	0.59410	0.59374
0.75	0.68461	0.64412	0.61453	0.60834	0.59999	0.59785	0.59468	0.59381	0.59247	0.59210

Table 1-B-8—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 16-Inch (400-Millimeter) Meter [D = 14.688 Inches (373.08 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59767	0.59693	0.59637	0.59626	0.59615	0.59613	0.59611	0.59610	0.59610	0.59610
0.04	0.59868	0.59746	0.59655	0.59638	0.59620	0.59617	0.59613	0.59612	0.59612	0.59611
0.06	0.59956	0.59794	0.59673	0.59651	0.59627	0.59622	0.59617	0.59617	0.59616	0.59615
0.08	0.60038	0.59841	0.59692	0.59665	0.59635	0.59630	0.59624	0.59623	0.59622	0.59621
0.10	0.60118	0.59887	0.59713	0.59631	0.59646	0.59640	0.59633	0.59631	0.59630	0.59630
0.12	0.60197	0.59934	0.59736	0.59699	0.59659	0.59652	0.59644	0.59642	0.59641	0.59640
0.14	0.60276	0.59982	0.59760	0.59719	0.59675	0.59666	0.59657	0.59655	0.59654	0.59653
0.16	0.60356	0.60032	0.59787	0.59742	0.59692	0.59683	0.59673	0.59671	0.59669	0.59668
0.18	0.60439	0.60084	0.59817	0.59767	0.59713	0.59702	0.59691	0.59689	0.59686	0.59686
0.20	0.60526	0.60140	0.59849	0.59795	0.59735	0.59724	0.59711	0.59709	0.59706	0.59705
0.22	0.60616	0.60200	0.59885	0.59826	0.59761	0.59749	0.59734	0.59732	0.59728	0.59728
0.24	0.60712	0.60264	0.59924	0.59860	0.59789	0.59776	0.59760	0.59757	0.59753	0.59752
0.26	0.60815	0.60333	0.59967	0.59898	0.59821	0.59806	0.59788	0.59784	0.59780	0.59779
0.28	0.60925	0.60408	0.60014	0.59940	0.59855	0.59839	0.59819	0.59815	0.59809	0.59808
0.30	0.61044	0.60489	0.60066	0.59985	0.59893	0.59874	0.59852	0.59847	0.59841	0.59840
0.32	0.61174	0.60577	0.60122	0.60034	0.59934	0.59913	0.59888	0.59882	0.59875	0.59873
0.34	0.61315	0.60673	0.60183	0.60088	0.59978	0.59955	0.59926	0.59920	0.59911	0.59909
0.36	0.61469	0.60777	0.60249	0.60146	0.60025	0.59999	0.59967	0.59960	0.59949	0.59947
0.38	0.61638	0.60891	0.60320	0.60208	0.60075	0.60047	0.60010	0.60001	0.59989	0.59986
0.40	0.61823	0.61015	0.60397	0.60275	0.60128	0.60096	0.60055	0.60045	0.60031	0.60027
0.42	0.62025	0.61149	0.60479	0.60345	0.60184	0.60148	0.60101	0.60089	0.60073	0.60069
0.44	0.62246	0.61294	0.60566	0.60420	0.60242	0.60201	0.60148	0.60134	0.60115	0.60110
0.46	0.62487	0.61450	0.60658	0.60498	0.60301	0.60256	0.60195	0.60179	0.60157	0.60151
0.48	0.62749	0.61618	0.60754	0.60579	0.60361	0.60310	0.60241	0.60223	0.60198	0.60191
0.50	0.63035	0.61798	0.60854	0.60662	0.60420	0.60363	0.60285	0.60265	0.60235	0.60227
0.52	0.63343	0.61988	0.60957	0.60746	0.60478	0.60414	0.60325	0.60302	0.60269	0.60259
0.54	0.63677	0.62190	0.61061	0.60829	0.60532	0.60461	0.60360	0.60334	0.60295	0.60285
0.56	0.64035	0.62402	0.61164	0.60909	0.60580	0.60500	0.60387	0.60358	0.60313	0.60301
0.58	0.64418	0.62622	0.61265	0.60984	0.60619	0.60530	0.60403	0.60370	0.60319	0.60305
0.60	0.64826	0.62848	0.61360	0.61051	0.60647	0.60548	0.60405	0.60367	0.60310	0.60294
0.62	0.65258	0.63079	0.61446	0.61106	0.60659	0.60549	0.60389	0.60346	0.60281	0.60264
0.64	0.65711	0.63312	0.61519	0.61145	0.60651	0.60528	0.60350	0.60302	0.60229	0.60208
0.66	0.66185	0.63541	0.61573	0.61162	0.60617	0.60481	0.60281	0.60228	0.60146	0.60123
0.68	0.66675	0.63763	0.61603	0.61152	0.60551	0.60400	0.60178	0.60118	0.60026	0.60000
0.70	0.67179	0.63971	0.61602	0.61107	0.60445	0.60278	0.60031	0.59964	0.59862	0.59833
0.72	0.67690	0.64158	0.61562	0.61019	0.60291	0.60106	0.59833	0.59758	0.59644	0.59612
0.74	0.68202	0.64316	0.61473	0.60878	0.60078	0.59874	0.59572	0.59489	0.59362	0.59327
0.75	0.68456	0.64382	0.61406	0.60784	0.59947	0.59733	0.59415	0.59328	0.59194	0.59157

Table 1-B-9—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 20-Inch (500-Millimeter) Meter [D = 19.000 Inches (482.60 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59768	0.59693	0.59637	0.59626	0.59615	0.59613	0.59611	0.59611	0.59610	0.59610
0.04	0.59868	0.59747	0.59656	0.59639	0.59621	0.59617	0.59614	0.59613	0.59612	0.59612
0.06	0.59957	0.59796	0.59674	0.59652	0.59628	0.59623	0.59619	0.59618	0.59617	0.59616
0.08	0.60040	0.59842	0.59694	0.59667	0.59637	0.59631	0.59626	0.59624	0.59623	0.59623
0.10	0.60120	0.59889	0.59715	0.59683	0.59648	0.59642	0.59635	0.59633	0.59632	0.59632
0.12	0.60199	0.59936	0.59738	0.59701	0.59662	0.59654	0.59646	0.59645	0.59643	0.59643
0.14	0.60279	0.59984	0.59763	0.59722	0.59677	0.59669	0.59660	0.59658	0.59656	0.59656
0.16	0.60360	0.60035	0.59790	0.59745	0.59696	0.59686	0.59676	0.59674	0.59672	0.59672
0.18	0.60443	0.60088	0.59821	0.59771	0.59716	0.59706	0.59695	0.59693	0.59690	0.59690
0.20	0.60529	0.60144	0.59854	0.59799	0.59740	0.59729	0.59716	0.59713	0.59710	0.59710
0.22	0.60620	0.60204	0.59890	0.59831	0.59766	0.59753	0.59739	0.59737	0.59733	0.59732
0.24	0.60717	0.60269	0.59930	0.59866	0.59795	0.59781	0.59765	0.59762	0.59758	0.59757
0.26	0.60820	0.60338	0.59973	0.59904	0.59827	0.59812	0.59794	0.59790	0.59786	0.59785
0.28	0.60930	0.60413	0.60020	0.59946	0.59862	0.59845	0.59825	0.59821	0.59816	0.59814
0.30	0.61050	0.60495	0.60072	0.59992	0.59900	0.59881	0.59859	0.59854	0.59848	0.59846
0.32	0.61180	0.60583	0.60129	0.60041	0.59941	0.59920	0.59895	0.59890	0.59882	0.59880
0.34	0.61321	0.60680	0.60190	0.60095	0.59985	0.59962	0.59934	0.59927	0.59919	0.59917
0.36	0.61476	0.60784	0.60256	0.60153	0.60033	0.60007	0.59975	0.59967	0.59957	0.59955
0.38	0.61645	0.60898	0.60328	0.60216	0.60083	0.60054	0.60018	0.60009	0.59997	0.59994
0.40	0.61830	0.61022	0.60404	0.60283	0.60136	0.60104	0.60063	0.60053	0.60039	0.60035
0.42	0.62032	0.61156	0.60486	0.60353	0.60192	0.60156	0.60109	0.60097	0.60081	0.60077
0.44	0.62253	0.61301	0.60574	0.60428	0.60249	0.60209	0.60156	0.60142	0.60123	0.60118
0.46	0.62494	0.61458	0.60665	0.60506	0.60308	0.60263	0.60202	0.60187	0.60165	0.60159
0.48	0.62756	0.61625	0.60762	0.60587	0.60368	0.60317	0.60248	0.60231	0.60205	0.60198
0.50	0.63042	0.61804	0.60861	0.60669	0.60427	0.60370	0.60292	0.60272	0.60242	0.60234
0.52	0.63350	0.61995	0.60963	0.60752	0.60484	0.60420	0.60331	0.60309	0.60275	0.60265
0.54	0.63684	0.62196	0.61066	0.60834	0.60537	0.60466	0.60365	0.60339	0.60300	0.60290
0.56	0.64042	0.62407	0.61169	0.60913	0.60584	0.60504	0.60391	0.60361	0.60317	0.60305
0.58	0.64424	0.62626	0.61268	0.60987	0.60622	0.60533	0.60406	0.60372	0.60321	0.60308
0.60	0.64832	0.62851	0.61361	0.61052	0.60648	0.60548	0.60406	0.60368	0.60310	0.60295
0.62	0.65263	0.63081	0.61445	0.61105	0.60657	0.60547	0.60387	0.60344	0.60279	0.60262
0.64	0.65716	0.63311	0.61515	0.61141	0.60647	0.60524	0.60345	0.60297	0.60224	0.60204
0.66	0.66189	0.63539	0.61567	0.61155	0.60609	0.60473	0.60273	0.60219	0.60137	0.60115
0.68	0.66679	0.63758	0.61593	0.61141	0.60539	0.60388	0.60166	0.60105	0.60014	0.59988
0.70	0.67181	0.63963	0.61588	0.61091	0.60428	0.60261	0.60014	0.59947	0.59844	0.59816
0.72	0.67691	0.64146	0.61542	0.60997	0.60268	0.60083	0.59809	0.59735	0.59620	0.59589
0.74	0.68201	0.64300	0.61446	0.60850	0.60048	0.59844	0.59541	0.59459	0.59332	0.59296
0.75	0.68455	0.64363	0.61376	0.60752	0.59912	0.59698	0.59380	0.59293	0.59159	0.59122

Table 1-B-10—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 24-Inch (600-Millimeter) Meter [D = 23.000 Inches (584.20 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59768	0.59693	0.59637	0.59627	0.59615	0.59613	0.59611	0.59611	0.59610	0.59610
0.04	0.59869	0.59747	0.59656	0.59639	0.59621	0.59618	0.59614	0.59613	0.59613	0.59613
0.06	0.59957	0.59796	0.59675	0.59653	0.59628	0.59624	0.59619	0.59618	0.59617	0.59617
0.08	0.60041	0.59843	0.59695	0.59668	0.59638	0.59632	0.59626	0.59625	0.59624	0.59624
0.10	0.60121	0.59890	0.59716	0.59684	0.59649	0.59643	0.59636	0.59635	0.59633	0.59633
0.12	0.60201	0.59937	0.59739	0.59703	0.59663	0.59656	0.59648	0.59646	0.59645	0.59644
0.14	0.60280	0.59986	0.59765	0.59724	0.59679	0.59671	0.59662	0.59660	0.59658	0.59658
0.16	0.60361	0.60037	0.59793	0.59747	0.59698	0.59689	0.59678	0.59676	0.59674	0.59674
0.18	0.60445	0.60090	0.59823	0.59773	0.59719	0.59709	0.59697	0.59695	0.59693	0.59692
0.20	0.60532	0.60147	0.59856	0.59802	0.59743	0.59731	0.59719	0.59716	0.59713	0.59713
0.22	0.60623	0.60207	0.59893	0.59834	0.59769	0.59757	0.59742	0.59740	0.59736	0.59736
0.24	0.60720	0.60272	0.59933	0.59869	0.59798	0.59785	0.59769	0.59766	0.59762	0.59761
0.26	0.60823	0.60342	0.59977	0.59908	0.59830	0.59815	0.59798	0.59794	0.59789	0.59788
0.28	0.60934	0.60417	0.60024	0.59950	0.59866	0.59849	0.59829	0.59825	0.59820	0.59818
0.30	0.61054	0.60499	0.60076	0.59996	0.59904	0.59885	0.59863	0.59858	0.59852	0.59851
0.32	0.61184	0.60587	0.60133	0.60046	0.59945	0.59925	0.59900	0.59894	0.59887	0.59885
0.34	0.61325	0.60684	0.60195	0.60100	0.59990	0.59967	0.59938	0.59932	0.59923	0.59921
0.36	0.61480	0.60789	0.60261	0.60158	0.60037	0.60012	0.59980	0.59972	0.59962	0.59959
0.38	0.61649	0.60903	0.60333	0.60221	0.60088	0.60059	0.60023	0.60014	0.60002	0.59999
0.40	0.61834	0.61027	0.60410	0.60288	0.60141	0.60109	0.60068	0.60058	0.60044	0.60040
0.42	0.62036	0.61161	0.60492	0.60358	0.60197	0.60161	0.60114	0.60102	0.60086	0.60082
0.44	0.62257	0.61306	0.60579	0.60433	0.60255	0.60215	0.60161	0.60148	0.60129	0.60123
0.46	0.62498	0.61463	0.60671	0.60511	0.60314	0.60269	0.60208	0.60192	0.60170	0.60164
0.48	0.62761	0.61630	0.60767	0.60592	0.60373	0.60323	0.60253	0.60236	0.60210	0.60203
0.50	0.63046	0.61809	0.60866	0.60674	0.60432	0.60375	0.60297	0.60276	0.60247	0.60239
0.52	0.63355	0.61999	0.60968	0.60757	0.60488	0.60425	0.60336	0.60313	0.60279	0.60270
0.54	0.63688	0.62200	0.61070	0.60838	0.60541	0.60470	0.60369	0.60343	0.60304	0.60294
0.56	0.64046	0.62411	0.61172	0.60917	0.60587	0.60507	0.60394	0.60365	0.60320	0.60308
0.58	0.64429	0.62629	0.61271	0.60989	0.60624	0.60535	0.60408	0.60375	0.60324	0.60310
0.60	0.64836	0.62854	0.61363	0.61054	0.60649	0.60550	0.60407	0.60369	0.60312	0.60296
0.62	0.65267	0.63083	0.61446	0.61105	0.60658	0.60547	0.60387	0.60345	0.60280	0.60262
0.64	0.65720	0.63313	0.61515	0.61140	0.60646	0.60523	0.60344	0.60296	0.60223	0.60202
0.66	0.66192	0.63539	0.61565	0.61153	0.60607	0.60470	0.60270	0.60216	0.60135	0.60112
0.68	0.66682	0.63757	0.61589	0.61137	0.60534	0.60383	0.60160	0.60100	0.60008	0.59983
0.70	0.67184	0.63960	0.61581	0.61084	0.60421	0.60253	0.60006	0.59939	0.59837	0.59808
0.72	0.67693	0.64142	0.61533	0.60987	0.60257	0.60072	0.59798	0.59724	0.59610	0.59578
0.74	0.68203	0.64293	0.61433	0.60836	0.60034	0.59829	0.59526	0.59444	0.59317	0.59281
0.75	0.68456	0.64355	0.61361	0.60736	0.59895	0.59681	0.59363	0.59276	0.59142	0.59105

Table 1-B-11—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 30-Inch (750-Millimeter) Meter [D = 29.000 Inches (736.60 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^4	50×10^6	100×10^6
0.02	0.59768	0.59693	0.59637	0.59627	0.59616	0.59614	0.59611	0.59611	0.59611	0.59610
0.04	0.59869	0.59748	0.59657	0.59640	0.59622	0.59618	0.59615	0.59614	0.59613	0.59613
0.06	0.59958	0.59797	0.59676	0.59653	0.59629	0.59625	0.59620	0.59619	0.59618	0.59618
0.08	0.60041	0.59844	0.59696	0.59668	0.59639	0.59633	0.59627	0.59626	0.59625	0.59625
0.10	0.60122	0.59891	0.59717	0.59685	0.59651	0.59644	0.59637	0.59636	0.59634	0.59634
0.12	0.60202	0.59939	0.59741	0.59704	0.59665	0.59657	0.59649	0.59648	0.59646	0.59646
0.14	0.60282	0.59988	0.59767	0.59726	0.59681	0.59673	0.59664	0.59662	0.59660	0.59660
0.16	0.60363	0.60039	0.59795	0.59749	0.59700	0.59691	0.59681	0.59679	0.59676	0.59676
0.18	0.60447	0.60093	0.59825	0.59776	0.59721	0.59711	0.59700	0.59698	0.59695	0.59695
0.20	0.60534	0.60150	0.59859	0.59805	0.59745	0.59734	0.59721	0.59719	0.59716	0.59715
0.22	0.60626	0.60210	0.59896	0.59837	0.59772	0.59760	0.59746	0.59743	0.59739	0.59739
0.24	0.60723	0.60275	0.59936	0.59872	0.59802	0.59788	0.59772	0.59769	0.59765	0.59764
0.26	0.60826	0.60345	0.59980	0.59911	0.59834	0.59819	0.59801	0.59798	0.59793	0.59792
0.28	0.60937	0.60421	0.60028	0.59954	0.59870	0.59853	0.59833	0.59829	0.59824	0.59822
0.30	0.61057	0.60503	0.60081	0.60000	0.59908	0.59890	0.59867	0.59863	0.59856	0.59855
0.32	0.61188	0.60592	0.60138	0.60050	0.59950	0.59929	0.59904	0.59899	0.59891	0.59889
0.34	0.61329	0.60689	0.60199	0.60105	0.59995	0.59972	0.59943	0.59937	0.59928	0.59926
0.36	0.61484	0.60794	0.60266	0.60163	0.60043	0.60017	0.59985	0.59977	0.59967	0.59965
0.38	0.61653	0.60908	0.60338	0.60226	0.60093	0.60065	0.60028	0.60020	0.60008	0.60005
0.40	0.61838	0.61032	0.60415	0.60293	0.60147	0.60115	0.60073	0.60063	0.60049	0.60046
0.42	0.62041	0.61166	0.60497	0.60364	0.60203	0.60167	0.60120	0.60108	0.60092	0.60087
0.44	0.62262	0.61312	0.60584	0.60439	0.60260	0.60220	0.60166	0.60153	0.60134	0.60129
0.46	0.62503	0.61468	0.60676	0.60517	0.60319	0.60274	0.60213	0.60198	0.60176	0.60170
0.48	0.62766	0.61635	0.60772	0.60597	0.60379	0.60328	0.60259	0.60241	0.60216	0.60209
0.50	0.63051	0.61814	0.60871	0.60679	0.60437	0.60380	0.60302	0.60282	0.60252	0.60244
0.52	0.63360	0.62005	0.60973	0.60762	0.60493	0.60430	0.60341	0.60318	0.60284	0.60275
0.54	0.63693	0.62205	0.61075	0.60843	0.60545	0.60474	0.60374	0.60348	0.60309	0.60298
0.56	0.64051	0.62415	0.61177	0.60921	0.60591	0.60512	0.60399	0.60369	0.60325	0.60312
0.58	0.64434	0.62634	0.61275	0.60993	0.60628	0.60539	0.60412	0.60378	0.60328	0.60314
0.60	0.64841	0.62858	0.61366	0.61057	0.60652	0.60553	0.60410	0.60372	0.60315	0.60299
0.62	0.65272	0.63086	0.61448	0.61107	0.60660	0.60549	0.60389	0.60346	0.60282	0.60264
0.64	0.65724	0.63315	0.61516	0.61141	0.60646	0.60523	0.60344	0.60296	0.60223	0.60203
0.66	0.66197	0.63540	0.61564	0.61152	0.60606	0.60469	0.60269	0.60215	0.60133	0.60111
0.68	0.66686	0.63757	0.61587	0.61134	0.60531	0.60380	0.60158	0.60097	0.60006	0.59980
0.70	0.67188	0.63959	0.61577	0.61080	0.60416	0.60248	0.60001	0.59934	0.59831	0.59803
0.72	0.67697	0.64139	0.61526	0.60980	0.60249	0.60064	0.59790	0.59716	0.59601	0.59570
0.74	0.68206	0.64289	0.61424	0.60825	0.60022	0.59818	0.59515	0.59432	0.59305	0.59270
0.75	0.68459	0.64349	0.61350	0.60724	0.59882	0.59668	0.59349	0.59262	0.59128	0.59091

APPENDIX 1-C—ADJUSTMENTS FOR INSTRUMENT CALIBRATION AND USE

Note: This appendix is not a part of this standard but is included for informational purposes only.

This appendix discusses the need to consider the determination of flow rate from a holistic viewpoint. To build, operate, and maintain the facility properly, the user must have defined the desired uncertainty for the designer.

The accuracy of the metered quantities depends on a combination of the following:

a. The design, installation, and operation of the orifice metering facility.
b. The choice of measurement equipment (charts, transmitters, smart transmitters, analog/digital converters, data loggers, and so forth).
c. The means of data transmission (analog, pneumatic, digital, manual).
d. The calculation procedure and means of computation (chart integration, flow computer, mainframe, minicomputer, personal computer, and so forth).
e. The effects on the operating/calibration equipment of ambient temperature, fluid temperature and pressure, response time, local gravitational forces, atmospheric pressure, and the like.
f. The traceability chain associated with the portable field standards.

The uncertainty depends not just on the hardware but also on the hardware's performance, the software's performance, the method of calibration, the calibration equipment, the calibration procedures, and the human factor.

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Manual of Petroleum Measurement Standards Chapter 14—Natural Gas Fluids Measurement

Section 3—Concentric, Square-Edged Orifice Meters

Part 2—Specification and Installation Requirements

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Chapter 14—Natural Gas Fluids Measurement

Section 3—Concentric, Square-Edged Orifice Meters

PART 2—SPECIFICATION AND INSTALLATION REQUIREMENTS

2.1 Construction and Installation Requirements

This document outlines the various design parameters that must be considered when designing metering facilities using orifice meters. The mechanical tolerances found in this document encompass a wide range of orifice diameter ratios for which experimental results are available. In several sections of this document, tolerances for the mechanical specifications have been changed relative to previous editions. In particular, this revision includes a change to the installation requirements (meter tube lengths). This change reduces the uncertainty attributable to installation effects to a magnitude smaller than the uncertainty of the database supporting the Reader-Harris/Gallagher (RG) equation and, therefore, should not affect the uncertainty previously defined for that equation.

This document does not require upgrading existing installations. If the meter installations are not upgraded to meet this current standard, however, measurement bias errors may exist due to inadequate flow conditioning and upstream straight pipe lengths. The decision to upgrade an existing installation shall be at the discretion of the parties involved.

Use of the calculation procedures and techniques shown in the *Manual of Petroleum Measurement Standards*, Chapter 14, Section 3, Parts 1 and 3, with existing equipment is recommended, since these represent significant improvements over the previous methods. However, the uncertainty levels for flow measurement using existing equipment may be different from those quoted in Part 1.

Use of orifice meters at the extremes of their diameter ratio (β_r) ranges should be avoided whenever possible. Good metering design and practice tend to be somewhat conservative. This means that the use of the tightest tolerances in the mid-diameter ratio (β_r) ranges would have the highest probability of producing the best measurement. An indication of this is found in the section on uncertainty in Part 1.

This standard is based on β_r between 0.10 and 0.75. Minimum uncertainty of the orifice plate coefficient of discharge (C_d) is achieved with β_r between 0.2 and 0.6 and orifice bore diameters greater than or equal to 0.45 inch. Diameter ratios and orifice bore diameters outside of this range may be used; however, the user should consult the uncertainty section in Part 1 for limitations.

Achieving the best level of measurement uncertainty begins with, but is not limited to, proper design. Two other aspects of the measurement process must accompany the design effort; otherwise it is of little value. These aspects are the application of the metering system and the maintenance of the meters, neither of which is considered directly in this standard. These aspects cannot be governed by a single standard as they cover metering applications that can differ widely in flow rate, fluid type, and operational requirements. Therefore, the user must therefore determine the best meter selection for the application and the level of maintenance for the measurement system under consideration.

2.2 Symbols/Nomenclature

This standard reflects orifice meter application to fluid flow measurement with symbols in general technical use.

Symbol	Represented Quantity
a	Speed of sound
C_d	Orifice plate coefficient of discharge
$C_d(FT)$	Flange tap orifice plate coefficient of discharge
$\Delta C_d(FT)/C_d$	Percent difference between baseline C_d and installation effect C_d
d	Orifice plate bore diameter calculated at flowing temperature, T_f
d_m	Orifice plate bore diameter measured at temperature, T_m
d_r	Orifice plate bore diameter calculated at reference temperature, T_r
D	Meter tube internal diameter calculated at flowing temperature, T_f
D_i	Published meter tube internal pipe diameter
DL	Meter tube length downstream of orifice plate in multiples of published internal pipe diameters (see Figure 2-6)
D_m	Meter tube internal diameter measured at T_m
D_n	Nominal pipe diameter

D_r	Meter tube internal diameter calculated at reference temperature, T_r
e	Orifice plate bore thickness
E	Orifice plate thickness
f	Frequency
°F	Temperature, in degrees Fahrenheit
l	Recommended lengths of gauge line
NPS	Nominal Pipe Size
ΔP	Orifice plate differential pressure
ΔP_{avg}	Average orifice plate differential pressure
ΔP_{rms}	Root mean square of the fluctuating differential pressure
ΔP_t	Instantaneous orifice plate differential pressure
P_f	Static pressure of the fluid at the pressure tap
°R	Temperature, in degrees Rankine
R_a	Absolute roughness average
Re	Reynolds number
T_f	Temperature of fluid at flowing conditions
T_m	Temperature of the orifice plate and/or meter tube at time of diameter measurements
T_r	Reference temperature (68°F) of orifice plate bore diameter and/or meter tube internal diameter
UL	Meter tube length upstream of orifice plate in multiples of published internal pipe diameters (Figure 2-6)
UL1	UL – UL2
UL2	Meter tube length from flow conditioner exit to orifice plate in multiples of published internal pipe diameters
α	Linear coefficient of thermal expansion
α_1	Linear coefficient of thermal expansion of the orifice plate material
α_2	Linear coefficient of thermal expansion of the meter tube material
β	Ratio of orifice plate bore diameter to meter tube internal diameter (d/D) calculated at flowing temperature, T_f
β_m	Ratio of orifice plate bore diameter to meter tube internal diameter (d_m/D_m) calculated at temperature, T_m
β_r	Ratio of orifice plate bore diameter to meter tube internal diameter (d_r/D_r) calculated at reference temperature, T_r
ε	Orifice plate bore eccentricity
θ	Orifice plate bevel angle

2.3 Definitions

The definitions are given to emphasize the particular meaning of the terms as used in this standard.

2.3.1 PRIMARY ELEMENT

The primary element is defined as the orifice plate, the orifice plate holder with its associated differential pressure sensing taps, the meter tube, and flow conditioner, if used.

2.3.1.1 Orifice Plate

The orifice plate is defined as a thin square-edged plate with a machined circular bore, concentric with the meter tube ID, when installed.

2.3.1.2 Orifice Plate Bore Diameter (d, d_m, d_r)

The calculated orifice plate bore diameter (d) is the internal diameter of the orifice plate measuring aperture (bore) computed at flowing temperature (T_f), as specified in 1.6.2 in Part 1. The calculated orifice plate bore diameter (d) is used in the flow equation for the determination of flow rate.

The measured orifice plate bore diameter (d_m) is the measured internal diameter of the orifice plate measuring aperture at the temperature of the orifice plate (T_m) at the time of bore diameter measurements, determined as specified in 2.4.3.

The reference orifice plate bore diameter (d_r) is the internal diameter of the orifice plate measuring aperture at reference temperature (T_r), calculated as specified in 2.4.3. The reference orifice plate bore diameter is the certified or stamped orifice plate bore diameter.

2.3.1.3 Orifice Plate Holder

The orifice plate holder is defined as a pressure containing piping element, such as a set of orifice flanges or an orifice fitting, used to contain and position the orifice plate in the piping system.

2.3.1.4 Meter Tube

The meter tube is defined as the straight sections of pipe, including all segments that are integral to the orifice plate holder, upstream and downstream of the orifice plate, as specified in 2.5.1.

2.3.1.5 Meter Tube Internal Diameter (D, D_i, D_m, D_r)

The calculated meter tube internal diameter (D) is the inside diameter of the upstream section of the meter tube computed at flowing temperature (T_f), as specified in 1.6.3 of Part 1. The calculated meter tube internal diameter (D) is used in the diameter ratio and Reynolds number equations.

The published meter tube internal diameter (D_i) is the inside diameter as published in standard handbooks for engineers. This internal diameter is used for determining the required meter run length in Tables 2-7 and 2-8.

The measured meter tube internal diameter (D_m) is the average inside diameter of the upstream section of the meter tube measured 1 inch upstream of the adjacent face of the orifice plate and at the temperature of the meter tube (T_m) at the time of internal diameter measurements, as specified in 2.5.1.2.

The reference meter tube internal diameter (D_r) is the inside diameter of the upstream section of the meter tube calculated at the reference temperature (T_r), as specified in 2.5.1.2. The reference meter tube internal diameter is the certified meter tube internal diameter.

2.3.1.6 Diameter Ratio (β, β_m, β_r)

The diameter ratio (β) is defined as the calculated orifice plate bore diameter (d) divided by the calculated meter tube internal diameter (D).

The diameter ratio (β_m) is defined as the measured orifice plate bore diameter (d_m) divided by the measured meter tube internal diameter (D_m).

The diameter ratio (β_r) is defined as the reference orifice plate bore diameter (d_r) divided by the reference meter tube internal diameter (D_r).

2.3.1.7 Flow Conditioners

Flow conditioners can be classified into two categories: straighteners or isolating flow conditioners.

Flow straighteners are devices that effectively remove or reduce the swirl component of a flowing stream, but may have limited ability to produce the flow conditions necessary to accurately replicate the orifice plate coefficient of discharge database values.

Isolating flow conditioners are devices that effectively remove the swirl component from the flowing stream while redistributing the stream to produce the flow conditions that accurately replicate the orifice plate coefficient of discharge database values.

2.3.2 PRESSURE MEASUREMENT

2.3.2.1 Tap Hole

A tap hole is a hole drilled radially in the wall of the meter tube or through the orifice fitting and perpendicular to the centerline of the meter tube or orifice plate holder, the inside edge of which is flush and without any burrs.

2.3.2.2 Flange Taps

Flange taps are a pair of tap holes positioned as follows:

a. the upstream tap center is located 1 inch upstream of the nearest plate face,
b. the downstream tap center is located 1 inch downstream of the nearest plate face,
c. the upstream and downstream taps must be in the same radial position.

2.3.2.3 Differential Pressure (ΔP, ΔP_{avg}, ΔP_{rms}, ΔP_t)

The differential pressure (ΔP) is the static pressure difference measured between the upstream and the downstream flange taps.

The average differential pressure (ΔP_{avg}) is a time mean of the static pressure difference measured between the upstream and downstream flange taps.

The instantaneous differential pressure (ΔP_t) is a single measurement of ΔP at any instance in time.

The root mean square differential pressure (ΔP_{rms})is the square root of the sum of squares of the difference between the instantaneous differential pressure (ΔP_t)and time mean differential (ΔP_{avg}).

2.3.3 TEMPERATURE MEASUREMENT (T_f, T_m, T_r)

The temperature (T_f) is the flowing fluid temperature measured at the designated location, as specified in 2.6.5.

In flow measurement, the temperature sensing device is inserted in the flowing stream to obtain the flowing temperature. However, if the fluid velocity is higher than 25% of the fluid sound speed at the point of measurement, corrections for the increase in temperature due to dynamic effects will have to be applied. Care should be taken to ensure that the temperature sensing elements are coupled to the flowing stream and not to the steel in the meter tube. This practice is recommended for all orifice meter installations. The sensed temperature is assumed to be the static temperature of the flowing fluid.

The temperature (T_m) is the measured temperature of the orifice plate and/or the meter tube at the time of the diameter measurements, as specified in 2.4.3 and 2.5.1.2.

The temperature (T_r) is the reference temperature used to determine the reference orifice plate bore diameter (d_r) and/or the reference internal meter tube diameter (D_r), as specified in 2.4.3 and 2.5.1.2.

2.3.4 ROUGHNESS AVERAGE (R_a)

The roughness average (R_a) used in this standard is that given in ANSI B46.1, and is "the arithmetic average of the absolute values of the measured profile height deviation taken within the sampling length and measured from the graphical centerline" of the surface profile.

2.4 Orifice Plate Specifications

The symbols for the orifice plate dimensions are shown in Figure 2-1.

2.4.1 ORIFICE PLATE FACES

The upstream and downstream faces of the orifice plate shall be flat. Deviations from flatness on the orifice plate of less than or equal to 1% of dam height (that is, 0.010 inch per inch of dam height) under nonflowing conditions are allowed. The dam height can be calculated from the formula $(D_m - d_m)/2$. This criterion for flatness applies to any two points on the orifice plate within the dimensions of the inside diameter of the pipe. The departure from flatness is illustrated in Figures 2-2a, 2-2b and 2-2c.

The surface roughness of the upstream and downstream faces of the orifice plate shall have no abrasions or scratches visible to the naked eye that exceed 50 microinches R_a.

The orifice plate surface roughness may be verified by using an electronic-averaging-type surface roughness instrument with a cutoff value of not less than 0.03 inch. Other surface roughness devices (for example, a visual comparator) are acceptable for determining orifice plate surface roughness if the same repeatability and reproducibility as those of the electronic-averaging-type surface roughness instrument can be demonstrated.

Due care shall be exercised to keep the plate clean and free from accumulation of dirt, ice, grit, grease, oil, free liquid and other extraneous materials, to the extent feasible, by instituting a regular inspection schedule (daily, weekly, monthly, quarterly, etc., depending on the service conditions). Damage and/or accumulation of extraneous materials on the orifice plate may result in a greater uncertainty for the orifice plate coefficient of discharge [$C_d\,(FT)$]. After any inspection of the plate, it shall be thoroughly cleaned (free from accumulations as stated above) prior to being placed back in service.

2.4.2 ORIFICE PLATE BORE EDGE

The upstream edge of the orifice plate bore shall be square and sharp. The orifice plate bore edge is considered too dull for accurate flow measurement if the upstream edge reflects a beam of light when viewed without magnification or if the upstream edge shows a beam of light when checked with an orifice edge gauge.

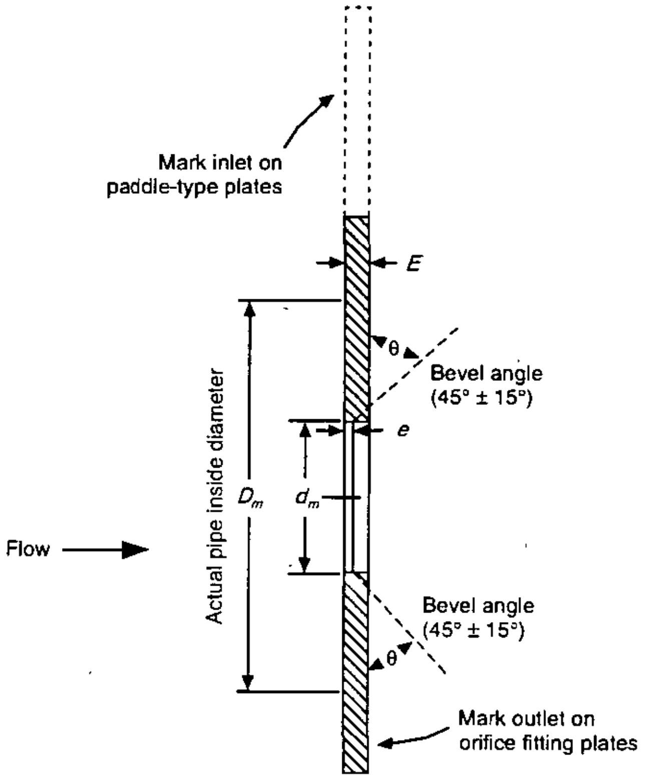
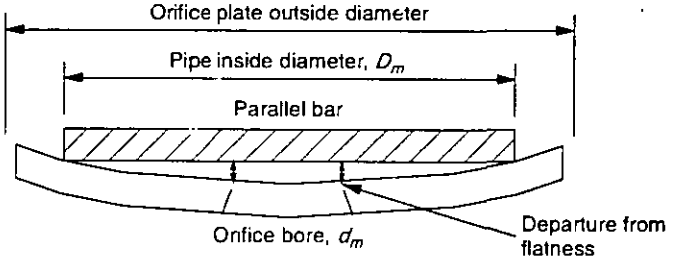


Figure 2-1—Symbols for Orifice Plate Dimensions



Maximum allowable departure from flatness = 0.005 $(D_m - d_m)$

Figure 2-2a—Orifice Plate Departure from Flatness
(Measured at Edge of Orifice Bore and Within Inside Pipe Diameter)

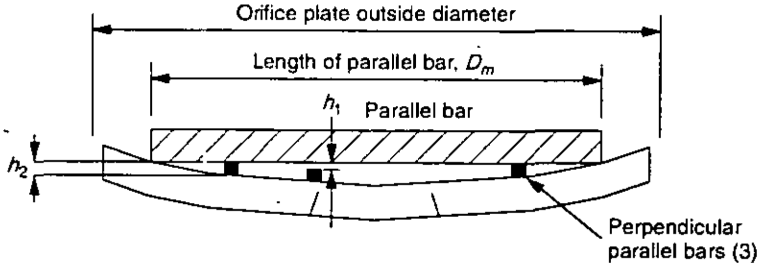
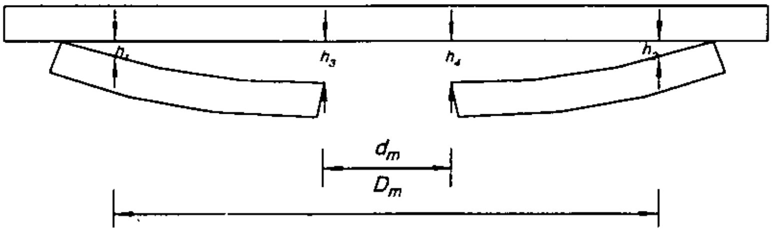


Figure 2-2b—Alternative Method for Determination of Orifice Plate Departure from Flatness
(Departure from Flatness = $h_2 - h_1$)



Maximum departure from flatness $= \dfrac{[h_3 + h_4] - [h_1 + h_2]}{2}$

Figure 2-2c—Maximum Orifice Plate Departure from Flatness

An estimation of suitable sharpness can be made by comparing the orifice plate bore edge with the bore edge of a properly sharp reference orifice plate of the same nominal diameter. The orifice plate bore edge being evaluated should feel and look the same as the edge of the reference orifice plate.

The upstream and downstream edges of the orifice plate bore shall be free from defects visible to the naked eye, such as flat spots, feathered texture, roughness, burrs, bumps, nicks, and notches.

If there is any doubt about whether the edge has sufficient quality for accurate metering, the orifice plate should be replaced.

2.4.3 ORIFICE PLATE BORE DIAMETER (d_m, d_r) and ROUNDNESS

The measured orifice bore diameter (d_m) is defined as the mean (arithmetic average) of four or more evenly spaced diameter measurements at the inlet edge. None of the four or more diameter measurements may vary from the mean value by more than the tolerances given in Table 2-1. The orifice plate temperature shall be recorded at the time the bore diameter measurements are made. These measurements shall be made under thermally stable conditions; i.e., during the measurement, the temperature should be constant within ± 1°F (± 0.5°C).

The orifice plate bore diameter (d_r) is defined as the calculated reference diameter at reference temperature (T_r) and can be determined using the following equation:

$$d_r = d_m[1 + \alpha_1(T_r - T_m)] \tag{2.1}$$

where

α_1 = linear coefficient of thermal expansion for the orifice plate material (see Table 2-2),

d_r = orifice plate bore diameter calculated at reference temperature (T_r),

d_m = orifice plate bore diameter measured at T_m,

T_m = temperature of the orifice plate at time of diameter measurements,

T_r = reference temperature of the orifice plate bore diameter.

Note: α_1, T_m, and T_r must be in consistent units. For the purpose of this standard, T_r is assumed to be 68°F.

The orifice plate bore diameter (d_r) calculated at T_r is the reference diameter used to calculate the bore diameter (d) at flowing conditions, as specified in Part 1.

2.4.4 ORIFICE PLATE BORE THICKNESS (e)

The inside surface of the orifice plate bore shall be in the form of a constant-diameter cylinder having no defects, such as grooves, ridges, pits, or lumps, visible to the naked eye. The length of the cylinder is the orifice plate bore thickness (e).

The minimum allowable orifice plate bore thickness (e) is defined by $e \geq 0.01d_r$ or $e > 0.005$ inch, whichever is larger.

The maximum allowable value for the orifice plate bore thickness (e) is defined by $e \leq 0.02D_r$ or $e \leq 0.125d_r$, whichever is smaller, but e shall not be greater than the maximum allowable orifice plate thickness (E).

Table 2-1—Roundness Tolerance for Orifice Plate Bore Diameter, d_m

Office Bore Diameter, d_m (inches)	Tolerance (± inches)
≤0.250[a]	0.0003
0.251 – 0.375[a]	0.0004
0.376 – 0.500[a]	0.0005
0.501 – 0.625	0.0005
0.626 – 0.750	0.0005
0.751 – 0.875	0.0005
0.876 – 1.000	0.0005
>1.000	0.0005 inch per inch of diameter

Note: [a]Use of diameters below 0.45 inch is not prohibited, but may result in uncertainties greater than those specified in Chapter 14, Section 3, Part 1.

Table 2-2—Linear Coefficient of Thermal Expansion

Material	Linear Coefficient of Thermal Expansion, α [U.S. Units (in./in. °F)]
Type 304 and 316 stainless steel[a]	0.00000925
Monel[a]	0.00000795
Carbon Steel[b]	0.00000620

Note: For flowing temperature conditions other than those stated in footnotes a and b and for other materials, refer to the American Society for Metals. *Metals Handbook*.

[a]For flowing conditions between – 100°F and + 300°F, ref. ASME PTC 19.5.

[b]For flowing conditions between – 7°F and + 154°F, ref. *API MPMS* Chapter 12, Section 2.

When the orifice plate thickness (E) exceeds the orifice bore thickness (e), a bevel (see 2.4.6) is required on the downstream side of the orifice bore.

Note: Existing orifice plates, whose edge thickness meets the value defined by $e < 0.033D_m$, need not be rebeveled unless reconditioning is required for other reasons.

For ease in machining, the next smaller values of e, in multiples of 0.03125 (1⁄32 inch), may be used.

Orifice plate bores that demonstrate any convergence from inlet to outlet are unacceptable.

Bi-directional flow through an orifice meter tube requires a specially configured meter tube and the use of an unbeveled orifice plate. Use of an unbeveled orifice plate with bore thickness (e) that exceeds the limits specified in this table is outside of the scope of this standard.

2.4.5 ORIFICE PLATE THICKNESS (E)

The minimum, maximum, and recommended values of orifice plate thickness (E) for Types 304 and 316 stainless steel orifice plates are given in Table 2-3.

Maximum allowable differential pressures for the recommended orifice plate thicknesses in Table 2-3 are for operating temperatures not exceeding 150°F. For operating conditions, orifice diameter ratios, meter tube sizes, and orifice plate thicknesses not covered in Table 2-3, see the tables found in Appendix 2-E. If a specific application is not covered by Table 2-3 or Appendix 2-E, the orifice plate and/or holding device manufacturer should be contacted for specific information on deflection (see 2.4.1 and Appendix 2-F—AGA Engineering Technical Note—High Differential Pressure Across Orifice Fittings) for a given diameter ratio, temperature, orifice plate material, orifice plate holder, and differential pressure.

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The use of an orifice plate thickness other than the recommended thickness is acceptable in either new or existing orifice plate holding devices as long as the thickness is within the maximum and minimum range shown in Table 2-3; and the orifice plate eccentricity, bore thickness, differential pressure tap hole, and expansion-factor pressure-ratio tolerances and limits are satisfied.

For incompressible fluids, the maximum differential pressure across the plate is limited by the structural integrity of the fitting design. The maximum differential pressure should be limited to those shown in Table 2-3 and Appendix 2-E. If the maximum differential pressure is to exceed the limits specified, the manufacturer should be consulted for allowable maximum pressure for the fitting design. In addition, the flowing conditions downstream of the orifice plate must remain above the local vapor pressure of the flowing fluid.

Orifice fitting manufacturers should be consulted to determine the maximum allowable differential pressure during the changing of orifice plates under flowing conditions. The high forces associated with using high differential pressures may make it difficult to remove the plate, and may possibly result in damage to the orifice plate or fitting.

The use of high differential pressures ($\Delta P/P_f > 0.7$ inch of water/psia, where the ΔP is in inches of water at 68°F and P_f is in psia) will result in expansion factor uncertainties in excess of 0.1% (See 1.12.4.2 of Part 1).

Operators should be aware, for a given orifice plate size, that when there is a wide swing from high to low flows, significant measurement errors will occur during the low-flow period if the orifice plate remains unchanged. Generally, operation between 10% and 90% of the calibrated differential span is considered good practice. Rangeability can also be increased using today's digital (electronic) transmitters. The effects on the accuracy of transducers and/or transmitters used for wide range should be evaluated versus savings on installation cost.

For the full range of orifice plate thicknesses, the maximum allowable orifice plate differential pressure can be obtained from Appendix 2-E.

Higher differential pressures will result in higher meter-run gas velocities and higher permanent pressure losses. It is recommended that the gas velocities be evaluated on a individual installation basis for such things as noise, erosion, and thermowell vibration. The meter run velocity is dependent on several different factors, and each individual user will have different practices and limits on velocity. Therefore, the allowable maximum differential pressures, shown in Table 2-3, do not consider meter-run gas velocity.

2.4.5.1 Permanent Pressure Drop

The permanent pressure drop is significant because the energy has been lost to transport the fluid through the pipeline. Several technical books list the permanent pressure loss versus β ratio for the concentric, square-edged, flange-tapped orifice meter.

$$\text{The permanent pressure loss} \approx \Delta P(1 - \beta^2)$$

Below is a table of these approximate values:

β	Losses as a % of ΔP
0.20	95
0.30	90
0.40	85
0.50	75
0.60	65
0 70	50
0 75	45

Examples:

a. If the user chooses to use a β of 0.30 at a ΔP of 400 inches of H_2O, then the permanent pressure loss would be approximately 90% of 400 inches of H_2O, which is about 360 inches of H_2O (about 13 psi).

b. If the user chooses to use a β of 0.50 at a ΔP of 100 inches of H_2O, then the permanent pressure loss would be approximately 75% of 100 inches of H_2O, which is about 75 inches of H_2O (about 3 psi).

2.4.6 ORIFICE PLATE BEVEL (θ)

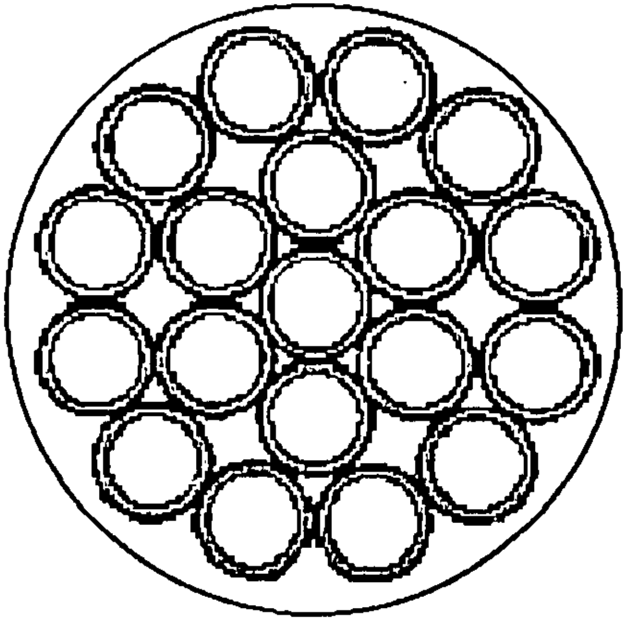
The plate bevel angle (θ) is defined as the angle between the bevel and the downstream face of the plate. The allowable value for the plate bevel angle (θ) is 45 degrees ± 15 degrees.

The surface of the plate bevel shall have no defects visible to the naked eye, such as grooves, ridges, pits, or lumps.

If a bevel is required, its minimum dimension, (E-e), measured along the axis of the bore shall not be less than 0.0625 (1⁄16) inch.

TUBE BUNDLE STRAIGHTENING VANES

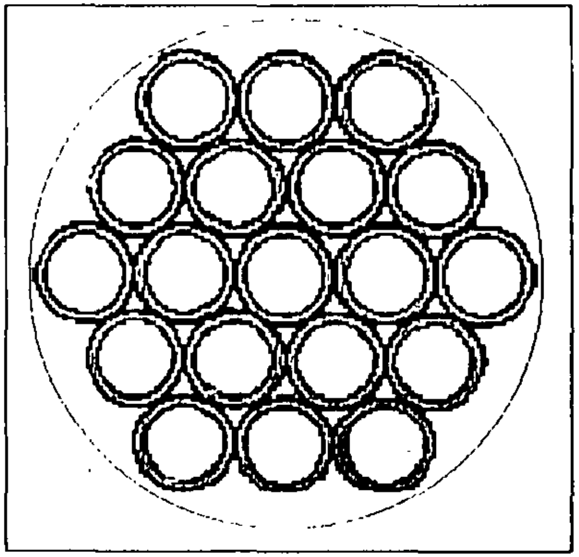
19 CONCENTRIC SAME SIZE TUBES



NEW, TIGHTER TOLERANCES

TUBE BUNDLE STRAIGHTENING VANES

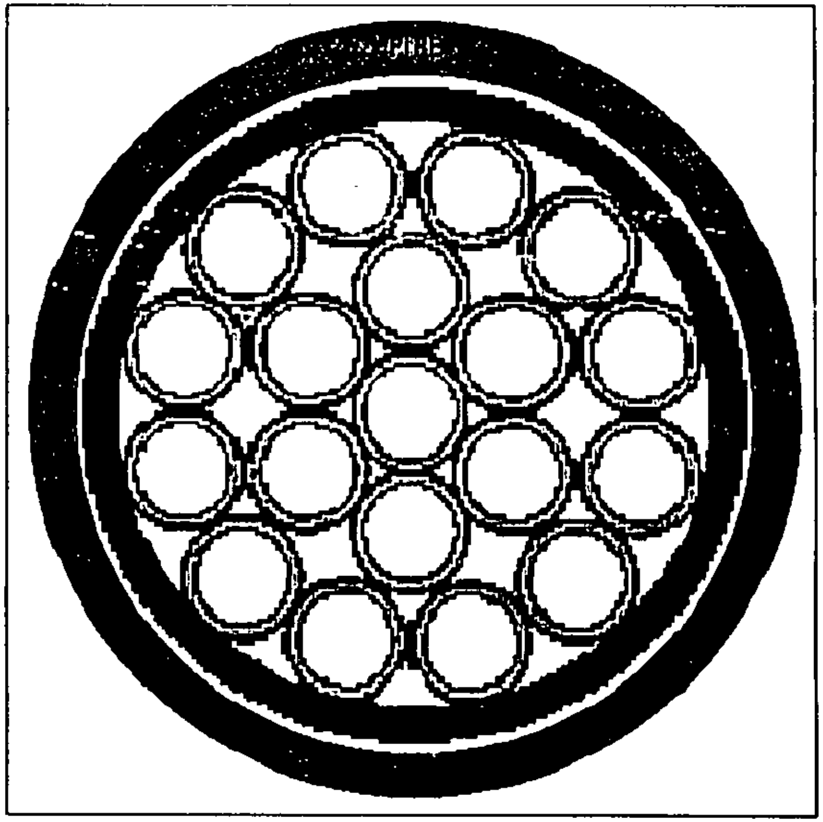
HEX PATTERN



NOT ALLOWED

TUBE BUNDLE STRAIGHTENING VANES

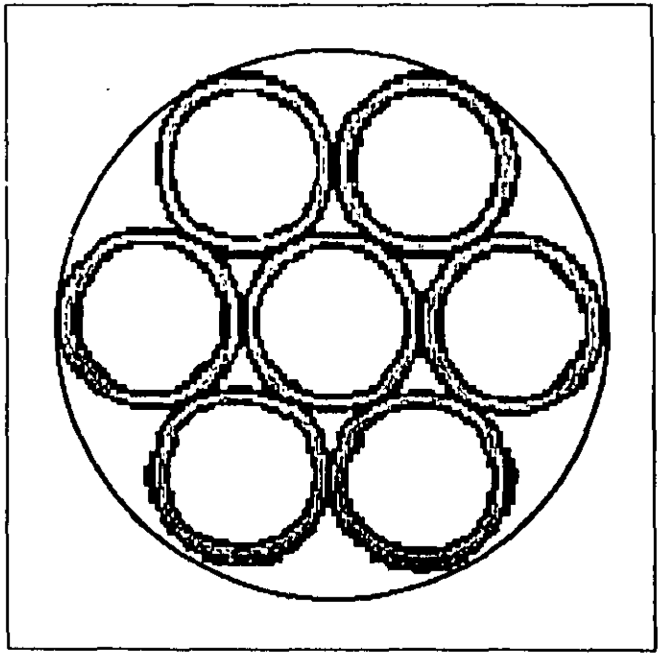
END BANDS



NOT ALLOWED

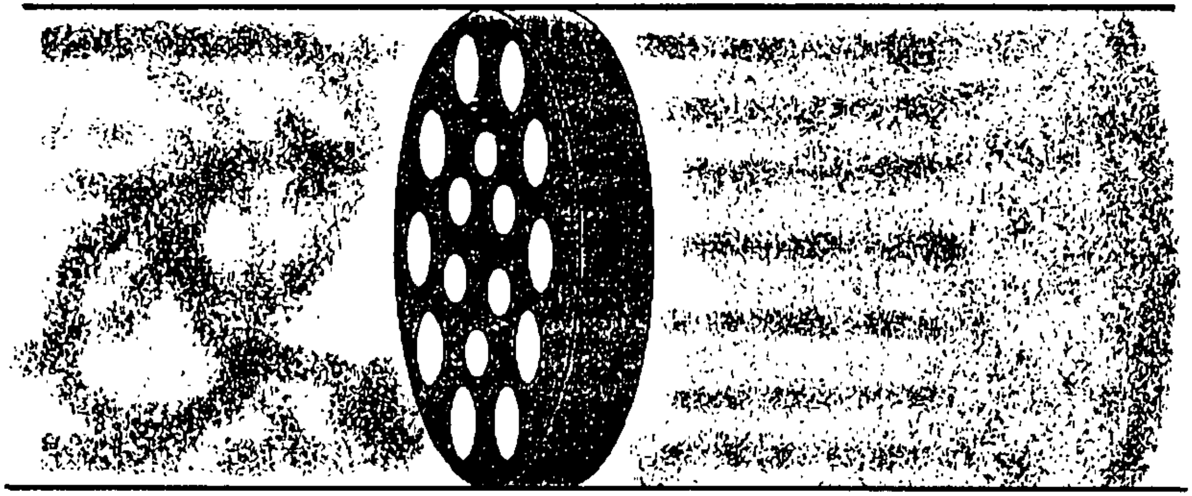
TUBE BUNDLE STRAIGHTENING VANES

7 TUBE BUNDLE



NOT ALLOWED

FLOW CONDITIONER



ELIMINATE SWIRL

GENERATE A NEAR FULLY
DEVELOPED FLOW PROFILE

Disturbance Tests

- **Good Flow Conditions** - test evaluating impact of flow conditioner on fully developed velocity profile.

- **Two 90^0 Elbows in Perpendicular Planes** - testing of flow conditioner performance in handling combination of a modest swirl and a non-symmetrical velocity profile.

- **Gate Valve 50% Closed** - test evaluating flow conditioner performance in strongly non-symmetrical velocity profile

- **High Swirl** - test assessing flow conditioner performance in flows with high swirl angle (over 25^0).

Additional Tests

- **Orifice β ratio**: Check swirl test at $\beta=0.40$ and $\beta=0.67$
- **Reynolds Number Sensitivity:** Test at two ranges $10^4 < Re < 5 \times 10^5$ and $Re > 10^6$ with approximately a 7:1 ratio.
- **Scaling:** Test at two sizes selected from $D \leq 4''$ and $D \geq 8''$

THE USE OF FLOW CONDITIONERS MAY RESULT IN SHORTER UPSTREAMS

BUT

A SERIES OF TESTS MUST BE RUN TO PROVE THE DEVICE MEETS REQUIREMENTS

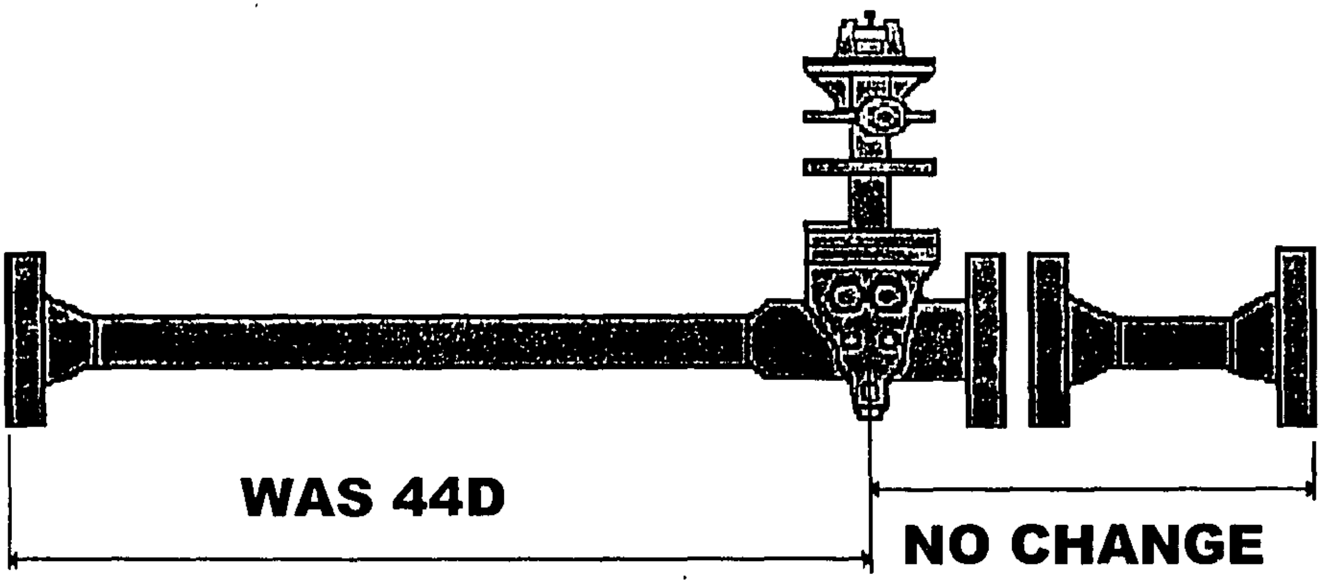
UPSTREAM LENGTH SELECTION

4 CATEGORIES

- **BARE TUBE (no vane or conditioner)**
- **SHORT TUBE WITH VANE**
- **LONG TUBE WITH VANE**
- **TUBE WITH CONDITIONER**

UNIVERSAL "CATCH ALL" METER TUBE

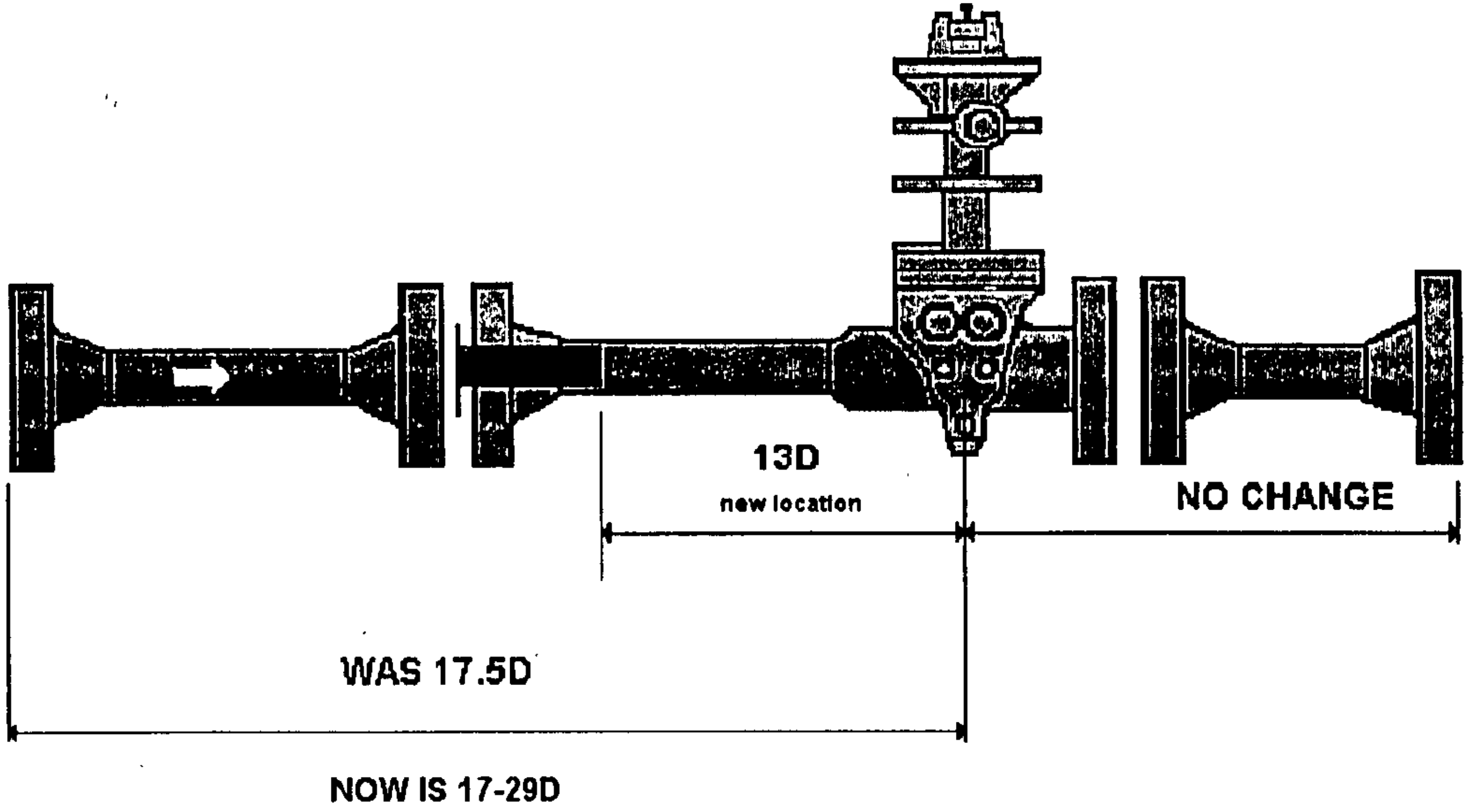
(no vane or conditioner)



NOW IS 145D

UNIVERSAL METER TUBE WITH VANE

SHORT VERSION



MAX .46 BETA

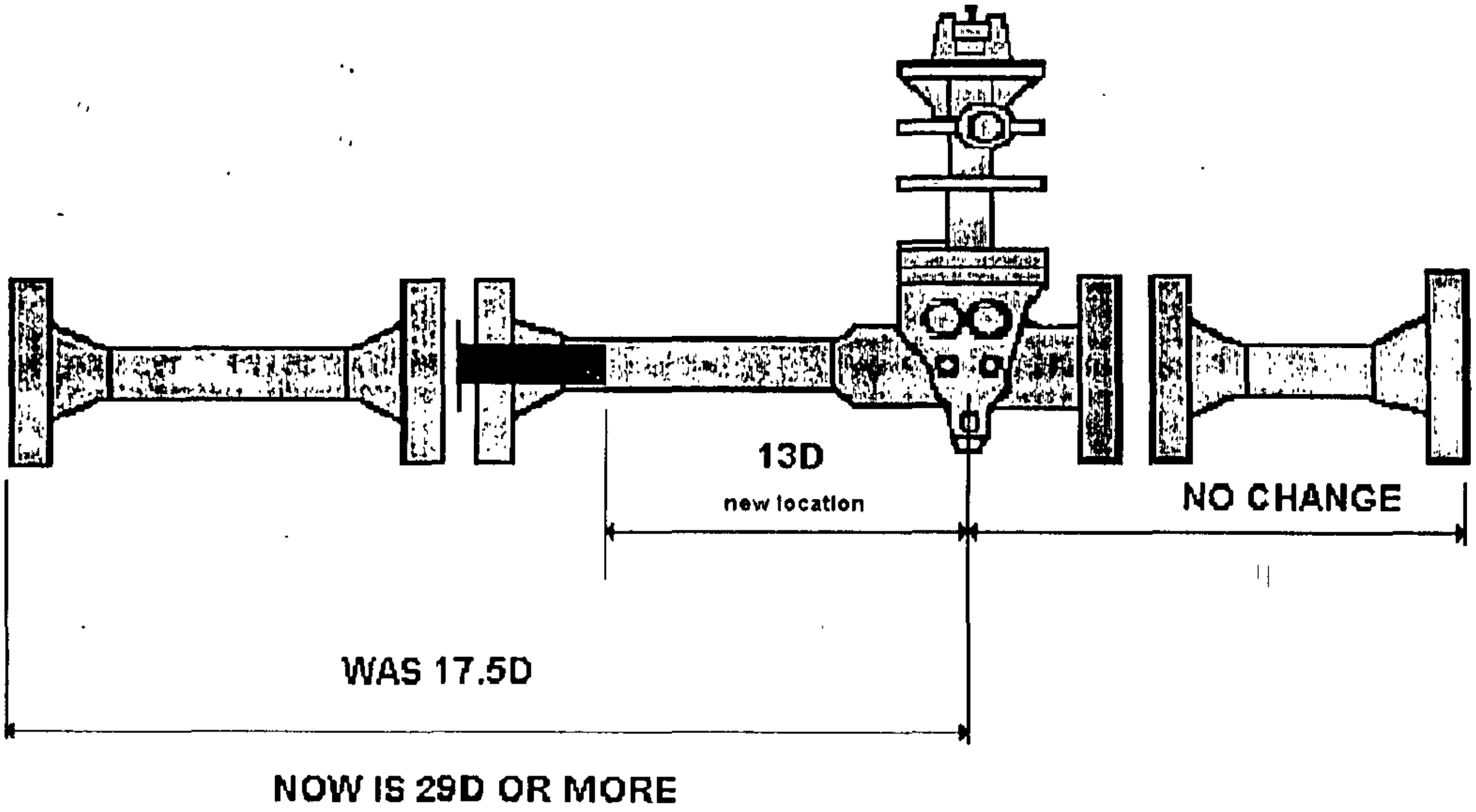
SHORT UPSTREAM LENGTH WITH TUBE BUNDLE

NEW vs OLD

CATEGORY	*WAS*	*BETA MAX*	*IS*	*BETA MAX*
1 ELL	16.5D	.75	17-29D	.75
2 ELLS out of plane	15D	.75	17-29D	.67
TEE	N/A	NEW	17-29D	.54
VALVE 50% MIN OPEN	17.5D	.75	17-29D	.47
HIGH SWIRL W/ 90° TEE	N/A	NEW	17-29D	.54
ANY CONFIGURATION (CATCH ALL)	17.5D	.75	17-29D	.46
2 ELLS close coupled	13.5D	.75	NO LONGER SHOWN	
2 ELLS /10D + space between	16.5D	.75		
Concentric Reducer	13.5D	.75		

UNIVERSAL METER TUBE WITH VANE

LONG VERSION



MAX .67 BETA

LONG METER TUBE WITH VANES

NEW vs OLD

CATEGORY	*WAS*	*BETA MAX*	*IS*	*BETA MAX*
1 ELL	16.5D	.75	29D/ +	.75
2 ELLS out of plane	15D	.75	29D/ +	.75
TEE	N/A	NEW	29D /+	.75
VALVE 50% OPEN +	17.5D	.75	29D /+	.75
High swirl combined with single 90° Tee	N/A	NEW	29D/ +	.75
Any Configuration (CATCH ALL)	17.5D	.75	29D /+	.67
2 ELLS close coupled	13.5D	.75	NO LONGER SHOWN	
2 ELLS 10D + space between	16.5D	.75		
Concentric Reducer	13.5D	.75		

THERMOMETER WELLS PRECEDING THE ORIFICE

- WAS 12” TO 36” BEFORE VANE

- NOW IS 36” BEFORE VANE

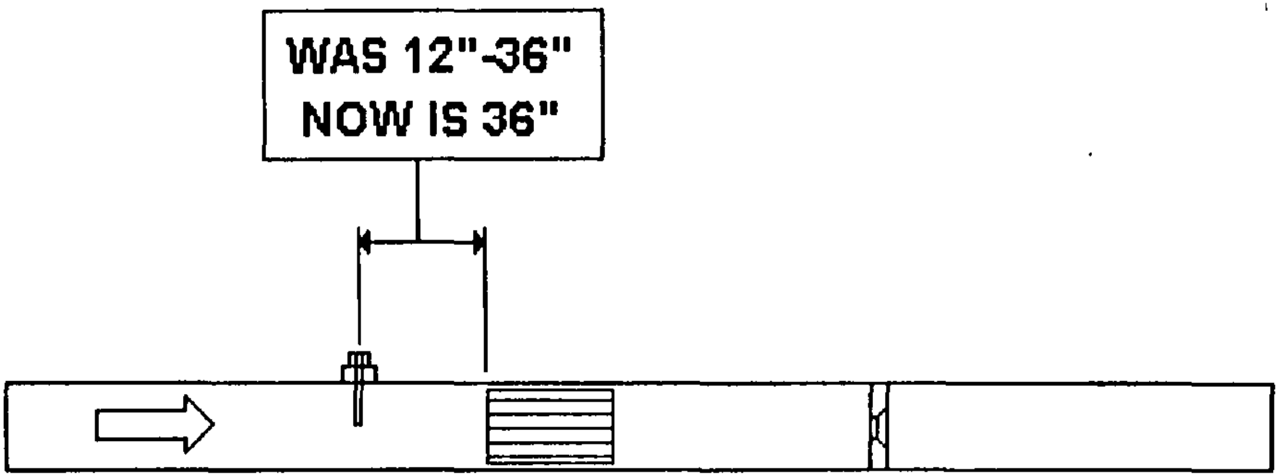


PLATE THICKNESS CHANGE
8” SIZE

- WAS 1/8” THICK
- NOW IS 1/4” THICK

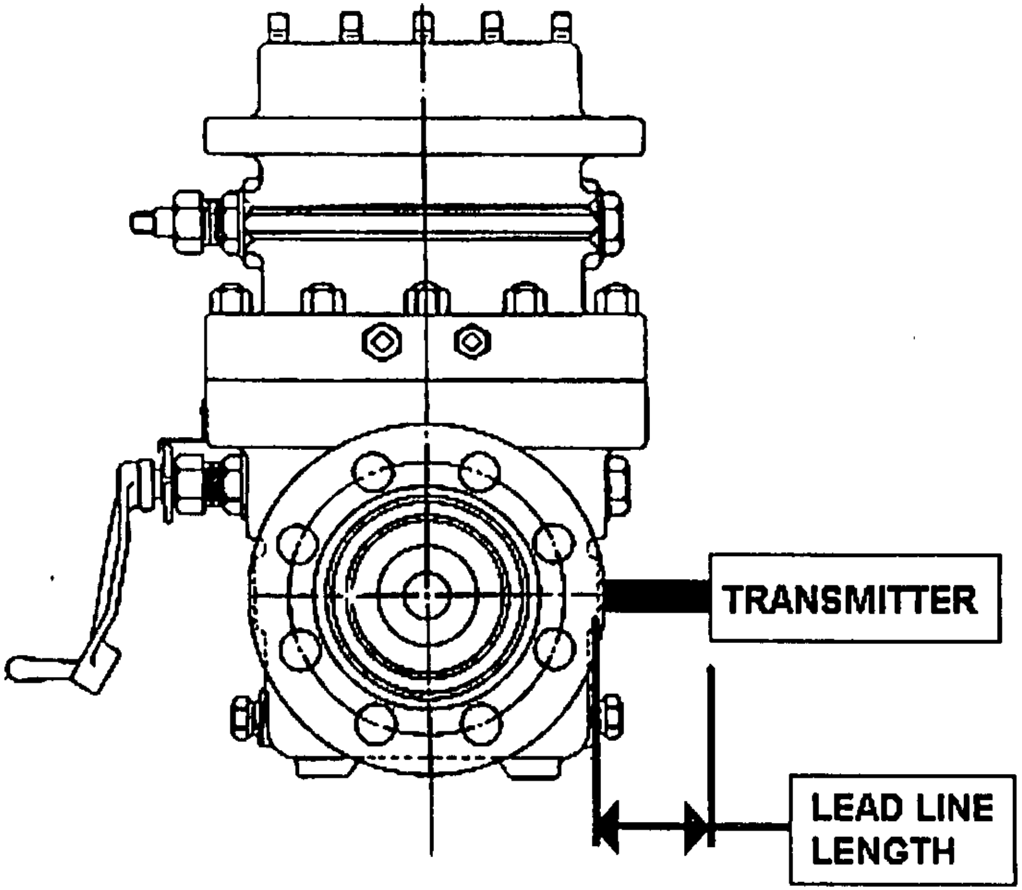
IMPACT OF 1/4” THICK 8” PLATES

PLATES WILL NOT INTERCHANGE WITH EXISTING FIELD UNITS

SEAL RINGS OR PLATE CARRIERS WILL DIFFER FROM EXISTING FIELD UNITS

POSSIBILITY EXISTS FOR WRONG PLATE IN RIGHT FITTING

DP TAP CONNECTION LINE LENGTHS



DIFFERENTIAL TAP LINE LENGTH

- **EQUAL LENGTH LINES**
- **SHORT AS POSSIBLE or**
- **CALCULATE PROPER LENGTH**
  - **5 EQUATIONS BASED ON FREQUENCY (f) AND SPEED OF SOUND IN FLUID (a)**
    - **length L = .25 a / (2 □ f)**

2.5

5.5

8.5

11.5

INCREASED DIFFERENTIAL PRESSURE

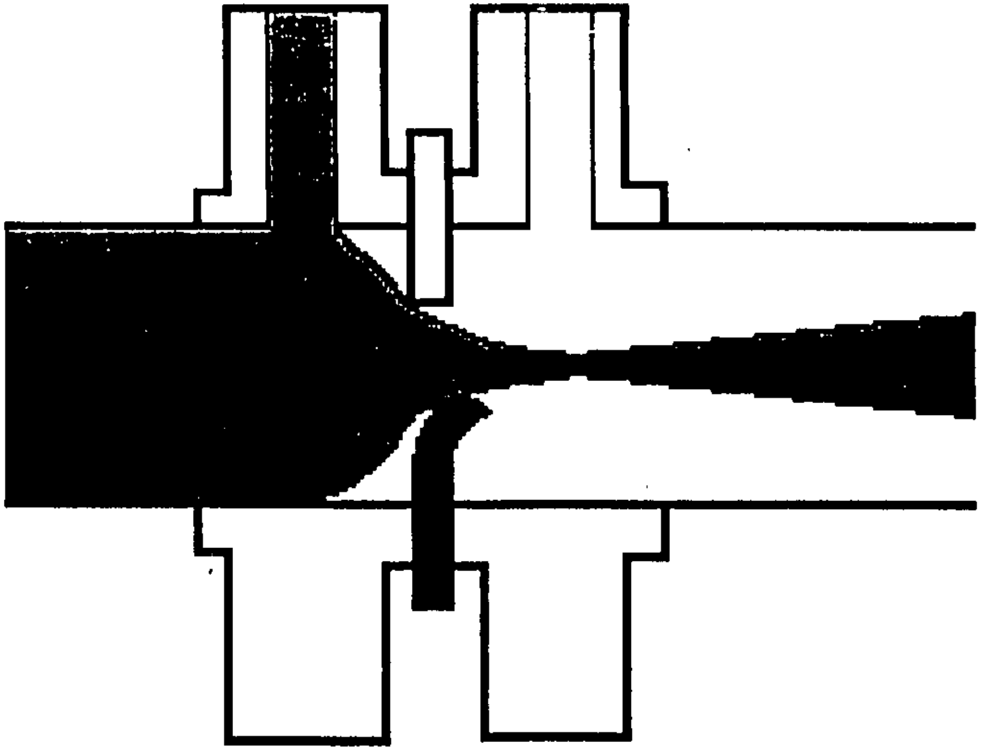
- TABLES SHOWING MAXIMUM DP FOR RECOMMENDED PLATE THICKNESSES
  - 304SS AND 316SS
  - TEMPERATURES TO 150°F (65°C)
  - INSTALLED IN BOTH FITTINGS AND FLANGES
    - FLANGES ALLOW MUCH HIGHER DIFFERENTIALS

INCREASED DIFFERENTIAL PRESSURE

CONTINUED

- SOME SIZES ALLOW UP TO 1000" DP
  - VALUES BASED ON PLATE DEFLECTION ONLY
  - ANY OPERATIONAL EFFECTS ON ORIFICE FITTINGS NOT CONSIDERED
- ADDITIONAL TABLES FOR OTHER THAN STANDARD PLATE THICKNESSES IN APPENDIX

POSSIBLE EFFECT OF DIFFERENTIAL PRESSURES EXCEEDING VALUES SHOWN



GRANDFATHER CLAUSE

- UPGRADING OF EXISTING INSTALLED UNITS
  - NOT REQUIRED
- EARLIER METER TUBE DESIGNS MAY CREATE ERRORS
  - TUBE BUNDLE DESIGN AND/OR LOCATION MAY CAUSE BIASED MEASUREMENT
- NEW INSTALLATIONS SHOULD MEET

  NEW GUIDELINES
- SHORTER THAN RECOMMENDED BARE TUBES MAY HAVE GREATER UNCERTAINTY

Manual of Petroleum Measurement Standards Chapter 14—Natural Gas Fluids Measurement

Section 3—Concentric, Square-Edged Orifice Meters

Part 3—Natural Gas Applications

Measurement Coordination Department

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American
Petroleum
Institute

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Chapter 14—Natural Gas Fluids Measurement

SECTION 3—CONCENTRIC, SQUARE-EDGED ORIFICE METERS

PART 3—NATURAL GAS APPLICATION

3.1 Introduction

3.1.1 APPLICATION

3.1.1.1 General

This part of Chapter 14, Section 3, has been developed as an application guide for the calculation of natural gas flow through a flange-tapped, concentric orifice meter, using the inch-pound system of units. For applications involving SI units, a conversion factor may be applied to the results (Q_m, Q_v, or Q_b) determined from the equations in 3.3. Intermediate conversion of units will not necessarily produce consistent results. As an alternative, the more universal approach specified in Chapter 14, Section 3, Part 1, should be used. The meter must be constructed and installed in accordance with Chapter 14, Section 3, Part 2.

3.1.1.2 Definition of *Natural Gas*

As used in this part, the term *natural gas* applies to fluids that for all practical purposes are considered to include both pipeline- and production-quality gas with single-phase flow and mole percentage ranges of components as given in American Gas Association (A.G.A.) Transmission Measurement Committee Report No. 8, "Compressibility and Supercompressibility for Natural Gas and Other Hydrocarbon Gases." For other hydrocarbon mixtures, the more universal approach specified in Part 1 may be more applicable. Diluents or mixtures other than those stipulated in A.G.A. Transmission Measurement Committee Report No.8 may increase the flow measurement uncertainty.

3.1.2 BASIS FOR EQUATIONS

The computation methods used in this part are consistent with those developed in Part 1 and include the Reader-Harris/Gallagher equation for flange-tapped orifice meter discharge coefficient. The equation has been modified to reflect the more common units of the inch-pound system. Since the new coefficient of discharge equation does not address pipe tap meters, the pipe tap methodology of the 1985 edition of ANSI/API 2530 has been retained for reference in Appendix 3-D.

3.1.3 ORGANIZATION OF PART 3

Chapter 14, Section 3, Part 3, is organized as follows: Symbols and units are defined in 3.2, the basic flow equation is presented in 3.3, the key equation components are defined in 3.4, and the gas properties applicable to orifice metering of natural gas are developed in 3.5. All values are assumed to be absolute. Factors to compensate for meter calibration and location are included in Appendix 3-A. The factor approach to orifice measurement is included in Appendix 3-B. Appendix 3-C covers examples to assist the user in interpreting this part. Appendix 3-D covers pipe tap meters. Appendix 3-E covers SI conversions, Appendix 3-F covers heating value calculation, and Appendix 3-G covers derivation of constants. The user is cautioned that the symbols as defined in 3.2 may be different from those used in previous orifice metering standards.

3.2 Symbols, Units, and Terminology

3.2.1 GENERAL

The symbols and units used are specific to Chapter 14, Section 3, Part 3, and were developed based on the customary inch-pound system of units. Regular conversion factors can

be used where applicable; however, if SI units are used, the more generic equations in Part 1 should be used for consistent results.

3.2.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
C_d	Orifice plate coefficient of discharge	—
C_d(FT)	Coefficient of discharge at a specified pipe Reynolds number for flange-tapped orifice meter	—
C_i(CT)	Coefficient of discharge at infinite pipe Reynolds number for corner-tapped orifice meter	—
C_i(FT)	Coefficient of discharge at infinite pipe Reynolds number for flange-tapped orifice meter	—
c_p	Specific heat at constant pressure	Btu/(lbm-°F)
c_v	Specific heat at constant volume	Btu/(lbm-°F)
d	Orifice plate bore diameter calculated at flowing temperature, T_f	in
D	Meter tube internal diameter calculated at flowing temperature, T_f	in
d_r	Orifice plate bore diameter calculated at reference temperature, T_r	in
D_r	Meter tube internal diameter calculated at reference temperature, T_r	in
e	Napierian constant	2.71828
E_v	Velocity of approach factor	—
°F	Temperature, in degrees Fahrenheit	—
°R	Temperature, in degrees Rankine	459.67 + °F
F_{pv}	Supercompressibility factor	—
G	Gas relative density (specific gravity)	—
G_i	Ideal gas relative density (specific gravity)	—
G_r	Real gas relative density (specific gravity)	—
h_w	Orifice differential pressure	inches of water column at 60°F
k	Isentropic exponent (see 3.4.5)	—
k_i	Ideal gas isentropic exponent	—
k_p	Perfect gas isentropic exponent	—
k_r	Real gas isentropic exponent	—
m	Mass	lbm
Mr_{air}	Molar mass (molecular weight) of air	28.9625 lbm/lb-mol
Mr_{gas}	Molar mass (molecular weight) of gas	lbm/lb-mol
Mr_i	Molar mass (molecular weight) of component	lbm/lb-mol
n	Number of moles	—
N_4	Unit conversion factor (discharge coefficient)	—
P	Pressure	lbf/in^2 (abs)
P_b	Base pressure	lbf/in^2 (abs)
$P_{b_{air}}$	Base pressure of air	lbf/in^2 (abs)
$P_{b_{gas}}$	Base pressure of gas	lbf/in^2 (abs)
P_f	Static pressure of fluid at the pressure tap	lbf/in^2 (abs)
P_{f_1}	Absolute static pressure at the orifice upstream differential pressure tap	lbf/in^2 (abs)
P_{f_2}	Absolute static pressure at the orifice downstream differential pressure tap	lbf/in^2 (abs)

P_s	Standard pressure	14.73 lbf/in² (abs)
Q_b	Volume flow rate at base conditions	ft³/hr
q_m	Mass flow rate per second	lbm/sec
Q_m	Mass flow rate per hour	lbm/hr
Q_v	Volume flow rate per hour at standard conditions	ft³/hr
R	Universal gas constant	1545.35 (lbf-ft)/(lb-mol-°R)
Re_D	Pipe Reynolds number	—
T	Temperature	°R
T_b	Base temperature	°R
$T_{b_{air}}$	Base temperature of air	°R
$T_{b_{gas}}$	Base temperature of gas	°R
T_f	Temperature of fluid at flowing conditions	°R
T_r	Reference temperature of the orifice plate bore diameter and/or meter tube inside diameter	68°F
T_s	Standard temperature	519.67°R
U_{f_1}	Flowing velocity at upstream tap	ft/sec
V	Volume	ft³
V_b	Volume at base conditions	ft³
V_{f_1}	Flowing volume at upstream tap	ft³
x	Ratio of differential pressure to absolute static pressure	—
x_1	Ratio of differential pressure to absolute static pressure at the upstream pressure tap	—
x_2	Ratio of differential pressure to absolute static pressure at the downstream pressure tap	—
x/k	Acoustic ratio	—
Y	Expansion factor	—
Y_1	Expansion factor based on upstream absolute static pressure	—
Y_2	Expansion factor based on downstream absolute static pressure	—
Z	Compressibility	—
Z_b	Compressibility at base conditions	—
$Z_{b_{air}}$	Compressibility of air at 14.73 psia and 60°F	0.999590
$Z_{b_{gas}}$	Compressibility of the gas at base conditions (P_b, T_b)	—
Z_f	Compressibility at flowing conditions (P_f, T_f)	—
Z_{f_1}	Compressibility at upstream flowing conditions	—
Z_{f_2}	Compressibility at downstream flowing conditions	—
Z_s	Compressibility at standard conditions (P_s, T_s)	—
α	Linear coefficient of thermal expansion	in/in-°F
α_1	Linear coefficient of thermal expansion of the orifice plate material	in/in-°F
α_2	Linear coefficient of thermal expansion of the meter tube material	in/in-°F
β	Ratio of orifice plate bore diameter to meter tube internal diameter (d/D) calculated at flowing temperature, T_f	—
μ	Absolute viscosity of flowing fluid	lbm/ft-sec

π	Universal constant	3.14159
ρ_b	Density of a fluid at base conditions (P_b, T_b)	lbm/ft^3
$\rho_{b_{air}}$	Density of air at base conditions (P_b, T_b)	lbm/ft^3
$\rho_{b_{gas}}$	Density of a gas at base conditions (P_b, T_b)	lbm/ft^3
ρ_s	Density of a fluid at standard conditions (P_s, T_s)	lbm/ft^3
$\rho_{t,p}$	Density of a fluid at flowing conditions (P_f, T_f)	lbm/ft^3
ρ_{t,p_1}	Density of a fluid at flowing conditions at upstream tap position (P_{f_1}, T_f)	lbm/ft^3
ρ_{t,p_2}	Density of a fluid at flowing conditions at downstream tap position (P_{f_2}, T_f)	lbm/ft^3
ϕ_i	Mole fraction of component	%/100

Note: Factors, ratios and coefficients are dimensionless.

3.2.3 TERMINOLOGY

3.2.3.1 Pressure

One pound force (lbf) per square inch pressure is defined as the force a 1-pound mass (lbm) exerts when evenly distributed on an area of 1 square inch and when acted on by the standard acceleration of free fall, 32.1740 feet per second per second.

3.2.3.2 Subscripts

The subscript 1 on the expansion factor (Y_1), the flowing density (ρ_{t,p_1}), the fluid flowing static pressure (P_{f_1}), and the fluid flowing compressibility (Z_{f_1}) indicates that these variables are to be measured, calculated, or otherwise determined relative to the fluid flowing at the conditions of the upstream differential tap. Variables related to the downstream differential pressure tap are identified by the subscript 2, including Y_2, ρ_{t,p_2}, P_{f_2}, and Z_{f_2}, and can be used in the equations with equal precision of the calculated flow rates (except for Y_2, which has a separate equation).

The subscript 1 is arbitrarily used in the equations in this part to emphasize the necessity of maintaining the relationship of these four variables to the chosen static pressure reference tap.

3.2.3.3 Temperature

The temperature of the flowing fluid (T_f) does not have a numerical subscript. This temperature is usually measured downstream of the orifice plate for minimum flow disturbance but may be measured upstream within the locations prescribed in Part 2. It is assumed that there is no difference between fluid temperatures at the two differential pressure tap locations and the measurement point, so the subscript is unnecessary.

3.2.3.4 Standard Conditions

Standard conditions are defined as a designated set of base conditions. In this part, standard conditions are defined as the absolute static pressure, P_s, of 14.73 pounds force per square inch absolute; the absolute temperature, T_s, of 519.67°R (60°F); and the fluid compressibility, Z_s, for a stated relative density (specific gravity), G.

3.2.3.5 Definitions

General definitions are covered in Parts 1 and 2. Definitions specific to Part 3 are incorporated in the text.

3.3 Flow Measurement Equations

3.3.1 GENERAL

The following equations express flow in terms of mass and volume per unit time and produce equivalent results. Since this section deals exclusively with the inch-pound system of units, the numeric constants defined in Part 1 have been converted to reflect these units.

The numeric constants for the basic flow equations, unit conversion values, density of water, and density of air are given in 3.5 and Appendix 3-G. The tables in this part that list solutions to these equations incorporate these constants and values. Other physical properties are given in 3.5. Key equation components are developed in 3.4.

3.3.2 EQUATIONS FOR MASS FLOW OF NATURAL GAS

The equations for the mass flow of natural gas, in pounds mass per hour, can be developed from the density of the flowing fluid (see Appendix 3-G), the ideal gas relative density (specific gravity), or the real gas relative density (specific gravity), using the following equations.

The mass flow developed from the density of the flowing fluid (ρ_{t,p_1}) is expressed as follows:

$$Q_m = 359.072 C_d(\mathrm{FT}) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w} \tag{3-1}$$

Mass flow developed from the ideal gas relative density (specific gravity), G_i, is expressed as follows:

$$Q_m = 589.885 C_d(\mathrm{FT}) E_v Y_1 d^2 \sqrt{\frac{G_i P_{f_1} h_w}{Z_{f_1} T_f}} \tag{3-2}$$

The mass flow equation developed from the real gas relative density (specific gravity), G_r, assumes a pressure of 14.73 pounds force per square inch absolute and a temperature of 519.67°R (60°F) as the reference base conditions for the determination of real gas relative density (specific gravity). This assumption allows the base compressibility of air at 14.73 pounds force per square inch absolute and 519.67°R (60°F) to be incorporated into the numeric constant of the flow rate equation. If the assumption about the base reference conditions is not valid, the results obtained from this flow rate equation will have an added increment of uncertainity. The mass flow equation developed from real gas relative density (specific gravity), G_r, is expressed as follows:

$$Q_m = 590.006 C_d(\mathrm{FT}) E_v Y_1 d^2 \sqrt{\frac{Z_s G_r P_{f_1} h_w}{Z_{f_1} T_f}} \tag{3-3}$$

Where:

$C_d(\mathrm{FT})$ = coefficient of discharge for flange-tapped orifice meter.
d = orifice plate bore diameter, in inches, calculated at flowing temperature (T_f).
E_v = velocity of approach factor.
G_i = ideal gas relative density (specific gravity).
G_r = real gas relative density (specific gravity).
h_w = orifice differential pressure, in inches of water at 60°F.
P_{f_1} = flowing pressure at upstream tap, in pounds force per square inch absolute.
Q_m = mass flow rate, in pounds mass per hour.
T_f = flowing temperature, in degrees Rankine.
Y_1 = expansion factor (upstream tap).
Z_s = compressibility at standard conditions (P_s, T_s).
Z_{f_1} = compressibility at upstream flowing conditions (P_{f_1}, T_f).
ρ_{t,p_1} = density of the fluid at upstream flowing conditions (P_{f_1}, T_f, and Z_{f_1}), in pounds mass per cubic foot.

3.3.3 EQUATIONS FOR VOLUME FLOW OF NATURAL GAS

The volume flow rate of natural gas, in cubic feet per hour at base conditions, can be developed from the densities of the fluid at flowing and base conditions and the ideal gas relative density (specific gravity) or real gas relative density (specific gravity) using the following equations.

The volume flow rate at base conditions, Q_b, developed from the density of the fluid at flowing conditions (ρ_{t,p_1}) and base conditions (ρ_b) is expressed as follows:

$$Q_b = \frac{359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_b} \tag{3-4a}$$

The volume flow rate at base conditions, developed from ideal gas relative density (specific gravity), G_i, is expressed as follows:

$$Q_b = 218.573 C_d(FT) E_v Y_1 d^2 \frac{T_b Z_b}{P_b} \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}} \tag{3-5a}$$

To correctly apply the real gas relative density (specific gravity) to the flow calculation, the reference base conditions for the determination of real gas relative density (specific gravity) and the base conditions for the flow calculation must be the same. Therefore, the volume flow rate at base conditions, developed from real gas relative density (specific gravity), G_r, is expressed as follows:

$$Q_b = 218.573 C_d(FT) E_v Y_1 d^2 \frac{T_b}{P_b} \sqrt{\frac{P_{f_1} Z_b Z_{b_{air}} h_w}{G_r Z_{f_1} T_f}} \tag{3-6a}$$

If standard conditions are substituted for base conditions in Equations 3-4a, 3-5a, and 3-6a, then

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ pounds force per square inch absolute} \\ T_b &= T_s \\ &= 519.67°\text{R } (60°\text{F}) \\ Z_{b_{air}} &= Z_{s_{air}} \\ &= 0.999590 \end{aligned}$$

The volume flow rate at standard conditions, Q_b, can then be determined using the following equations.

The volume flow rate at standard conditions, developed from the density of the fluid at flowing conditions (ρ_{t,p_1}) and standard conditions (ρ_s), is expressed as follows:

$$Q_v = \frac{359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_s} \tag{3-4b}$$

The volume flow rate at standard conditions, developed from ideal gas relative density (specific gravity), G_i, is expressed as follows:

$$Q_v = 7711.19 C_d(FT) E_v Y_1 d^2 Z_s \sqrt{\frac{P_f h_w}{G_i Z_{f_1} T_f}} \tag{3-5b}$$

The volume flow rate equation at standard conditions, Q_v, developed from the real gas relative density (specific gravity), requires standard conditions as the reference base conditions for G_r and incorporates $Z_{b_{air}}$ at 14.73 pounds force per square inch absolute and 519.67°R (60°F) in its numeric constant. Therefore, the volume flow rate at standard conditions, developed from real gas relative density (specific gravity), G_r, is expressed as follows:

$$Q_v = 7709.61 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \tag{3-6b}$$

Where:

$C_d(FT)$ = coefficient of discharge for flange-tapped orifice meter.
d = orifice plate bore diameter calculated at flowing temperature (T_f), in inches.
E_v = velocity of approach factor.
G_i = ideal gas relative density (specific gravity).
G_r = real gas relative density (specific gravity).
h_w = orifice differential pressure, in inches of water at 60°F.
P_b = base pressure, in pounds force per square inch absolute.
P_{f_1} = flowing pressure (upstream tap), in pounds force per square inch absolute.
P_s = standard pressure
= 14.73 pounds force per square inch absolute.
Q_b = volume flow rate per hour at base conditions, in cubic feet per hour.
Q_s = volume flow rate per hour at standard conditions, in cubic feet per hour.
T_b = base temperature, in degrees Rankine.
T_f = flowing temperature, in degrees Rankine.
T_s = standard temperature
= 519.67°R (60°F).
Y_1 = expansion factor (upstream tap).
Z_b = compressibility at base conditions (P_b, T_b).
$Z_{b_{air}}$ = compressibility of air at base conditions (P_b, T_b).
Z_{f_1} = compressibility at upstream flowing conditions (P_{f_1}, T_f).
Z_s = compressibility at standard conditions (P_s, T_s).
$Z_{s_{air}}$ = compressibility of air at standard conditions (P_s, T_s).
ρ_b = density of the flowing fluid at base conditions (P_b, T_b), in pounds mass per cubic foot.
ρ_s = density of the flowing fluid at standard conditions (P_s, T_s), in pounds mass per cubic foot.
ρ_{t,p_1} = density of the fluid at upstream flowing conditions (P_{f_1}, T_f), in pounds mass per cubic foot.

3.3.4 VOLUME CONVERSION FROM STANDARD TO BASE CONDITIONS

For the purposes of Part 3, standard and base conditions are assumed to be the same. However, if base conditions are different from standard conditions, the volume flow rate calculated at standard conditions can be converted to the volume flow rate at base conditions through the following relationship:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \qquad (3\text{-}7)$$

Where:

P_b = base pressure, in pounds force per square inch absolute.
P_s = standard pressure, in pounds force per square inch absolute.
Q_b = base volume flow rate, in cubic feet per hour.
Q_v = standard volume flow rate, in cubic feet per hour.
T_b = base temperature, in degrees Rankine.
T_s = standard temperature, in degrees Rankine.
Z_b = compressibility at base conditions (P_b, T_b).
Z_s = compressibility at standard conditions (P_s, T_s).

3.4 Flow Equation Components Requiring Additional Computation

3.4.1 GENERAL

Some of the terms in Equations 3-1 through 3-6 require additional computation and are developed in this section.

3.4.2 DIAMETER RATIO (β)

The diameter ratio (β), which is used in determining (a) the orifice plate coefficient of discharge (C_d), (b) the velocity of approach factor (E_v), and (c) the expansion factor (Y), is the ratio of the orifice bore diameter (d) to the internal diameter of the meter tube (D). For the most precise results, the actual dimensions should be used, as determined in Parts 1 and 2.

$$\beta = d / D \qquad (3\text{-}8)$$

Where

$$d = d_r[1 + \alpha_1(T_f - T_r)] \qquad (3\text{-}9)$$

And

$$D = D_r[1 + \alpha_2(T_f - T_r)] \qquad (3\text{-}10)$$

Where:

d = orifice plate bore diameter calculated at flowing temperature, T_f.
d_r = reference orifice plate bore diameter calculated at reference temperature, T_r.
D = meter tube internal diameter calculated at flowing temperature, T_f.
D_r = reference meter tube internal diameter calculated at reference temperature, T_r.
T_f = temperature of the fluid at flowing conditions.
T_r = reference temperature for the orifice plate bore diameter and/or the meter tube internal diameter.
α_1 = linear coefficient of thermal expansion of the orifice plate material (see Table 3-1).
α_2 = linear coefficient of thermal expansion of the meter tube material (see Table 3-1).
β = diameter ratio.

Note: α, T_f, and T_r must be in consistent units. For the purpose of this standard, T_r is assumed to be 68°F.

The orifice plate bore diameter, d_r, and the meter tube internal diameter, D_r, calculated at T_r are the diameters determined in accordance with Part 2.

3.4.3 COEFFICIENT OF DISCHARGE FOR FLANGE-TAPPED ORIFICE METER, C_d(FT)

The coefficient of discharge for a flange-tapped orifice meter (C_d) has been determined from test data. It has been correlated as a function of diameter ratio (β), tube diameter, and pipe Reynolds number. In this part, the equation for the flange-tapped orifice meter coefficient of discharge developed in Part 1 has been adapted to the inch-pound system of units.

The equation for the concentric, square-edged flange-tapped orifice meter coefficient of discharge, C_d(FT), developed by Reader-Harris and Gallagher, is structured into distinct

Table 3-1—Linear Coefficient of Thermal Expansion

Material	Linear Coefficient of Thermal Expansion (α), in/in-°F
Type 304 and 316 stainless steel[a]	0.00000925
Monel[a]	0.00000795
Carbon steel[b]	0.00000620

Note: For flowing temperature conditions other than those stated in Footnotes a and b and for other materials, refer to the American Society for Metals *Metals Handbook* (Desk Edition, 1985).

[a] For flowing conditions between −100°F and +300°F, refer to the American Society of Mechanical Engineers data in PTC 19.5, *Application, Part II of Fluid Meters Supplement on Instruments and Apparatus*.

[b] For flowing conditions between −7°F and +154°F, refer to Chapter 12, Section 2.

linkage terms and is considered to best represent the current regression data base. The equation is applicable to nominal pipe sizes of 2 inches and larger; diameter ratios (β) of 0.1–0.75, provided the orifice plate bore diameter, d_r, is greater than 0.45 inches; and pipe Reynolds numbers (Re_D) greater than or equal to 4000. For orifice diameters, diameter ratios, and pipe Reynolds numbers outside the stated limits, the uncertainty statement increases. For guidance, refer to Part 1, 1.12.4.1.

The Reader-Harris/Gallagher equation is defined as follows:

$$C_d(FT) = C_i(FT) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4C \quad (3\text{-}11)$$

$$C_i(FT) = C_i(CT) + Tap\ Term \quad (3\text{-}12)$$

$$C_i(CT) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1-\beta)M_1 \quad (3\text{-}13)$$

$$Tap\ Term = Upstrm + Dnstrm \quad (3\text{-}14)$$

$$Upstrm = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \quad (3\text{-}15)$$

$$Dnstrm = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \quad (3\text{-}16)$$

Also,

$$B = \frac{\beta^4}{1-\beta^4} \quad (3\text{-}17)$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4},\ 0.0\right) \quad (3\text{-}18)$$

$$M_2 = \frac{2L_2}{1-\beta} \quad (3\text{-}19)$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \quad (3\text{-}20)$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \quad (3\text{-}21)$$

Where:

$C_d(FT)$ = coefficient of discharge at a specified pipe Reynolds number for a flange-tapped orifice meter.
$C_i(CT)$ = coefficient of discharge at an infinite pipe Reynolds number for a corner-tapped orifice meter.
$C_i(FT)$ = coefficient of discharge at an infinite pipe Reynolds number for a flange-tapped orifice meter.
d = orifice plate bore diameter calculated at T_f, in inches.
D = meter tube internal diameter calculated at T_f, in inches.
e = Napierian constant.
= 2.71828.
L_1 = L_2
= dimensionless correction for tap location
= N_4/D for flange taps.
N_4 = 1.0 when D is in inches.
Re_D = pipe Reynolds number.
β = diameter ratio
= d/D.

Note: The equation for the coefficient of discharge for a flange-tapped orifice meter, $C_d(FT)$, is different from those included in prior editions of this standard

3.4.4 VELOCITY OF APPROACH FACTOR (E_v)

The velocity of approach factor (E_v) is a mathematical expression that relates the velocity of the flowing fluid in the orifice meter approach section (upstream meter tube) to the fluid velocity in the orifice plate bore.

The velocity of approach factor, E_v, is calculated as follows:

$$E_v = \frac{1}{\sqrt{1 - \beta^4}} \tag{3-22}$$

Where:

E_v = velocity of approach factor.
β = diameter ratio
= d/D.

3.4.5 REYNOLDS NUMBER (Re_D)

The pipe Reynolds number (Re_D) is used as a correlation parameter to represent the change in the orifice plate coefficient of discharge with reference to the meter tube diameter, the fluid flow rate, the fluid density, and the fluid viscosity. The use of the pipe Reynolds number is an additional change from prior editions of this standard. The Reynolds number is a dimensionless ratio when consistent units are used and is expressed as follows:

$$Re_D = \frac{U_{f_1} D \rho_{t,p_1}}{12\mu} \tag{3-23}$$

Or

$$Re_D = \frac{48 q_{m}}{\pi \mu D} \tag{3-24}$$

Note: The constant, 12, in the denominator of Equation 3-23 is required by the use of D in inches

The fluid velocity can be obtained in terms of the volumetric flow rate at base conditions from the following relationship:

$$\begin{aligned} U_{f_1} &= \frac{Q_b \rho_b}{D^2 \rho_{t,p_1}} \left[\frac{(4)(144)}{3600\pi}\right] \\ &= 0.0509296 \frac{Q_b \rho_b}{D^2 \rho_{t,p_1}} \end{aligned} \tag{3-25}$$

Substituting Equation 3-25 into Equation 3-23 results in the following relationship:

$$\begin{aligned} Re_D &= \left(\frac{0.0509296}{12}\right)\left(\frac{Q_b \rho_b}{\mu D}\right)\left(\frac{D \rho_{t,p}}{D \rho_{t,p_1}}\right) \\ &= (0.00424413)\left(\frac{Q_b \rho_b}{\mu D}\right) \end{aligned} \tag{3-26}$$

The Reynolds number for natural gas can be approximated by substituting the following relationship for ρ_b (see 3.5.5.3 for equation development) into Equation 3-26:

$$\rho_b = \frac{2.69881 P_b}{T_b Z_{b_{air}}}\left(G_r \frac{Z_{b_{air}}}{Z_{b_w}}\right) \tag{3-27}$$

$$Re_D = 0.0114541\left(\frac{Q_b P_b G_r}{\mu D T_b Z_{b_w}}\right) \tag{3-28}$$

By using an average value of 0.0000069 pounds mass per foot-second for μ and substituting the standard conditions of 519.67°R, 14.73 pounds force per square inch, and 0.999590 for T_b, P_b, and $Z_{b_{air}}$, Equation 3-28 reduces to the following:

$$Re_D = 47.0723 \frac{Q_v G_r}{D} \tag{3-29}$$

Where:

D = meter tube internal diameter calculated at the flowing temperature (T_f), in inches.
G_r = real gas relative density (specific gravity).
P_b = base pressure.
Q_b = volume flow rate at base conditions, in cubic feet per hour.
q_m = mass flow rate, in pounds mass per second.
Q_v = volume flow rate at standard conditions, in cubic feet per hour.
Re_D = pipe Reynolds number.
T_b = base temperature, in degrees Rankine.
U_{f_1} = velocity of the flowing fluid at the upstream tap location, in feet per second.
$Z_{b_{air}}$ = compressibility of air at 14.73 pounds force per square inch absolute and 60°F.
$Z_{b_{gas}}$ = compressibility of the gas at base conditions (P_b, T_b).
μ = absolute (dynamic) viscosity, in pounds mass per foot-second.
π = 3.14159.
ρ_b = density of the flowing fluid at base conditions (P_b, T_b), in pounds mass per cubic foot.
ρ_{t,P_1} = density of the fluid at upstream flowing conditions (P_{f_1}, T_f), in pounds mass per cubic foot.

If the fluid being metered has a viscosity, temperature, or real gas relative density (specific gravity) quite different from those shown above, the assumptions are not applicable. For variations in viscosity from 0.0000059 to 0.0000079 pounds mass per foot-second, variations in temperature from 30°F to 90°F, or variations in real gas relative density (specific gravity) from 0.55 to 0.75, the variation should not be significant in terms of its effect on the orifice plate coefficient of discharge at higher Reynolds numbers.

When the flow rate is not known, the Reynolds number can be developed through iteration, assuming an initial value of 0.60 for the coefficient of discharge for a flange-tapped orifice meter, C_d(FT), and using the volume computed to estimate the Reynolds number.

3.4.6 EXPANSION FACTOR (Y)

3.4.6.1 General

When a gas flows through an orifice, the change in fluid velocity and static pressure is accompanied by a change in the density, and a factor must be applied to the coefficient to adjust for this change. The factor is known as the expansion factor (Y) and can be calculated from the following equations taken from the report to the A.G.A. Committee by the National Bureau of Standards dated May 26, 1934, and prepared by Howard S. Bean. The expansion factor (Y) is a function of diameter ratio (β), the ratio of differential pressure to static pressure at the designated tap, and the isentropic exponent (k).

The real compressible fluid isentropic exponent, k_r, is a function of the fluid and the pressure and temperature. For an ideal gas, the isentropic exponent, k_i, is equal to the ratio of the specific heats (c_p/c_v) of the gas at constant pressure (c_p) and constant volume (c_v) and is independent of pressure. A perfect gas is an ideal gas that has constant specific heats. The perfect gas isentropic exponent, k_p, is equal to k_i evaluated at base conditions.

It has been found that for many applications, the value of k_r is nearly identical to the value of k_i, which is nearly identical to k_p. From a practical standpoint, the flow equation is not particularly sensitive to small variations in the isentropic exponent. Therefore, the perfect gas isentropic exponent, k_p, is often used in the flow equation. Accepted practice for natural gas applications is to use $k_p = k = 1.3$. This greatly simplifies the calculations and is used in the tables. This approach was adopted by Buckingham in his correlation for the expansion factor.

The application of the expansion factor is valid as long as the following dimensionless criterion for pressure ratio is followed:

$$0 < \frac{h_w}{27.707\,P_f} \leq 0.20 \qquad (3\text{-}30)$$

Or

$$0.8 \leq \frac{P_{f_2}}{P_{f_1}} < 1.0 \qquad (3\text{-}31)$$

Where:

h_w = flange tap differential pressure across the orifice plate, in inches of water at 60°F.
P_f = flowing pressure, in pounds force per square inch absolute.
P_{f_1} = absolute static pressure at the upstream pressure tap, in pounds force per square inch absolute.
P_{f_2} = absolute static pressure at the downstream pressure tap, in pounds force per square inch absolute.

The expansion factor equation for flange taps may be used for a range of diameter ratios from 0.10 to 0.75. For diameter ratios (β) outside the stated limits, increased uncertainty will occur.

3.4.6.2 Expansion Factor Referenced to Upstream Pressure

If the absolute static pressure is taken at the upstream differential pressure tap, the value of the expansion factor, Y_1, can be calculated using the following equation:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \qquad (3\text{-}32)$$

When the upstream static pressure is measured,

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\,P_{f_1}} \qquad (3\text{-}33)$$

When the downstream static pressure is measured,

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_2} + (P_{f_1} - P_{f_2})} = \frac{h_w}{27.707\,P_{f_2} + h_w} \qquad (3\text{-}34)$$

Where.

h_w = differential pressure, in inches of water at 60°F.
k = isentropic exponent (see 3.4.6.1).
P_{f_1} = absolute static pressure at the upstream tap, in pounds force per square inch absolute.
P_{f_2} = absolute static pressure at the downstream tap, in pounds force per square inch absolute.
x_1 = ratio of differential pressure to absolute static pressure at the upstream tap.
Y_1 = expansion factor based on the absolute static pressure measured at the upstream tap.
β = diameter ratio (d/D).

The quantity x_1/k is known as the *acoustic ratio.*

3.4.6.3 Expansion Factor Referenced to Downstream Pressure

If the absolute static pressure is taken at the downstream differential tap, the value of the expansion factor, Y_2, can be calculated using the following equation:

$$Y_2 = Y_1 \sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \qquad \text{(3-35)}$$

And

$$Y_2 = Y_1 \frac{1}{\sqrt{1 - x_1}} \sqrt{\frac{Z_{f_2}}{Z_{f_1}}} \qquad \text{(3-36)}$$

Or

$$Y_2 = \left[\sqrt{1 + x_2} - (0.41 + 0.35\beta^4)\frac{x_2}{k\sqrt{1 + x_2}}\right]\sqrt{\frac{Z_{f_2}}{Z_{f_1}}} \qquad \text{(3-37)}$$

And

$$x_2 = \frac{P_{f_1} - P_{f_2}}{P_{f_2}} = \frac{h_w}{27.707\, P_{f_2}} \qquad \text{(3-38)}$$

Where:

h_w = differential pressure, in inches of water at 60°F.
k = isentropic exponent (see 3.4.5.1).
P_{f_1} = absolute static pressure at the upstream tap, in pounds force per square inch absolute.
P_{f_2} = absolute static pressure at the downstream tap, in pounds force per square inch absolute.
x_1 = ratio of differential pressure to absolute static pressure at the upstream tap.
x_2 = ratio of differential pressure to absolute static pressure at the downstream tap.
Y_1 = expansion factor based on the absolute static pressure measured at the upstream tap.
Y_2 = expansion factor based on the absolute static pressure measured at the downstream tap.
Z_{f_1} = compressibility at upstream flowing conditions (P_{f_1}, T_f).
Z_{f_2} = compressibility at downstream flowing conditions (P_{f_2}, T_f).
β = diameter ratio (d/D).

Note: x_2 equals the ratio of the differential pressure to the static pressure at the downstream tap (P_{f_2})

3.5 Gas Properties

3.5.1 GENERAL

The measurement of gaseous flow rate in volume units under other than standard or base conditions requires conversion for pressure, temperature, and the deviation of the measured volume from the ideal gas laws (compressibility). Energy measurement also requires adjustment for heat content. The standard conditions used in Part 3 are a base pressure of 14.73 pounds force per square inch absolute and a base temperature of 519.67°R (60°F).

As a mixture of compounds, natural gas complicates the calculation of some of these conversion factors. The factors that cannot be determined by simple calculations can be derived from gas composition and/or other measurements. Certain factors can be measured in the field, using instruments calibrated against standard gas samples. Either approach will produce equivalent results when rigorous methods are applied.

3.5.2 PHYSICAL PROPERTIES

Table 3-F-1 in Appendix 3-F lists physical properties taken from GPA 2145-91. The data for ideal density and ideal heating value per cubic foot from GPA 2145-91 have, where nec-

essary, been corrected in Table 3-F-1 for the base pressure of 14.73 pounds force per square inch absolute through the following relationship:

$$\text{Table 3-F-1 value} = \frac{14.73}{14.696} \times \text{GPA 2145-91 table value} \tag{3-39}$$

Table 3-F-1 provides the best currently available data on physical properties. These data are subject to modification yearly as additional research is accomplished. Future revisions to GPA 2145 may include updated values. The values from the most recent edition of GPA 2145 should be used, and the values for density and British thermal units per cubic foot should be corrected through the use of Equation 3-39.

In addition, GPA Publication 2172 and Publication 181 are incorporated in this standard as the method of calculating heating values of natural gas mixtures from compositional analysis. An abbreviated form of that methodology is included in Appendix 3-F as a reference.

In this edition, the compressibility of air at standard conditions ($Z_{b_{air}}$) has been updated to the value of 0.999590.

3.5.3 COMPRESSIBILITY

3.5.3.1 Ideal and Real Gas

The terms *ideal gas* and *real gas* are used to define calculation or interpretation methods. An ideal gas is one that conforms to the thermodynamic laws of Boyle and Charles (ideal gas laws), such that the following is true:

$$144PV = nRT \tag{3-40}$$

If Subscript 1 represents a gas volume measured at one set of temperature–pressure conditions and Subscript 2 represents the same volume measured at a second set of temperature–pressure conditions, then

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \tag{3-41}$$

The numerical constant in Equation 3-40 is required to convert P, in pounds force per square inch absolute, to units that are consistent with the value of R given in Part 2.

All gases deviate from the ideal gas laws to some extent. This deviation is known as *compressibility* and is denoted by the symbol Z. Additional discussion of compressibility and the method for determining the value of Z for natural gas are developed in detail in A.G.A. Transmission Measurement Committee Report No. 8. The method used in that report is included as a part of this standard.

The application of Z changes the ideal relationship in Equation 3-40 to the following real relationship:

$$144PV = nZRT \tag{3-42}$$

As modified by Z, Equation 3-41 allows the volume at the upstream flowing conditions to be converted to the volume at base conditions by use of the following equation:

$$V_b = V_{f_1}\left(\frac{P_{f_1}}{P_b}\right)\left(\frac{Z_b}{Z_{f_1}}\right)\left(\frac{T_b}{T_f}\right) \tag{3-43}$$

Where:

n = number of pound-moles of a gas
P = absolute static pressure of a gas, in pounds force per square inch absolute.
P_b = absolute static pressure of a gas at base conditions, in pounds force per square inch absolute.

P_{f_1} = absolute static pressure of a gas at the upstream tap, in pounds force per square inch absolute.
R = universal gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T = absolute temperature of a gas, in degrees Rankine.
T_b = absolute temperature of a gas at base conditions, in degrees Rankine.
T_f = absolute temperature of a flowing gas, in degrees Rankine.
V = volume of a gas, in cubic feet.
V_b = volume of a gas at base conditions (P_b, T_b), in cubic feet.
V_{f_1} = volume of a gas at flowing conditions (P_{f_1}, T_f), in cubic feet.
Z = compressibility of a gas at P and T.
Z_b = compressibility of a gas at base conditions (P_b, T_b).
Z_{f_1} = compressibility of a gas at flowing conditions (P_{f_1}, T_f).

3.5.3.2 Compressibility at Base Conditions

The value of Z at base conditions (Z_b) is required and is calculated from the procedures in A.G.A. Transmission Measurement Committee Report No. 8.

3.5.3.3 Supercompressibility

In orifice measurement, Z_b and Z_{f_1} appear as a ratio to the 0.5 power. This relationship is termed the *supercompressibility factor* and may be calculated from the following equation:

$$F_{pv} = \sqrt{\frac{Z_b}{Z_{f_1}}} \tag{3-44}$$

Or

$$Z_{f_1} = \frac{Z_b}{F_{pv}^{\,2}} \tag{3-45}$$

Where:

F_{pv} = supercompressibility factor.
Z_b = compressibility of the gas at base conditions (P_b, T_b).
Z_{f_1} = compressibility of the gas at flowing conditions (P_{f_1}, T_f).

3.5.4 RELATIVE DENSITY (SPECIFIC GRAVITY)

3.5.4.1 General

Relative density (specific gravity), G, is a component in several of the flow equations. The relative density (specific gravity) is defined as a dimensionless number that expresses the ratio of the density of the flowing fluid to the density of a reference gas at the same reference conditions of temperature and pressure. The gas industry has historically referred to the relative density (specific gravity) as either ideal or real and has designated the reference gas as air and the standard reference conditions as a pressure of 14.73 pounds force per square inch absolute and a temperature of 519.67°R (60°F). The value for relative density (specific gravity) may be determined by measurement or by calculation from the gas composition.

3.5.4.2 Ideal Gas Relative Density (Specific Gravity)

The ideal gas relative density (specific gravity), G_i, is defined as the ratio of the ideal density of the gas to the ideal density of dry air at the same reference conditions of pressure and temperature. Since the ideal densities are defined at the same reference conditions of pressure and temperature, the ratio reduces to a ratio of molar masses (molecular weights).

Therefore, the ideal gas relative density (specific gravity) is set forth in the following equation:

$$G_i = \frac{Mr_{gas}}{Mr_{air}} = \frac{Mr_{gas}}{28.9625} \tag{3-46}$$

Where:

G_i = ideal gas relative density (specific gravity).
Mr_{air} = molar mass (molecular weight) of air
= 28.9625 pounds mass per pound-mole.
Mr_{gas} = molar mass (molecular weight) of a flowing gas, in pounds mass per pound-mole.

3.5.4.3 Real Gas Relative Density (Real Specific Gravity)

Real gas relative density (specific gravity), G_r, is defined as the ratio of the real density of the gas to the real density of dry air at the same reference conditions of pressure and temperature. To correctly apply the real gas relative density (specific gravity) to the flow calculation, the reference conditions for the determination of the real gas relative density (specific gravity) must be the same as the base conditions for the flow calculation. At reference (base) conditions (P_b, T_b), real gas relative density (specific gravity) is expressed as follows:

$$G_r = \frac{144 \dfrac{P_{b_{gas}} Mr_{gas}}{Z_{b_{gas}} RT_{b_{gas}}}}{144 \dfrac{P_{b_{air}} Mr_{air}}{Z_{b_{air}} RT_{b_{air}}}}$$

Since the pressures and temperatures are defined to be at the same designated base conditions,

$$P_{b_{gas}} = P_{b_{air}}$$

$$T_{b_{gas}} = T_{b_{air}}$$

And the real gas relative density (specific gravity) is expressed as follows:

$$G_r = \left(\frac{Mr_{gas}}{Mr_{air}}\right)\left(\frac{Z_{b_{air}}}{Z_{b_{gas}}}\right) \tag{3-47}$$

The use of real gas relative density (specific gravity) in the flow calculations has a historic basis but may add an increment of uncertainty to the calculation as a result of the limitations of field gravitometer devices. When real gas relative densities (specific gravities) are directly determined by relative density measurement equipment, the observed values must be adjusted so that both air and gas measurements reflect the same pressure and temperature. The fact that the temperature and/or pressure are not always at base conditions results in small variations in determinations of relative density (specific gravity). Another source of variation is the use of atmospheric air. The composition of atmospheric air—and its molecular weight and density—varies with time and geographical location.

When recording gravitometers are used and calibration is performed with reference gases, either ideal or real gas relative density (specific gravity) can be obtained as a recorded relative density (specific gravity) by proper certification of the reference gas. The relationship between ideal gas relative density (specific gravity) and real gas relative density (specific gravity) is expressed as follows:

$$G_r = G_i \frac{Z_{b_{air}}}{Z_{b_{gas}}} \tag{3-48}$$

Where:

G_i = ideal gas relative density (specific gravity).
G_r = real gas relative density (specific gravity).
Mr_{air} = molar mass (molecular weight) of air
= 28.9625 pounds mass per pound-mole.
Mr_{gas} = molar mass (molecular weight) of the flowing gas, in pounds mass per pound-mole.
P_b = absolute static pressure of a gas at base conditions, in pounds force per square inch absolute.
$P_{b_{air}}$ = base pressure of air, in pounds force per square inch absolute.
$P_{b_{gas}}$ = base pressure of a gas, in pounds force per square inch absolute.
R = universal gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T_b = absolute temperature of a gas at base conditions, in degrees Rankine.
$T_{b_{air}}$ = base temperature of air, in degrees Rankine.
$T_{b_{gas}}$ = base temperature of a gas, in degrees Rankine.
$Z_{b_{air}}$ = compressibility of air at base conditions (P_b, T_b).
$Z_{b_{gas}}$ = compressibility of a gas at base conditions (P_b, T_b).

3.5.5 DENSITY OF FLUID AT FLOWING CONDITIONS

3.5.5.1 General

The flowing density ($\rho_{t,p}$) is a key component of certain flow equations. It is defined as the mass per unit volume at flowing pressure and temperature and is measured at the selected static pressure tap location. The value for flowing density can be calculated from equations of state or from the relative density (specific gravity) at the selected static pressure tap. The fluid density at flowing conditions can also be measured using commercial densitometers. Most densitometers, because of their physical installation requirements and design, cannot accurately measure the density at the selected pressure tap location. Therefore, the fluid density difference between the density measured and that existing at the defined pressure tap location must be checked to determine whether changes in pressure or temperature have an impact on the flow measurement uncertainty.

An approximation for field calculation is the direct application of tables from the equation of state. Such density tables have considerable bulk if they cover a wide range of conditions in small increments. Tables have a further deficiency in that they do not readily lend themselves to interpolation or extrapolation with fluctuating temperature and/or pressure.

At the time of publication, it was anticipated that a computer program for IBM and compatible personal computers that generates density and/or compressibility tables for user-defined gas and pressure–temperature ranges would be available through A.G.A. This program uses the equations in A.G.A. Transmission Measurement Committee Report No.8.

3.5.5.2 Density Based on Gas Composition

When the composition of a gas mixture is known, the gas densities $\rho_{t,p}$ and ρ_b may be calculated from the gas law equations. The molecular weight of the gas may be determined from composition data, using mole fractions of the components and their respective molecular weights.

$$\begin{aligned} Mr_{gas} &= \phi_1 Mr_1 + \phi_2 Mr_2 + \ldots + \phi_w Mr_w \\ &= \sum_{i=1}^{w} \phi_i Mr_i \end{aligned} \qquad (3\text{-}49)$$

In the following, the gas law equation, Equation 3-42, is rearranged to obtain density values:

$$144PV = nZRT$$

$$n = \frac{m}{Mr_{gas}} \tag{3-50}$$

Therefore:

$$144PV = \left(\frac{m}{Mr_{gas}}\right)ZRT \tag{3-51}$$

And

$$\rho_{t,p_1} = \frac{m}{V_{f_1}} = \frac{144\,P_{f_1}\,Mr_{gas}}{Z_{f_1}RT_f} \tag{3-52}$$

Or

$$\rho_b = \frac{m}{V_b} = \frac{144\,P_b\,Mr_{gas}}{Z_bRT_b} \tag{3-53}$$

Where:

G_i = ideal gas relative density (specific gravity).
m = mass of a fluid, in pounds mass.
Mr_{air} = molar mass (molecular weight) of air
= 28.9625 pounds mass per pound-mole.
Mr_{gas} = molar mass (molecular weight) of the flowing gas, in pounds mass per pound-mole.
Mr_i = molar mass (molecular weight) of a component, in pounds mass per pound-mole.
n = number of moles.
P = absolute static pressure of a gas, in pounds force per square inch absolute.
P_b = absolute static pressure of a gas at base conditions, in pounds force per square inch absolute.
P_{f_1} = absolute static pressure of a gas at the upstream tap, in pounds force per square inch absolute.
R = universal gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T = absolute temperature of a gas, in degrees Rankine.
T_b = absolute temperature of a gas at base conditions, in degrees Rankine.
T_f = absolute temperature of a flowing gas, in degrees Rankine.
V = volume of a gas, in cubic feet.
Z = compressibility of a gas at P, T.
Z_b = compressibility of a gas at base conditions (P_b, T_b).
Z_{f_1} = compressibility of a gas at flowing conditions (P_{f_1}, T_f).
ρ_b = density of a gas at base conditions (P_b, T_b), in pounds mass per cubic foot.
ρ_{t,p_1} = density of a gas at upstream flowing conditions (P_{f_1}, T_f), in pounds mass per cubic foot.
ϕ_i = mole fraction of a component.

3.5.5.3 Density Based on Ideal Gas Relative Density (Specific Gravity)

The gas densities ρ_{t,p_1} and ρ_b may be calculated from the ideal gas relative density (specific gravity), as defined in 3.5.5.2. The following equations are applicable when a gas analysis is available:

$$G_i = \frac{Mr_{gas}}{Mr_{air}} = \frac{Mr_{gas}}{28.9625} \tag{3-46}$$

Note: The molecular weight of dry air, from GPA 2145-91, is given as 28.9625 pounds mass per pound-mole (exactly).

$$Mr_{gas} = G_i Mr_{air} = G_i (28.9625) \qquad (3\text{-}54)$$

Substituting for Mr_{gas} in Equations 3-52 and 3-53, ρ_{t,p_1} and ρ_b are determined as follows:

$$\rho_{t,p_1} = \frac{P_{f_1} G_i (28.9625)(144)}{Z_{f_1} R T_f}$$

$$= 2.69881 \frac{P_{f_1} G_i}{Z_{f_1} T_f} \qquad (3\text{-}55)$$

And

$$\rho_b = \frac{P_b G_i (28.9625)(144)}{Z_b R T_b}$$

$$= 2.69881 \frac{P_b G_i}{Z_b T_b} \qquad (3\text{-}56)$$

Where:

G_i = ideal gas relative density (specific gravity).
Mr_{air} = molar mass (molecular weight) of air
= 28.9625 pounds mass per pound-mole.
Mr_{gas} = molar mass (molecular weight) of a flowing gas, in pounds mass per pound-mole.
P_b = absolute static pressure of the gas at base conditions, in pounds force per square inch absolute.
P_{f_1} = absolute static pressure of a gas at the upstream tap, in pounds force per square inch absolute.
R = universal gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T_b = absolute temperature of a gas at base conditions, in degrees Rankine.
T_f = absolute temperature of a flowing gas, in degrees Rankine.
Z_b = compressibility of a gas at base conditions (P_b, T_b).
Z_{f_1} = compressibility of a gas at flowing conditions (P_{f_1}, T_f).
ρ_b = density of a gas at base conditions (P_b, T_b, and Z_b), in pounds mass per cubic foot.
ρ_{t,p_1} = density of a gas at upstream flowing conditions (P_{f_1}, T_f, and Z_{f_1}), in pounds mass per cubic foot.

3.5.5.4 Density Based on Real Gas Relative Density (Specific Gravity)

The relationship of real gas relative density (specific gravity) to ideal gas relative density (specific gravity) is given by the following equation:

$$G_r = G_i \frac{Z_{b_{air}}}{Z_{b_{gas}}} \qquad (3\text{-}48)$$

Or

$$G_i = G_r \frac{Z_{b_{gas}}}{Z_{b_{air}}}$$

Note: The real gas relative density (specific gravity) of dry air at base conditions is defined as exactly 1.00000.

Substituting for G_i in Equations 3-55 and 3-56 results in the following:

$$\rho_{t,p_1} = \frac{2.69881\,P_{f_1} G_r Z_{b_{gas}}}{Z_{f_1} T_f Z_{b_{air}}} \tag{3-57}$$

$$\rho_b = \frac{2.69881\,P_b G_r}{T_b Z_{b_{air}}} \tag{3-58}$$

To correctly apply the density equations, Equations 3-57 and 3-58, which were developed from the real gas relative density (specific gravity), to the flow calculation, the reference base conditions for the determination of real gas relative density (specific gravity) and the base conditions for the flow calculation must be the same. When standard conditions are substituted for base conditions,

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ pounds force per square inch absolute} \\ T_b &= T_s \\ &= 519.67°\text{R } (60°\text{F}) \\ Z_{b_{air}} &= Z_{s_{air}} \\ &= 0.999590 \end{aligned}$$

The gas density based on real gas relative density (specific gravity) is given by the following equations:

$$\begin{aligned} \rho_{t,p_1} &= \frac{2.69881\,P_{f_1} G_r Z_{s_{gas}}}{0.999590\,Z_{f_1} T_f} \\ &= 2.69992\frac{P_{f_1} Z_{s_{gas}} G_r}{Z_{f_1} T_f} \end{aligned} \tag{3-59}$$

And

$$\begin{aligned} \rho_s &= \frac{(2.69881)(14.73)G_r}{(0.999590)(519.67)} \\ &= 0.0765289\,G_r \end{aligned} \tag{3-60}$$

Where:

G_i = ideal gas relative density.
G_r = real gas relative density.
P_b = absolute static pressure of a gas at base conditions, in pounds force per square inch absolute
P_{f_1} = absolute static pressure of a gas at the upstream tap, in pounds force per square inch absolute.
T_b = absolute temperature of a gas at base conditions, in degrees Rankine.
T_f = absolute temperature of a flowing gas, in degrees Rankine.
$Z_{b_{air}}$ = compressibility of air at base conditions (P_b, T_b).
$Z_{b_{gas}}$ = compressibility of a gas at base conditions (P_b, T_b).
Z_{f_1} = compressibility of a gas at flowing conditions (P_{f_1}, T_f).
$Z_{s_{air}}$ = compressibility of air at standard conditions (P_s, T_s).
$Z_{s_{gas}}$ = compressibility of a gas at standard conditions (P_s, T_s).
ρ_b = density of a gas at base conditions (P_b, T_b, and Z_b), in pounds mass per cubic foot.
ρ_s = density of a gas at standard conditions (P_s, T_s, and Z_s), in pounds mass per cubic foot.
ρ_{t,p_1} = density of a gas at upstream flowing conditions (P_{f_1}, T_f, and Z_{f_1}), in pounds mass per cubic foot

The density equations for standard conditions based on the real gas relative density (specific gravity) developed above require standard conditions as the designated reference base conditions for G_r and incorporate $Z_{s_{air}}$ at 14.73 pounds force per square inch absolute and 519.67°R in their numeric constants.

APPENDIX 3-A—ADJUSTMENTS FOR INSTRUMENT CALIBRATION

3-A.1 Scope

This appendix provides equations and procedures for adjusting and correcting field measurement calibrations of secondary instruments.

3-A.2 General

Field practices for secondary instrument calibrations and calibration standard applications contribute to the overall uncertainty of flow measurement.

Calibration standards for differential pressure and static pressure instruments are often used in the field without local gravitational force adjustment or correction of the values indicated by the calibrating standards. For example, it is common to use water column manometers to calibrate differential pressure instruments without making field corrections to the manometer readings for changes in water density. The manometer readings are affected by local gravitational effects, water temperatures, and the use of other than distilled water.

Pressure devices that employ weights are also used to calibrate differential pressure instruments without correction for the local gravitational force. Similarly, deadweight testers are used to calibrate static pressure measuring equipment without correction for the local gravitational force. It is usually more convenient and accurate to incorporate these adjustments in the flow computation than for the person calibrating the instrument to apply these small corrections during the calibration process. Therefore, additional factors are added to the flow equation for the purpose of including the appropriate calibration standard corrections in the flow computation either by the flow calculation procedure in the office or by the meter technician in the field.

Six factors are provided that may be used individually or in combination, depending on the calibration device and the calibration procedure used:

F_{am}	Correction for air over the water in the water manometer during the differential instrument calibration.
F_{wl}	Local gravitational correction for the water column calibration standard.
F_{wt}	Water density correction (temperature or composition) for the water column calibration standard.
F_{pwl}	Local gravitational correction for the deadweight tester static pressure standard.
F_{hgm}	Manometer factor (correction for the gas column in mercury manometers).
F_{hgt}	Mercury manometer temperature factor (span correction for instrument temperature change after calibration).

These factors expand the base volume flow equation to the following:

$$Q'_b = Q_b F_{am} F_{wt} F_{wl} F_{pwl} F_{hgm} F_{hgt} \qquad (3\text{-A-}1)$$

All of the flow factors that are pertinent to gas flow and are defined in this standard are included in Equation 3-A-1. Some of the factors are not applicable to all measurement systems and may therefore be considered equal to 1 or ignored, as preferred by the user. For other applications, particularly those involving mass flow calculation, specific factors may be included in the selected equation as appropriate for the system, the calibration of the instrumentation, and particular operating procedures.

3-A.3 Symbols, Units, and Terminology

3-A.3.1 GENERAL

The symbols and units used are specific to this appendix and were developed based on the customary inch-pound system of units. Regular conversion factors can be used where applicable; however, if SI units are used, the more generic equations in Part 1 should be used for consistent results.

3–A.3.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
°F	Temperature, in degrees Fahrenheit	—
°R	Temperature, in degrees Rankine	—
F_{aml}	Correction for air over the water in the water manometer	—
F_{hgml}	Manometer factor	—
F_{hgt}	Mercury manometer temperature factor	—
F_{pwl}	Local gravitational correction for deadweight tester	—
F_{wl}	Local gravitational correction for water column	—
F_{wt}	Water density correction	—
g_l	Local acceleration due to gravity	ft/sec^2
g_o	Acceleration of gravity used to calibrate weights or deadweight calibrator	ft/sec^2
G_i	Ideal gas relative density (specific gravity)	—
G_r	Real gas relative density (specific gravity)	—
h_{wa}	Differential pressure above atmospheric	inches of water column at 60°F
H	Elevation above sea level	ft
L	Latitude on earth's surface	degrees
Mr	Molar mass of gas	lbm/lb-mol
Mr_{air}	Molar mass of air	28.9625 lbm/lb-mol
P	Absolute gas pressure	lbf/in^2 (abs)
P_{atml}	Local atmospheric pressure	lbf/in^2 (abs)
P_b	Base pressure	lbf/in^2 (abs)
P_f	Absolute pressure of flowing gas	lbf/in^2 (abs)
Q_v'	Volume flow rate at standard conditions modified for instrument calibration adjustments	ft^3/hr
R	Universal gas constant	1545.35 (lbf-ft)/(lb-mol-°R)
T	Absolute gas temperature	°R
T_b	Base temperature	°R
T_f	Absolute temperature of a flowing gas	°R
T_{hga}	Mercury ambient temperature	°R
T_{gas_a}	Gas ambient temperature	°R
Z	Compressibility of a gas at T and P	—
Z_b	Compressibility of a gas at standard conditions (G_r, P_b, and T_b)	—
Z_a	Compressibility of air at $P_{atm} + h_{wa}$ and 519.67°R	—
Z_{aatm}	Compressibility of air at P_{atm} and 519.67°R	—
Z_{bair}	Compressibility of air at 14.73 psia and 519.67°R	0.999590
Z_f	Compressibility of gas at flowing conditions (G_r, P_f, and T_f)	—
ρ_a	Density of air at pressure above atmospheric	lbm/ft^3
ρ_{atml}	Density of atmospheric air	lbm/ft^3
ρ_g	Density of gas or vapor in the differential pressure instrument	lbm/ft^3
ρ_{hg}	Density of mercury in the differential pressure instrument	lbm/ft^3

ρ_{hgc}	Density of mercury in the differential pressure instrument at the time of its calibration	lbm/ft³
ρ_{hgo}	Density of mercury in the differential pressure instrument at the mercury gauge operating conditions	lbm/ft³
ρ_w	Density of water in the manometer at other than 60°F	lbm/ft³

3–A.4 Water Manometer Gas Leg Correction Factor (F_{am})

The factor F_{am} corrects for the gas leg over water when a water manometer is used to calibrate a differential pressure instrument:

$$F_{am} = \sqrt{\frac{\rho_w - \rho_a}{\rho_w}} \tag{3-A-2}$$

When atmospheric air is used as the medium to pressure both the differential pressure instrument and the water U-tube manometer during calibration, the density of air at atmospheric pressure and 60°F must be calculated using the following equation:

$$\rho = \frac{Mr\,G_i\,P}{RZT} \tag{3-A-3}$$

Substituting local atmospheric pressure (P_{atm}) for absolute pressure (P), 519.67°R (60°F) for the absolute temperature (T), 28.9625 for Mr_{air}, 1.0 for the ideal relative density (specific gravity) of air (G_i), and 1545.35 for the universal gas constant (R) provides the following relationship:

$$\rho_{am} = \frac{(28.9625)(1.0)P_{atm}}{\frac{1545.35}{144} Z_{a_{atm}} (519.67)}$$

$$= \frac{P_{atm}}{192.556\,Z_{a_{atm}}} \tag{3-A-4}$$

The local atmospheric pressure may be calculated using an equation published in the *Smithsonian Meteorological Tables*:

$$P_{atm} = 14.54\left[\frac{55096 - (\text{Elevation, ft} - 361)}{55096 + (\text{Elevation, ft} - 361)}\right] \tag{3-A-5}$$

The density of air at any given differential pressure (h_{wa}) above atmospheric pressure can then be represented by the following:

$$\rho_a = \frac{P_{atm} + \frac{h_{wa}}{27.707}}{192.477\,Z_a} \tag{3-A-6}$$

The density of water can be obtained from Table 3-A-1 or calculated from the following Wegenbreth density equation:

$$\begin{aligned}\rho_w = {} & 0.0624280[999.8395639 + 0.06798299989T_w - 0.009106025564T_w^2 \\ & + 0.0001005272999T_w^3 - 0.000001126713526T_w^4 \\ & + 0.000000006591795606T_w^5]\end{aligned} \tag{3-A-7}$$

Where:

G_i = ideal gas relative density (specific gravity).
h_{wa} = differential pressure above atmospheric, in inches of water at 60°F.
Mr = molar mass of a gas, in pounds mass per pound-mole.

Table 3-A-1—Water Density Based on Wegenbreth Equation

Temperature (°F)	Density (lbm/ft³)	Temperature (°F)	Density (lbm/ft³)
45	62.4212	63	62.3490
46	62.4193	64	62.3427
47	62.4172	65	62.3363
48	62.4148	66	62.3297
49	62.4121	67	62.3228
50	62.4092	68	62.3157
51	62.4060	69	62.3085
52	62.4026	70	62.3010
53	62.3980	71	62.2934
54	62.3949	72	62.2855
55	62.3908	73	62.2775
56	62.3863	74	62.2692
57	62.3817	75	62.2608
58	62.3768	76	62.2522
59	62.3717	77	62.2434
60	62.3663	78	62.2344
61	62.3608	79	62.2252
62	62.3550	80	62.2159

P = absolute gas pressure, in pounds force per square inch absolute.
P_{atm} = local atmospheric pressure, in pounds force per square inch absolute.
R = universal gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T = absolute gas temperature, in degrees Rankine.
T_w = temperature of water, in degrees Celsius.
Z = compressibility of a gas at P and T.
Z_a = compressibility of air at $P_{atm} + h_{wa}$ and 519.67°R.
$Z_{a_{atm}}$ = compressibility of air at P_{atm} and 519.67°R.
ρ = density of a gas, in pounds mass per cubic foot.
ρ_a = density of air at pressure above atmospheric, in pounds mass per cubic foot.
ρ_{atm} = density of atmospheric air, in pounds mass per cubic foot.
ρ_w = density of water in a manometer at a temperature other than 60°F, in pounds mass per cubic foot.

3–A.5 Water Manometer Temperature Correction Factor (F_{wt})

The factor F_{wt} corrects for variations in the density of water used in the manometer when the water is at a temperature other than 60°F. The F_{wt} correction factor should be included in the flow measurement computation when a differential instrument is calibrated with a water manometer.

$$F_{wt} = \frac{\rho_w}{62.3663} \tag{3-A-8}$$

Where.

ρ_w = density of water in a manometer at a temperature other than 60°F, in pounds mass per cubic foot.

3–A.6 Local Gravitational Correction Factor for Water Manometers (F_{wl})

The factor F_{wl} corrects the weight of the manometer fluid for the local gravitational force. The effect on the quantity is the square root of the ratio of the local gravitational force to the standard gravitational force used in the equation derivations. This relationship is expressed as follows:

$$F_{wl} = \sqrt{\frac{g_l}{32.1740}} \qquad (3\text{-}A\text{-}9)$$

Where:

g_l = local acceleration due to gravity, in feet per second per second.

The local value of gravity at any location may be obtained from a U.S. Coast and Geodetic Survey reference to aeronautical data or from the *Smithsonian Meteorological Tables*. Using Equation E11 from the 1985 edition of ANSI/API 2530 and the 45°-latitude-at-sea-level reference value, approximate values of g_l may be obtained from the following curve-fit equation covering latitudes from 0° to 90°:

$$\begin{aligned} g_l = {} & 0.0328095[978.01855 - 0.0028247L + 0.0020299L^2 \\ & - 0.000015058L^3 - 0.000094H] \end{aligned} \qquad (3\text{-}A\text{-}10)$$

Where:

L = latitude, in degrees.
H = elevation, in feet above sea level.

3–A.7 Local Gravitational Correction Factor for Deadweight Calibrators Used to Calibrate Differential and Static Pressure Instruments (F_{pwl})

The factor F_{pwl} is used to correct for the effect of local gravity on the weights of a deadweight calibrator. The calibrator weights are usually sized for use at a standard gravitational force or at some specified gravitational force. A correction factor must then be applied to correct the calibrations to the local gravitational force:

$$F_{pwl} = \frac{g_l}{g_o} \qquad (3\text{-}A\text{-}11)$$

Where:

g_l = acceleration due to local gravitational force, in feet per second per second.
g_o = acceleration of gravity used to calibrate the weights of a deadweight calibrator, in feet per second per second.

When a deadweight calibrator is used for the differential pressure and the static pressure, both must be corrected for local gravity. This involves using F_{pwl} twice.

3–A.8 Correction for Gas Column in Mercury Manometer Instruments (F_{hgm})

The factor F_{hgm} corrects for the gas or vapor leg of fluid at static pressure and the temperature of the manometer or other instrument. Mercury U-tube manometers and mercury-manometer-type differential pressure instruments are sometimes used to measure h_w. The manometer factor F_{hgm} is added to the flow equation to correct for the effect of the gas column above the mercury during flow measurements:

$$F_{hgm} = \sqrt{\frac{\rho_{hg} - \rho_g}{\rho_{hg}}} \qquad (3\text{-}A\text{-}12)$$

Where:

ρ_{hg} = density of mercury in the differential pressure instrument, in pounds mass per cubic foot. The effect of atmospheric air (usually defined as the weight *in vacuo* of

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ERRATA

On page 25, Equation 3-A-10 should read as follows:

$$g_l = 0.0328096[978.01855 - 0.0028247L + 0.0020299L^2 - 0.000015085L^3 - 0.000094H] \qquad \text{(3-A-10)}$$

On page 33, Equation 3-B-9 should read as follows:

$$F_{sl} = 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000}{Re_D}\right)^{0.35} \qquad \text{(3-B-9)}$$

On page 56, the second equation under 3–C.3.1.7 should read as follows:

$$Re_D = (0.0114541)\left(\frac{Q_s(14.73)(0.570)}{(0.0000069)(8.07085)(519.67)(0.999590)}\right)$$
$$= 3.32446Q_s$$

On page 57, Equation 3-6b should read as follows:

$$Q_s = 7709.61C_d(\text{FT})E_vY_1d^2\sqrt{\frac{P_{f1}Z_sh_w}{G_rZ_{f1}T_f}} \qquad \text{(3-6b)}$$
$$= 7709.61(0.60)(1.03160)(0.998383)(3.99989)^2 \times \sqrt{\frac{(370.0)(0.997971)(50.0)}{(0.570)(0.951308)(524.67)}}$$
$$= 614.033 \text{ cubic feet per hour at standard conditions}$$

On page 57, the second equation in 3-6b should read as follows.

$$Re_D = 3.32446Q_s$$
$$= 3.32446(614.033)$$
$$= 2{,}041.328 \text{ (initial estimate of Reynolds number)}$$

the mercury sample at the base pressure and temperature defined for the flow measurement) is excluded.

ρ_g = density of the gas or vapor in the differential pressure instrument, in pounds mass per cubic foot. The effect of atmospheric air (usually defined as weight in vacuo of the fluid sample at the flowing pressure existing at the orifice meter during the flow measurement and at the temperature existing at the differential pressure instrument during the flow measurement) is excluded.

The density of mercury at ambient temperature T_{hga}, in degrees Rankine, may be calculated from the following equation:

$$\rho_{hg} = 846.324[1.0 - 0.000101(T_{hga} - 519.67)] \qquad (3\text{-A-}13)$$

The density of a gas at ambient temperature may be calculated using the following equation:

$$\rho_g = \frac{Mr_{air} Z_b G_r P_f}{Z_{b_{air}} R Z_f T_{gas_a}} \qquad (3\text{-A-}14)$$

For standard conditions of

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ lbf/in}^2 \text{ (abs)} \\ T_b &= T_s \\ &= 519.67°\text{R (60°F)} \\ Z_{b_{air}} &= Z_{s_{air}} \\ &= 0.999590 \end{aligned}$$

Then

$$\rho_g = 2.69992 \frac{P_f Z_b G_r}{Z_f T_{gas_a}} \qquad (3\text{-A-}15)$$

Where:

G_r = real gas relative density (specific gravity).
Mr_{air} = molar mass of air
= 28.9625 pounds mass per pound-mole.
P_f = absolute pressure of a flowing gas, in pounds force per square inch absolute
R = univeral gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T_f = absolute temperature of a flowing gas, in degrees Rankine.
T_{gas_a} = gas ambient temperature, in degrees Rankine.
T_{hga} =, mercury ambient temperature, in degrees Rankine.
Z_b = compressibility of a gas at G_r, T_b, and P_b.
$Z_{b_{air}}$ = compressibility of air at 519.67°R and 14.73 pounds force per square inch absolute
= 0.999590.
Z_f = compressibility of a gas at flowing conditions (G_r, T_f and P_f).
Z_s = compressibility of a gas at 519.67°R and 14.73 pounds force per square inch absolute.

Tabular data for F_{hgm} are given in Table 3-A-2.

Correction for a liquid leg over the mercury can also be made if the liquid density is substituted for ρ_g in Equation 3-A-12. If the mercury differential pressure instrument is calibrated using a water column or a weight calibrator, the F_{wl} and F_{wt} factors are also needed.

Table 3-A-2—Mercury Manometer Factors (F_{hgm})

Real Gas Relative Density	Ambient Temperature (°F)	Static Pressure (pounds force per square inch gauge)						
		0	500	1000	1500	2000	2500	3000
0.550	0	1.0030	1.0019	1.0006	0.9990	0.9973	0.9960	0.9951
0.600	0	1.0030	1.0018	1.0002	0.9982	0.9962	0.9949	0.9940
0.650	0	1.0030	1.0017	0.9997	0.9971	0.9950	0.9938	0.9930
0.700	0	1.0030	1.0015	0.9991	0.9957	0.9937	0.9926	0.9920
0.750	0	1.0030	1.0014	0.9984	0.9940	0.9923	0.9913	0.9910
0.550	20	1.0020	1.0010	0.9997	0.9983	0.9969	0.9956	0.9947
0.600	20	1.0020	1.0009	0.9994	0.9977	0.9959	0.9946	0.9937
0.650	20	1.0020	1.0008	0.9990	0.9968	0.9949	0.9936	0.9927
0.700	20	1.0020	1.0007	0.9985	0.9957	0.9936	0.9924	0.9917
0.750	20	1.0020	1.0005	0.9980	0.9944	0.9924	0.9912	0.9907
0.550	40	1.0010	1.0000	0.9989	0.9977	0.9964	0.9952	0.9942
0.600	40	1.0010	0.9999	0.9986	0.9972	0.9956	0.9943	0.9933
0.650	40	1.0010	0.9998	0.9983	0.9965	0.9947	0.9933	0.9923
0.700	40	1.0010	0.9997	0.9980	0.9957	0.9936	0.9922	0.9913
0.750	40	1.0010	0.9996	0.9975	0.9947	0.9925	0.9912	0.9903
0.550	60	1.0000	0.9991	0.9980	0.9969	0.9957	0.9946	0.9936
0.600	60	1.0000	0.9990	0.9978	0.9965	0.9951	0.9938	0.9928
0.650	60	1.0000	0.9989	0.9975	0.9959	0.9943	0.9929	0.9919
0.700	60	1.0000	0.9988	0.9972	0.9953	0.9933	0.9919	0.9909
0.750	60	1.0000	0.9987	0.9968	0.9944	0.9923	0.9909	0.9900
0.550	80	0.9990	0.9981	0.9971	0.9961	0.9950	0.9940	0.9931
0.600	80	0.9990	0.9980	0.9969	0.9957	0.9945	0.9933	0.9923
0.650	80	0.9990	0.9979	0.9967	0.9953	0.9938	0.9925	0.9915
0.700	80	0.9990	0.9978	0.9964	0.9948	0.9930	0.9916	0.9905
0.750	80	0.9990	0.9977	0.9961	0.9941	0.9921	0.9906	0.9896
0.550	100	0.9980	0.9972	0.9962	0.9953	0.9943	0.9933	0.9925
0.600	100	0.9980	0.9971	0.9960	0.9949	0.9938	0.9926	0.9917
0.650	100	0.9980	0.9970	0.9958	0.9945	0.9932	0.9919	0.9909
0.700	100	0.9980	0.9969	0.9956	0.9941	0.9925	0.9912	0.9901
0.750	100	0.9980	0.9968	0.9953	0.9935	0.9917	0.9903	0.9892
0.550	120	0.9970	0.9962	0.9953	0.9944	0.9935	0.9926	0.9918
0.600	120	0.9970	0.9961	0.9951	0.9941	0.9930	0.9920	0.9911
0.650	120	0.9970	0.9960	0.9949	0.9937	0.9925	0.9914	0.9904
0.700	120	0.9970	0.9959	0.9947	0.9933	0.9920	0.9907	0.9896
0.750	120	0.9970	0.9958	0.9945	0.9929	0.9913	0.9899	0.9888

Note: This table is for use with mercury-type recording gauges that have gas in contact with the mercury surface.

A.9 Mercury Manometer Instrument Temperature Factor (F_{hgl})

The factor F_{hgl} corrects for the change in mercury density in the mercury differential pressure instrument due to temperature change from the time of instrument calibration. The mercury manometer temperature factor is introduced to correct for the error in differential pressure reading caused by a change in mercury temperature and the associated change in the density of mercury after calibration of the instrument. The factor is defined by the following equation:

$$F_{hgl} = \sqrt{\frac{\rho_{hgo}}{\rho_{hgc}}} \qquad (3\text{-A-}16)$$

Where:

ρ_{hgo} = density of the mercury in the differential pressure instrument, in pounds mass per cubic foot, at the mercury gauge operating conditions. The effect of atmospheric air (usually defined as the weight *in vacuo* of the mercury sample at the pressure for the flow measurement and the temperature of the mercury gauge) is excluded.

ρ_{hgc} = density of the mercury in the differential pressure instrument, in pounds mass per cubic foot, at the time of its calibration. The effect of atmospheric air (usually defined as the weight *in vacuo* of the mercury sample at a pressure of 1 atmosphere and the temperature of the mercury gauge) is excluded.

The mercury manometer temperature factor applies only to mercury-manometer-type gauges without internal temperature compensation when such gauges are used at operating temperatures different from the temperature of calibration.

APPENDIX 3-B—FACTORS APPROACH

3-B.1 Introduction

The factors approach can provide answers identical to those developed in this part of Chapter 14, Section 3. *The user is cautioned that when the tables in this appendix are used, the values are only precise for the variables stated.* For different dimensions or other input parameters, the true value can only be developed from computation.

3-B.2 Symbols, Units, and Terminology

3-B.2.1 GENERAL

Some of the symbols and units listed below are specific to this appendix and were developed based on the customary inch-pound system of units. Regular conversion factors can be used where applicable; however, if SI units are used, the more generic equations in Part 1 should be used for consistent results.

3-B.2.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
C'	Composite orifice flow factor	—
$C_d(FT)$	Orifice plate coefficient of discharge	—
d	Orifice plate bore diameter calculated at flowing temperature, T_f	in
D	Meter tube internal diameter calculated at flowing temperature, T_f	in
e	Napierian constant	2.71828
E_v	Velocity of approach factor	—
°F	Temperature, in degrees Fahrenheit	°F
°R	Absolute temperature, in degrees Rankine	°R
F_c	Orifice calculation factor	—
F'_c	Orifice calculation factor for $D < 2.8$	—
F_{gr}	Real gas relative density factor	—
F_n	Numeric conversion factor (see Table 3-B-2)	—
F_{pb}	Base pressure factor	—
F_{pv}	Supercompressibility factor	—
F_{sl}	Orifice slope factor	—
F_{tb}	Base temperature factor	—
F_{tf}	Flowing temperature factor	—
G_r	Real gas relative density (specific gravity)	—
h_w	Orifice differential pressure	inches of water column at 60°F
P_b	Absolute base pressure	lbf/in^2 (abs)
P_{f_1}	Absolute flowing pressure (upstream tap)	lbf/in^2 (abs)
P_s	Standard pressure	14.73 lbf/in^2 (abs)
Re_D	Pipe Reynolds number	—
Q_b	Volume flow rate per hour at base conditions	ft^3/hr
Q_v	Volume flow rate per hour at standard conditions of Z_b, T_b, and P_b	ft^3/hr
T_b	Absolute base temperature	°R
T_f	Absolute flowing temperature	°R
T_s	Standard temperature	519.67°R
Y	Expansion factor	—
Y_1	Expansion factor (upstream tap)	—

Y_2	Expansion factor (downstream tap)	—
Z_b	Compressibility at base conditions (P_b, T_b)	—
Z_{f_1}	Compressibility at upstream flowing conditions (P_{f_1}, T_f)	—
Z_s	Compressibility at standard conditions (P_s, T_s)	—
β	Diameter ratio (d/D)	—

3–B.3 Equations for Volume Flow Rate of Natural Gas

In the measurement of natural gas, the general practice is to state the flow in cubic feet per hour at some specified standard or base conditions of pressure and temperature using the real gas relative density. For the purpose of this appendix, the following standard or base conditions are assumed:

$$
\begin{aligned}
G_{r_{air}} &= 1.00000 \text{ (exactly)}\\
P_b &= P_s\\
&= 14.73 \text{ pounds force per square inch absolute}\\
T_b &= T_s\\
&= 519.67°\text{R}\\
T_f &= 519.67°\text{R}\\
Z_b &= Z_s
\end{aligned}
$$

The volumetric flow rate equation, Equation 3-6a, can be expressed in the historically more familiar format through the inclusion of calculation factors. These factors (ratios) are formed to allow the various terms in Equation 3-6a to be calculated individually.

The factors are derived from combining Equation 3-6a with four numeric ratios, each having a value of 1.00000 (exactly). These ratios are 14.73/14.73, 519.67/519.67, $(519.67/519.67)^{0.5}$, and 1/1. One half of each ratio is combined with P_b, T_b, T_f, and G_r, respectively, to form the F_{pb}, F_{tb}, F_{tf}, and F_{gr} factors. The other half of each ratio is combined with the numeric constant in Equation 3-6a to form the numeric conversion factor, F_n. Therefore, starting with Equation 3-6a,

$$Q_b = 218.573 C_d(\text{FT}) E_v Y_1 d^2 \frac{T_b}{P_b} \sqrt{\frac{P_{f_1} Z_b Z_{b_{air}} h_w}{G_r Z_{f_1} T_f}} \qquad (3\text{-}6\text{a})$$

Reformatting to incorporate the factor approach and standard conditions results in the following:

$$
\begin{aligned}
Q_v = {} & 218.573\left(\frac{519.67}{14.73}\right)\sqrt{\frac{1}{519.67}}\, C_d(\text{FT}) E_v Y_1 d^2 \left(\frac{T_b}{519.67}\right)\sqrt{0.999590}\\
& \times \left(\frac{14.73}{P_b}\right)\sqrt{\left(\frac{519.67}{T_f}\right)\left(\frac{1}{G_r}\right)\left(\frac{Z_b}{Z_{f_1}}\right)}\sqrt{P_{f_1} h_w} \qquad (3\text{-B-}1)
\end{aligned}
$$

Note: Variations in the base compressibility of dry air, $Z_{b_{air}}$, from the value given at 14.73 pounds force per square inch absolute and 519.67°R (60°F) for base pressures between 14.4 and 15.025 pounds force per square inch absolute at 519.67°R (60°F), are within the basic uncertainty statement of the compressibility data determination. Therefore, the value 0.999590 can be used in the development of the numeric constant for the flow equation

Thus, Equation 3-B-1 can be simplified to the following form:

$$Q_v = F_n(F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \sqrt{P_{f_1} h_w} \qquad (3\text{-B-}2)$$

Or

$$Q_v = C' \sqrt{P_{f_1} h_w} \qquad (3\text{-B-}3)$$

Where

$$C' = F_n(F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \qquad (3\text{-B-}4)$$

Where:

C' = composite orifice flow factor.
$C_d(FT)$ = coefficient of discharge for a flange-tapped orifice plate.
d = orifice plate bore diameter calculated at flowing temperature (T_f), in inches.
E_v = velocity of approach factor.
F_c = orifice calculation factor.
F_c' = orifice calculation factor for $D < 2.8$.
F_{gr} = real gas relative density factor.
F_n = numeric conversion factor (see Table 3-B-2).
F_{pb} = base pressure factor.
F_{pv} = supercompressibility factor.
F_{sl} = orifice slope factor.
F_{tb} = base temperature factor.
F_{tf} = flowing temperature factor.
G_r = real gas relative density (specific gravity).
h_w = orifice differential pressure, in inches of water at 60°F.
P_b = base pressure, in pounds force per square inch absolute.
P_{f_1} = absolute flowing pressure (upstream tap), in pounds force per square inch absolute.
Q_v = volume flow rate at standard conditions of Z_b, T_b, and P_b, in cubic feet per hour.
T_b = base temperature, in degrees Rankine.
T_f = absloute flowing temperature, in degrees Rankine.
Y_1 = expansion factor (upstream tap).
Z_b = compressibility at base conditions (P_b, T_b).
Z_{f_1} = compressibility at upstream flowing conditions (P_{f_1}, T_f).

The content of the composite orifice flow factor C' is different from what has been used in the past. The $F_n(F_c + F_{sl})$ product is a replacement for the F_b and F_r factors previously used in C'. Because of the form of the new discharge coefficient equation, the numeric constant (F_n) has been separated, and F_c and F_{sl} are treated as combined additive terms. The composite orifice flow factor assumes that the measured values are absolute. Adjustment factors to compensate for the type of instrumentation used, the calibration methods, and the elements of meter location are treated separately in Appendix 3-A. When the instruments are not calibrated or read to absolute values, adjustment factors may be applied as a multiplier to C'.

3–B.4 Numeric Conversion Factor (F_n)

The numeric conversion factor F_n (see Table 3-B-2) combines the numeric element of Equation 3-B-1 with the orifice diameter (d) and the velocity of approach factor (E_v) to provide the following equation:

$$\begin{aligned} F_n &= (218.573)(1.54761)E_v d^2\sqrt{Z_{b_{air}}} \\ &= 338.265E_v d^2\sqrt{Z_{b_{air}}} \\ &= 338.265E_v D^2\beta^2\sqrt{Z_{b_{air}}} \qquad (3\text{-B-5}) \end{aligned}$$

When standard conditions are substituted for base conditions,

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ pounds force per square inch absolute} \\ T_b &= T_s \\ &= 519.67°\text{R } (60°\text{F}) \\ Z_{b_{air}} &= Z_{s_{air}} \\ &= 0.999590 \end{aligned}$$

The numeric conversion factor, F_n, reduces to the following:

$$F_n = 338.196 E_v d^2 \tag{3-B-5a}$$

Or

$$F_n = 338.196 E_v D^2 \beta^2 \tag{3-B-5b}$$

Where:

d = orifice plate bore diameter calculated at flowing temperature, T_f, in inches.
D = meter tube internal diameter calculated at flowing temperature, T_f, in inches.
E_v = velocity of approach factor
= $1/(1 - \beta^4)^{0.5}$.
F_n = numeric conversion factor.
β = diameter ratio (d/D).

For the purpose of the tables in this appendix, the numeric conversion factor, F_n, is specified at standard conditions. The velocity of approach factor is more fully described in 3.4.4.

3–B.5 Orifice Calculation Factor (F_c)

A modification of the basic form of the equation for the orifice plate coefficient of discharge in 3.4.3 resulted in the equation being divided into two parts. The first part is the orifice calculation factor (F_c). The second part is the slope factor (F_{sl}). The orifice plate coefficient of discharge, C_d(FT), is the sum of F_c (see Table 3-B-3) and F_{sl} (see Table 3-B-4):

$$C_d(\text{FT}) = F_c + F_{sl} \tag{3-B-6}$$

The sum of F_c and F_{sl} is applicable to nominal pipe sizes of 2 inches and larger; diameter ratios (β) of 0.1–0.75, provided the orifice plate bore diameter, d, is greater than 0.45 inch; and pipe Reynolds numbers (Re_D) greater than or equal to 4000. For diameter ratios and pipe Reynolds numbers outside the limits stated, refer to Part 1, 1.12.4.1, and Part 4.

The orifice calculation factor (F_c) for meter tubes whose internal diameter is greater than or equal to 2.8 inches is computed by the following equation:

$$\begin{aligned} F_c = {} & 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 \\ & + \left(0.0433 + 0.0712 e^{-8.5/D} - 0.1145 e^{-6.0/D}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4} \\ & - 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{11}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right] \end{aligned} \tag{3-B-7}$$

For meter tubes whose internal diameter is less than than 2.8 inches, F_c is modified by an additional term such that

$$F_c' = F_c + 0.003(1 - \beta)(2.8 - D) \tag{3-B-8}$$

Where:

d = orifice plate bore diameter calculated at flowing temperature, T_f, in inches.
D = meter tube internal diameter calculated at flowing temperature, T_f, in inches
e = Napierian constant
= 2.71828
F_c = orifice calculation factor.
F_c' = orifice calculation factor for $D < 2.8$.
Re_D = pipe Reynolds number.
β = diameter ratio
= d/D.

Equation 3-B-8 is only valid for tubes whose internal diameter is less than 2.8 inches.

The inclusion of Reynolds number in the calculation term (F_c) makes this function three-dimensional, including β, D, and Re_D. The expression can be simplified by assuming Reynolds number values for various meter tubes from Table 3-B-1. These assumed values can introduce an error greater than 0.01 percent for meter tubes with nominal diameters of less than 3 inches and β ratios greater than 0.6. The most precise values are obtained by computing the orifice calculation factor (F_c) using the actual Reynolds number.

Table 3-B-3 was developed using the approximate values for Re_D from Table 3-B-1.

The assumed values for Reynolds number may not be used to compute the orifice slope factor (F_{sl}). The value of F_{sl} can only be obtained through iteration.

3–B.6 Slope Factor (F_{sl})

The slope factor, F_{sl} (see Table 3-B-4), is the slope term from the coefficient of discharge equation developed in 3.4.3. It is expressed as follows:

$$F_{sl} = 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.35} \qquad (3\text{-B-}9)$$

Where:

d = orifice plate bore diameter calculated at flowing temperature, T_f, in inches.
D = meter tube internal diameter calculated at flowing temperature, T_f, in inches.
F_{sl} = slope factor for flange-tapped coefficient of discharge equation (see Table 3-B-4).
Re_D = pipe Reynolds number.
β = diameter ratio
= d/D.

Since Re_D is a function of the flow rate (Q_v), F_{sl} can only be obtained through iteration. The values of Re_D given in Table 3-B-1 will not provide precise results but can be used as the first approximation in an iterative solution. Typically, three iterations of Q_v and Re_D are required to provide an accurate solution for F_{sl}.

As covered in 3.4.5, for most natural gases Equation 3-29 can be used to estimate Re_D from Q_v and D:

$$Re_D = 47.0723\frac{Q_v G_r}{D} \qquad (3\text{-}29)$$

Where:

Q_v = volume flow rate at standard conditions (Z_s, T_s, and P_s), in cubic feet per hour.
D = meter tube internal diameter calculated at flowing temperature, T_f, in inches.
G_r = real gas relative density (specific gravity).

Table 3-B-5 was developed using Equation 3-29. Table 3-B-4 provides values for F_{sl} based on a normalized pipe Reynolds number ($Re_D/1{,}000{,}000$) and diameter ratio (β).

3–B.7 Expansion Factor (Y)

The expansion factor, Y, is a function of β ratio, the ratio of differential pressure to static pressure, and the ratio of specific heats (also called the isentropic exponent, or the ratio of specific heat capacity). Equations for the determinations of Y_1 and Y_2 are found in 3.4.6. Tabular values for Y_1 are found in Table 3-B-6.

3–B.8 Pressure Base Factor (F_{pb})

The pressure base factor, F_{pb}, is applied to change the base pressure from 14.73 pounds force per square inch absolute and is calculated by dividing 14.73 by the required (contract) absolute base pressure (see Table 3-B-7). Using this factor is equivalent to substituting the contract absolute base pressure for P_b in Equation 3-6a:

$$F_{pb} = \frac{14.73}{P_b} \tag{3-B-10}$$

Where:

P_b = contract absolute base pressure (see Table 3-B-7), in pounds force per square inch absolute.

3–B.9 Temperature Base Factor (F_{tb})

The temperature base factor, F_{tb}, is applied where the base temperature is other than 60°F and is calculated by dividing the required (contract) base temperature in degrees Rankine by 519.67°R (see Table 3-B-8). The use of this factor is equivalent to substituting the contract absolute base temperature for T_b in Equation 3-6a:

$$F_{tb} = \frac{T_b}{519.67} \tag{3-B-11}$$

Where:

T_b = contract absolute base temperature, in degrees Rankine.

3–B.10 Flowing Temperature Factor (F_{tf})

The flowing temperature factor, F_{tf}, is required to change from the assumed flowing temperature of 60°F to the actual flowing temperature, T_f. F_{tf} is calculated by dividing 519.67°R by the flowing temperature in degrees Rankine and taking the square root of the result (see Table 3-B-9). The use of this factor is equivalent to substituting the actual absolute flowing temperature for T_f in Equation 3-6a:

$$F_{tf} = \sqrt{\frac{519.67}{T_f}} \tag{3-B-12}$$

Where:

T_f = flowing temperature, in degrees Rankine.

3–B.11 Real Gas Relative Density (Specific Gravity) Factor (F_{gr})

The real gas relative density (specific gravity) factor, F_{gr}, is applied to change from a real gas relative density of 1.0 to the real gas relative density of the flowing gas and is obtained as shown in Equation 3-B-13 (see Table 3-B-10). The use of this factor is equivalent to substituting the real gas relative density for G_r in Equation 3-6a:

$$F_{gr} = \sqrt{\frac{1}{G_r}} \tag{3-B-13}$$

Where:

G_r = real gas relative density (specific gravity).

Real gas relative density (specific gravity) is defined in 3.5.4.3.

3–B.12 Supercompressibility Factor (F_{pv})

The supercompressibility factor, F_{pv}, may be calculated from the following equation:

$$F_{pv} = \sqrt{\frac{Z_b}{Z_{f_1}}} \tag{3-B-14}$$

Where:

Z_b = gas compressibility at base conditions (P_b, T_b).
Z_{f_1} = gas compressibility at upstream flowing conditions (P_{f_1}, T_f).

The development of compressibility and supercompressibility is covered in 3.5.3.2 and 3.5.3.3.

Historically, the natural gas industry has used a tabular approach to compressibility for field applications where there is no ready access to a computer. Table 3-B-11 has been included as a typical supercompressibility factor (F_{pv}) table. It is only applicable to a hydrocarbon gas with a specific gravity of 0.6 and no nitrogen or carbon dioxide. The table is provided as an example only and may not be interpolated; neither may values from the table be adjusted for diluent content. It is typical of the tables that can be developed for the user's specific application (gas quality, temperature range, and pressure range). The alternative is the direct calculation of F_{pv} for the specific measurement conditions using A.G.A. Transmission Measurement Committee Report No. 8.

3–B.13 Tables

The values of all the factors of C' as defined in Equation 3-B-4 are obtained from Equations 3-B-5 through 3-B-14. Tabular data are included in this appendix as alternative means of determining all factor values except for F_{pv} values. The tables can also be used to check calculated values. The tables are only precise for the values listed.

Table 3-B-1—Assumed Reynolds Numbers for Various Meter Tube Sizes

Nominal Tube Diameter (inches)	Assumed Reynolds Number, Re_D
2	500,000
3	750,000
4	1,000,000
6	1,500,000
8	2,000,000
10	2,500,000
12	3,000,000
16	4,000,000
20	5,000,000
24	6 000,000
30	8,000,000

Table 3-B-2—Numeric Conversion Factor (F_n)

$$F_n = \frac{338.196 D^2 \beta^2}{\sqrt{1 - \beta^4}}$$

	Nominal Pipe Diameter										
	2 Inches			3 Inches				4 Inches			
β Ratio	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.200	38.531	50.902	57.844	71.620	93.219	113.86	127.43	134.51	160.03	198.18	219.44
0.220	46.639	61.614	70.017	86.692	112.84	137.82	154.25	162.82	193.70	239.89	265.63
0.240	55.532	73.362	83.367	103.22	134.35	164.10	183.66	193.86	230.63	285.63	316.27
0.260	65.214	86.152	97.902	121.22	157.77	192.71	215.69	227.66	270.85	335.43	371.41
0.280	75.693	99.995	113.63	140.70	183.13	223.68	250.34	264.24	314.37	389.33	431.09
0.300	86 978	114.90	130.57	161 67	210.43	257.02	287.67	303.63	361.23	447.37	495.36
0.320	99.080	130.89	148.74	184.17	239.71	292.79	327.69	345.88	411.50	509.62	564.29
0.340	112.02	147.98	168.16	208.21	271.00	331.01	370.47	391.04	465.22	576.15	637.96
0.360	125.80	166.19	188.86	233.83	304.35	371.75	416.07	439.16	522.47	647.06	716.47
0.380	140.46	185.55	210.86	261.08	339.81	415.06	464.54	490.32	583.34	722.44	799.94
0.400	156.01	206.10	234.21	289.99	377.44	461.02	515.98	544.62	647.94	802.44	888.52
0.420	172.49	227.87	258.95	320.62	417.31	509.72	570.48	602.15	716.38	887.20	982.38
0.440	189.93	250.91	285.13	353.04	459.51	561.26	628.17	663.04	788.83	976.92	1,081.7
0.460	208.38	275.29	312.83	387.34	504 15	615.78	689.20	727.45	865.45	1,071.8	1,186.8
0.480	227.89	301.06	342.12	423.60	551.34	673.43	753.71	795.55	946.47	1,172.2	1,297.9
0.500	248.52	328.31	373.08	461.93	601.24	734.38	821.93	867.55	1,032.1	1,278.2	1,415.4
0.520	270.33	357.12	405.83	502.48	654.02	798.84	894.07	943.70	1,122.7	1,390.4	1,539.6
0.540	293.42	387.62	440.49	545.39	709.87	867.06	970 43	1,024.3	1,218.6	1,509.2	1,671.1
0.560	317.87	419.93	477.21	590.85	769.05	939.33	1,051.3	1,109.7	1,320.2	1,635.0	1,810.4
0.580	343.82	454.21	516.16	639.09	831.82	1,016.0	1,137.1	1,200.3	1,428.0	1,768.5	1,958.2
0.600	371.40	490.64	557.56	690.35	898.54	1,097.5	1,228.4	1,296.5	1,542.5	1,910.3	2,115.2
0.620	400.78	529.45	601.66	744.95	969.62	1,184.3	1,325.5	1,399.1	1,664.5	2,061.4	2,282.5
0.640	432.15	570.90	648.77	803.27	1,045.5	1,277.0	1,429.3	1,508.6	1,794.8	2,222.8	2,461.2
0.660	465.78	615.32	699.24	865.77	1,126.9	1,376.4	1,540.5	1,626.0	1,934.5	2,395.7	2,652.7
0.680	501 94	663.10	753.54	932.99	1,214.4	1,483.3	1,660.1	1,752.2	2,084 7	2,581.7	2,858.7
0.700	541.02	714.73	812.21	1,005.6	1,308.9	1,598.8	1,789.4	1,888.7	2,247.0	2,782.8	3,081.3
0.720	583.48	770.82	875.95	1,084.6	1,411.6	1,724.2	1,929.8	2,036.9	2,423.3	3,001.1	3,323.1
0.740	629.90	832.14	945.63	1,170.8	1,523.9	1,861.4	2,083.3	2,198.9	2,616.1	3,239.9	3,587.5

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-2—(Continued)

$$F_n = \frac{338.196 D^2 \beta^2}{\sqrt{1 - \beta^4}}$$

Nominal Pipe Diameter

β Ratio	6 Inches				8 Inches			10 Inches			12 Inches		
	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.036	11.374	11.938	12.090
0.200	324.67	364.26	449.34	498.01	787.15	862.36	881.92	1,237.9	1,359.3	1,363.6	1,751.5	1,929.5	1,978.9
0.220	392.99	440.92	543.90	602.82	952.80	1,043.8	1,067.5	1,498.4	1,645.4	1,650.6	2,120.1	2,335.5	2,395.4
0.240	467.92	524.98	647.60	717.75	1,134.5	1,242.9	1,271.1	1,784.1	1,959.1	1,965.3	2,524.3	2,780.8	2,852.1
0.260	549.50	616.51	760.51	842.89	1,332.3	1,459.6	1,492.7	2,095.1	2,300.6	2,308.0	2,964.4	3,265.7	3,349.4
0.280	637.80	715.58	882.71	978.33	1,546.3	1,694.1	1,732.5	2,431.8	2,670.3	2,678.8	3,440.7	3,790.4	3,887.6
0 300	732.89	822.26	1,014.3	1,124.2	1,776.9	1,946.7	1,990.8	2,794.3	3,068.4	3,078.2	3,953.7	4,355.5	4,467.1
0 320	834.87	936.68	1,155.5	1,280.6	2,024.1	2,217.5	2,267.8	3,183.1	3,495.4	3,506.5	4,503.8	4,961.6	5,088.7
0.340	943.86	1,059.0	1,306.3	1,447.8	2,288.4	2,507.0	2,563.9	3,598.7	3,951.7	3,964.3	5,091.8	5,609.3	5,753.1
0.360	1,060.0	1,189.3	1,467.1	1,626.0	2,570.0	2,815.6	2,379.4	4,041.6	4,438.0	4,452.2	5,718.4	6.299.6	6,461.1
0.380	1,183.5	1,327.8	1,638.0	1,815.4	2,869.4	3,143.6	3,214.9	4,512.4	4,955.0	4,970.9	6,384.7	7,033.6	7,213.8
0.400	1,314.6	1,474.9	1,819.3	2,016.4	3,187.1	3,491.7	3,570.9	5,012.1	5,503.7	5,521.3	7,091.6	7,812.4	8,012.6
0.420	1,453.4	1,630.7	2,011.5	2,229.4	3,523.8	3,860.5	3,948.1	5,541.5	6,085.1	6,104.5	7,840.8	8,637.6	8,859.0
0.440	1,600.4	1,795.6	2,215.0	2,454.9	3,880.2	4,250.9	4,347.3	6,101.9	6,700.5	6,721.9	8,633.7	9,511.1	9,754.9
0.460	1,755.9	1,970.0	2,430.1	2,693.4	4,257.1	4,663.9	4,769.6	6,694.7	7,351.3	7,374.8	9,472.4	10,435.0	10,702.5
0.480	1,920.2	2,154.4	2,657.6	2,945.5	4,655.6	5,100.5	5,216.2	7,321.4	8,039.5	8,065.2	10,359.1	11,411.9	11,704.4
0.500	2,094.0	2,349.4	2,898.1	3,212.1	5,076.9	5,562.1	5,688.2	7,984.0	8,767.2	8,795.2	11,296.6	12,444.8	12,763.7
0.520	2,277.8	2,555.6	3,152.5	3,494.0	5,522.6	6,050.3	6,187.5	8,684.8	9,536.7	9,567.2	12,288.2	13,537.1	13,884.0
0.540	2,472.4	2,773.9	3,421.8	3,792.4	5,994.2	6,567.0	6,716.0	9,426.5	10,351.1	10,384.2	13,337.6	14,693.2	15,069.7
0.560	2,678.5	3,005.1	3,707.0	4,108.5	6,493.9	7,114.4	7,275.8	10,212.3	11,214.0	11,249.8	14,449.4	15,918.0	16,325.9
0.580	2,897.1	3,250.4	4,009.6	4,443.9	7,024.0	7,695.2	7,869.7	11,045.9	12,129.4	12,168.1	15,628.9	17,217.3	17,658.6
0.600	3,129.5	3,511.1	4,331.2	4,800.4	7,587.4	8,312.4	8,500.9	11,931.9	13,102.3	13,144.2	16,882.5	18,598.4	19,075.0
0.620	3,377.0	3,788.8	4,673.8	5,180.0	8,187.5	8,969.9	9,173.3	12,875.7	14,138.6	14,183.8	18,217.9	20,069.4	20,583.7
0.640	3,641.4	4,085.4	5,039.7	5,585.6	8,828.5	9,672.1	9,891.5	13,883.7	15,245.5	15,294.3	19,644.2	21,640.7	22,195.2
0 660	3,924.7	4,403.3	5,431.8	6,020.2	9,515.4	10,424.6	10,661.1	14,963.9	16,431.7	16,484.2	21,172.5	23,324.3	23,922.1
0 680	4,229.4	4,745.2	5,853.5	6,487.6	10,254.2	11,234.1	11,488.9	16,125.8	17,707.6	17,764.2	22,816.5	25,135.4	25,779.6
0 700	4,558.8	5,114.7	6,309.3	6,992.7	11,052.6	12,108.8	12,383.4	17,381.4	19,086.3	19,147.3	24,593.1	27,092.5	27,786.8
0.720	4,916.5	5,516.1	6,804.4	7,541.5	11,920.0	13,059.1	13,355.2	18,745.4	20,584.1	20,649.9	26,523.0	29,218.6	29,967.4
0.740	5,307.6	5,954.9	7,345.8	8,141.5	12,868.3	14,097.9	14,417.7	20,236.6	22,221.7	22,292.7	28,633.0	31,543.1	32,351.4

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-2—(Continued)

$$F_n = \frac{338.196 D^2 \beta^2}{\sqrt{1 - \beta^4}}$$

	Nominal Pipe Diameter											
	16 Inches			20 Inches			24 Inches			30 Inches		
β Ratio	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
0.200	2,920.8	3,046.2	3,148.6	4,791.2	4,887.5	5,016.9	6,929.7	7,162.0	7,318.5	11,190.6	11,386.0	11,583.2
0.220	3,535.5	3,687.3	3,811.2	5,799.5	5,916.0	6,072.7	8,388.1	8,669.2	8,858.7	13,545.6	13,782.2	14,020.9
0.240	4,209.6	4,390.3	4,537.9	6,905.3	7,044.0	7,230.6	9,987.4	10,322.1	10,547.7	16,128.3	16,410.0	16,694.2
0.260	4,943.5	5,155.8	5,329.0	8,109.2	8,272.1	8,491.2	11,728.7	12,121.8	12,386.7	18,940.2	19,271.1	19,604.8
0.280	5,737.8	5,984.2	6,185.3	9,412.2	9,601.3	9,855.6	13,613.3	14,069.5	14,377.0	21,983.6	22,367.6	22,754.9
0.300	6,593.3	6,876.4	7,107.5	10,815.5	11,032.8	11,325.0	15,642.9	16,167.1	16,520.5	25,261.1	25,702.4	26,147.4
0.320	7,510.7	7,833.2	8,096.5	12,320.5	12.568 0	12,900.9	17,819.5	18,416.8	18,819.3	28,776.2	29,278.8	29,785.8
0.340	8,491.3	8,855.9	9,153.5	13,928.9	14,208.7	14,585.1	20,145.9	20,821.1	21,276.2	32,533 0	33,101.2	33,674.4
0.360	9,536.2	9,945.7	10,280.0	15,643.1	15,957.3	16,380.0	22,625.1	23,383.4	23,894.5	36,536.5	37,174.7	37,818.4
0.380	10,647.2	11,104.4	11,477.6	17,465.5	17,816.3	18,288.3	25,261.0	26,107.6	26,678.3	40,793.1	41,505.7	42,224.4
0.400	11,826.2	12,334.0	12,748.5	19,399.5	19,789.2	20,313.3	28,058.1	28,998.5	29,632.3	45,310.2	46,101.6	46,899.9
0.420	13,075.5	13,636.9	14,095.2	21.448 7	21,879.6	22,459.1	31,022.0	32,061.8	32,762.5	50,096.5	50,971.5	51,854.1
0.440	14,397.8	15,015.9	15,520.6	23,617.8	24,092.2	24,730.4	34,159.2	35,304.1	36,075.7	55,162.6	56,126.2	57,098.0
0.460	15,796.3	16,474.6	17,028.3	25,912.0	26,432.5	27,132.7	37,477.5	38,733.5	39,580.1	60,521.1	61,578.3	62,644.5
0.480	17,275.1	18,016.8	18,622.4	28,337.8	28,907 0	29,672.7	40,985.9	42,359.5	43,285.4	66,186.8	67,342.8	68,508.9
0.500	18,838.6	19,647.4	20,307.8	30,902.5	31,523.2	32,358.2	44,695.3	46,193.3	47,202.9	72,177.0	73,437.7	74,709.3
0.520	20,492.2	21,372.0	22,090.3	33,615.0	34,290.2	35,198.5	48,618.5	50,248.0	51,346.2	78,512.4	79,883.8	81,267.0
0.540	22,242.2	23,197.2	23,976.9	36,485.7	37,218.6	38,204.5	52,770.6	54,539.2	55,731.2	85,217.5	86,705.9	88,207.3
0.560	24,096.3	25,130.8	25,975.5	39,527.1	40,321.0	41,389.1	57,169.3	59,085.4	60,376.8	92,320.9	93,933.5	95,560.0
0.580	26,063.2	27,182.3	28,095.9	42,753.6	43,612.4	44,767.7	61,836.1	63,908.5	65,305.4	99,857.1	101,601.3	103,360.6
0.600	28,153.8	29,362.6	30,349.5	46,182.9	47,110.6	48,358.5	66,796.0	69,034.7	70,543.6	107,866.7	109,750.8	111,651.2
0.620	30,380.7	31,685.0	32,750.0	49,835.8	50,836.9	52,183.5	72,079.3	74,495.1	76,123.3	116,398.5	118,431.6	120,482.4
0.640	32,759.1	34,165.7	35,314.0	53,737.5	54,816.9	56,268.9	77,722.4	80,327.3	82,083.0	125,511.3	127,703.6	129,914.9
C.560	35,307.9	36,823.8	38,061.5	57,918.3	59,081.7	60,646.8	83,769.3	86,576.8	88,469.2	135,276.3	137,639.2	140,022.5
0.680	38,049.5	39,683.1	41,016.9	62,415.6	63,669.4	65,355.9	90,273 9	93,299.5	95,338.7	145,780.4	148,326.8	150,895.1
0.700	41,012.1	42,772.9	44,210.6	67,275 4	68,626.8	70,444.6	97,302 7	100,563.9	102,761.9	157,131.0	159,875.6	162,644.0
0.720	44,230.5	46,129.6	47,680.0	72,554.9	74,012 4	75,972.9	104,938.7	108,455.8	110,826.3	169,462.1	172,422.1	175,407.7
0.740	47,749.2	49,799.3	51,473.2	78,326.9	79,900.3	82,016.8	113.287.0	117,083.8	119,642.9	182,943 4	186,138.9	189,362.0

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-3—Orifice Calculation Factor: F_c From Equations in 3-B.5

	Nominal Pipe Diameter										
	2 Inches (Re_D = 500,000)			3 Inches (Re_D = 750,000)				4 Inches (Re_D = 1,000,000)			
β Ratio	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.200	0.59879	0.59828	0.59801	0.59752	0.59683	0.59646	0.59649	0.59651	0.59655	0.59661	0.59663
0.220	0.59884	0.59836	0.59810	0.59763	0.59697	0.59662	0.59665	0.59667	0.59672	0.59678	0.59681
0.240	0.59892	0.59846	0.59822	0.59777	0.59713	0.59680	0.59684	0.59686	0.59691	0.59698	0.59701
0.250	0.59903	0.59860	0.59837	0.59794	0.59733	0.59701	0.59705	0.59707	0.59713	0.59720	0.59723
0.280	0.59918	0.59876	0.59855	0.59814	0.59755	0.59725	0.59730	0.59732	0.59738	0.59745	0.59749
0.300	0.59935	0.59896	0.59875	0.59836	0.59780	0.59752	0.59757	0.59759	0.59766	0.59773	0.59777
0.320	0.59956	0.59919	0.59899	0.59862	0.59809	0.59782	0.59787	0.59789	0.59796	0.59804	0.59808
0.340	0.59980	0.59946	0.59927	0.59892	0.59841	0.59815	0.59820	0.59823	0.59830	0.59839	0.59842
0.360	0.60009	0.59976	0.59959	0.59925	0.59877	0.59852	0.59857	0.59860	0.59867	0.59876	0.59880
0.380	0.60041	0.60011	0.59994	0.59962	0.59916	0.59893	0.59898	0.59900	0.59908	0.59917	0.59920
0.400	0.60079	0.60050	0.60034	0.60004	0.59959	0.59937	0.59943	0.59945	0.59952	0.59961	0.59965
0.420	0.60121	0.60093	0.60078	0.60050	0.60007	0.59986	0.59991	0.59993	0.60001	0.60009	0.60012
0.440	0.60168	0.60142	0.60128	0.60100	0.60059	0.60039	0.60044	0.60046	0.60053	0.60061	0.60064
0.460	0.60221	0.60196	0.60182	0.60156	0.60116	0.60097	0.60101	0.60103	0.60110	0.60117	0.60120
0.480	0.60281	0.60256	0.60243	0.60217	0.60179	0.60159	0.60163	0.60165	0.60171	0.60177	0.60180
0.500	0.60347	0.60323	0.60309	0.60284	0.60246	0.60227	0.60231	0.60232	0.60237	0.60242	0.60244
0.520	0.60420	0.60396	0.60383	0.60358	0.60320	0.60301	0.60303	0.60305	0.60308	0.60312	0.60313
0.540	0.60502	0.60477	0.60463	0.60438	0.60400	0.60380	0.60382	0.60383	0.60385	0.60386	0.60387
0.560	0.60592	0.60566	0.60552	0.60526	0.60488	0.60466	0.60467	0.60467	0.60467	0.60467	0.60466
0.580	0.60693	0.60664	0.60650	0.60623	0.60583	0.60560	0.60559	0.60559	0.60556	0.60553	0.60551
0.600	0.60805	0.60773	0.60757	0.60729	0.60686	0.60661	0.60658	0.60657	0.60652	0.60645	0.60641
0.620	0.60929	0.60894	0.60876	0.60845	0.60800	0.60772	0.60767	0.60764	0.60756	0.60744	0.60739
0.640	0.61069	0.61028	0.61008	0.60974	0.60924	0.60892	0.60884	0.60881	0.60868	0.60852	0.60844
0.660	0.61226	0.61178	0.61155	0.61116	0.61060	0.61024	0.61013	0.61008	0.60990	0.60968	0.60957
0.680	0.61404	0.61347	0.61320	0.61275	0.61212	0.61169	0.61154	0.61147	0.61123	0.61093	0.61079
0.700	0.61608	0.61538	0.61506	0.61454	0.61380	0.61330	0.61310	0.61302	0.61270	0.61231	0.61213
0.720	0.61842	0.61758	0.61719	0.61657	0.61571	0.61511	0.61485	0.61474	0.61433	0.61384	0.61360
0.740	0.62117	0.62012	0.61965	0.61890	0.61788	0.61716	0.61683	0.61668	0.61617	0.61554	0.61524

Note: Assumed values of Re_D are used in this table. These may induce an error greater than 0.01 percent for line sizes less than 4 inches with β ratios greater than 0.60. This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R

Table 3-B-3—Continued

	Nominal Pipe Diameter												
	6 Inches (Re_D = 1,500,000)				8 Inches (Re_D = 2,000,000)			10 Inches (Re_D = 2,500,000)			12 Inches (Re_D = 3,000,000)		
β Ratio	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.036	11.374	11.938	12.090
0.200	0.59672	0.59674	0.59679	0.59680	0.59688	0.59689	0.59690	0.59695	0.59696	0.59696	0.59699	0.59700	0.59700
0.220	0.59690	0.59693	0.59698	0.59700	0.59708	0.59710	0.59710	0.59715	0.59717	0.59717	0.59720	0.59721	0.59722
0.240	0.59711	0.59714	0.59719	0.59721	0.59731	0.59732	0.59733	0.59738	0.59740	0.59740	0.59744	0.59745	0.59745
0.260	0.59735	0.59738	0.59743	0.59746	0.59756	0.59757	0.59758	0.59764	0.59766	0.59766	0.59770	0.59771	0.59771
0.280	0.59761	0.59764	0.59770	0.59772	0.59783	0.59785	0.59785	0.59792	0.59794	0.59794	0.59798	0.59799	0.59800
0.300	0.59790	0.59793	0.59799	0.59802	0.59813	0.59815	0.59815	0.59822	0.59824	0.59824	0.59829	0.59830	0.59831
0.320	0.59821	0.59825	0.59831	0.59834	0.59845	0.59847	0.59848	0.59855	0.59857	0.59857	0.59862	0.59864	0.59864
0.340	0.59856	0.59859	0.59866	0.59869	0.59880	0.59883	0.59883	0.59891	0.59893	0.59893	0.59897	0.59899	0.59900
0.360	0.59893	0.59897	0.59903	0.59906	0.59916	0.59921	0.59921	0.59929	0.59931	0.59931	0.59936	0.59937	0.59938
0.380	0.59934	0.59938	0.59944	0.59947	0.59959	0.59961	0.59962	0.59969	0.59971	0.59971	0.59976	0.59978	0.59979
0.400	0.59978	0.59982	0.59988	0.59991	0.60002	0.60005	0.60005	0.60013	0.60015	0.60015	0.60020	0.60021	0.60022
0.420	0.60025	0.60029	0.60035	0.60037	0.60049	0.60051	0.60051	0.60058	0.60060	0.60060	0.60065	0.60067	0.60068
0.440	0.60076	0.60079	0.60085	0.60087	0.60098	0.60100	0.60100	0.60107	0.60109	0.60109	0.60114	0.60115	0.60116
0.460	0.60131	0.60133	0.60138	0.60141	0.60150	0.60152	0.60152	0.60158	0.60160	0.60160	0.60164	0.60166	0.60167
0.480	0.60189	0.60191	0.60195	0.60197	0.60205	0.60207	0.60207	0.60212	0.60214	0.60214	0.60218	0.60219	0.60220
0.500	0.60251	0.60253	0.60256	0.60257	0.60263	0.60264	0.60265	0.60269	0.60270	0.60270	0.60274	0.60275	0.60275
0.520	0.60317	0.60318	0.60320	0.60321	0.60324	0.60325	0.60325	0.60328	0.60329	0.60329	0.60332	0.60333	0.60333
0.540	0.60388	0.60388	0.60388	0.60388	0.60389	0.60389	0.60389	0.60390	0.60391	0.60391	0.60392	0.60393	0.60393
0.560	0.60463	0.60462	0.60460	0.60459	0.60456	0.60456	0.60456	0.60455	0.60455	0.60455	0.60455	0.60456	0.60456
0.580	0.60543	0.60540	0.60536	0.60534	0.60527	0.60525	0.60525	0.60522	0.60521	0.60521	0.60520	0.60520	0.60520
0.600	0.60627	0.60623	0.60616	0.60613	0.60600	0.60598	0.60598	0.60591	0.60590	0.60590	0.60587	0.60587	0.60586
0.620	0.60718	0.60712	0.60701	0.60696	0.60677	0.60674	0.60673	0.60663	0.60661	0.60661	0.60656	0.60655	0.60654
0.640	0.60814	0.60805	0.60791	0.60784	0.60757	0.60753	0.60752	0.60737	0.60734	0.60734	0.60727	0.60724	0.60724
0.660	0.60917	0.60905	0.60885	0.60876	0.60841	0.60835	0.60833	0.60814	0.60809	0.60809	0.60799	0.60795	0.60794
0.680	0.61027	0.61012	0.60986	0.60974	0.60928	0.60920	0.60918	0.60892	0.60886	0.60886	0.60872	0.60867	0.60866
0.700	0.61146	0.61127	0.61094	0.61078	0.61019	0.61009	0.61006	0.60973	0.60965	0.60965	0.60947	0.60940	0.60939
0.720	0.61275	0.61251	0.61209	0.61190	0.61115	0.61102	0.61098	0.61056	0.61046	0.61046	0.61022	0.61014	0.61012
0.740	0.61417	0.61387	0.61334	0.61310	0.61216	0.61199	0.61196	0.61143	0.61130	0.61129	0.61099	0.61089	0.61086

Note: Assumed values of Re_D are used in this table. These may induce an error greater than 0.01 percent for line sizes less than 4 inches with β ratios greater than 0.60. This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-3—Continued

β Ratio	Nominal Pipe Diameter											
	16 Inches (Re_D = 4,000,000)			20 Inches (Re_D = 5,000,000)			24 Inches (Re_D = 6,000,000)			30 Inches (Re_D = 8,000,000)		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
0.200	0.59704	0.59705	0.59705	0.59708	0.59709	0.59709	0.59711	0.59711	0.59711	0.59714	0.59714	0.59714
0.220	0.59726	0.59726	0.59727	0.59731	0.59731	0.59731	0.59734	0.59734	0.59734	0.59737	0.59737	0.59737
0.240	0.59750	0.59751	0.59751	0.59755	0.59756	0.59756	0.59759	0.59759	0.59759	0.59762	0.59762	0.59762
0.260	0.59777	0.59777	0.59778	0.59782	0.59782	0.59783	0.59786	0.59786	0.59786	0.59790	0.59790	0.59790
0.280	0.59805	0.59806	0.59806	0.59812	0.59812	0.59812	0.59815	0.59816	0.59816	0.59820	0.59820	0.59820
0.300	0.59837	0.59837	0.59838	0.59843	0.59843	0.59844	0.59847	0.59848	0.59848	0.59852	0.59852	0.59852
0.320	0.59870	0.59871	0.59871	0.59877	0.59877	0.59878	0.59881	0.59882	0.59882	0.59886	0.59886	0.59887
0.340	0.59906	0.59907	0.59907	0.59913	0.59914	0.59914	0.59918	0.59918	0.59919	0.59923	0.59923	0.59923
0.360	0.59945	0.59945	0.59946	0.59952	0.59952	0.59953	0.59957	0.59957	0.59958	0.59962	0.59962	0.59963
0.380	0.59986	0.59986	0.59987	0.59993	0.59993	0.59994	0.59998	0.59998	0.59999	0.60004	0.60004	0.60004
0.400	0.60029	0.60029	0.60030	0.60036	0.60037	0.60037	0.60041	0.60042	0.60042	0.60047	0.60047	0.60048
0.420	0.60074	0.60075	0.60076	0.60082	0.60082	0.60083	0.60087	0.60088	0.60088	0.60093	0.60093	0.60093
0.440	0.60122	0.60123	0.60124	0.60130	0.60130	0.60131	0.60135	0.60136	0.60136	0.60141	0.60141	0.60141
0.460	0.60173	0.60174	0.60174	0.60180	0.60181	0.60181	0.60185	0.60186	0.60186	0.60191	0.60191	0.60192
0.480	0.60226	0.60226	0.60227	0.60233	0.60233	0.60233	0.60237	0.60238	0.60238	0.60243	0.60243	0.60244
0.500	0.60281	0.60281	0.60282	0.60287	0.60287	0.60288	0.60292	0.60292	0.60292	0.60297	0.60297	0.60298
0.520	0.60338	0.60338	0.60338	0.60343	0.60344	0.60344	0.60348	0.60348	0.60348	0.60353	0.60353	0.60353
0.540	0.60397	0.60397	0.60397	0.60402	0.60402	0.60402	0.60405	0.60406	0.60406	0.60410	0.60410	0.60411
0.560	0.60458	0.60458	0.60458	0.60461	0.60461	0.60462	0.60465	0.60465	0.60465	0.60469	0.60469	0.60469
0.580	0.60520	0.60521	0.60521	0.60523	0.60523	0.60523	0.60525	0.60525	0.60525	0.60529	0.60529	0.60529
0.600	0.60585	0.60585	0.60585	0.60585	0.60585	0.60585	0.60586	0.60587	0.60587	0.60589	0.60589	0.60590
0.620	0.60650	0.60650	0.60650	0.60648	0.60648	0.60648	0.60648	0.60649	0.60649	0.60650	0.60650	0.60650
0.640	0.60717	0.60716	0.60716	0.60712	0.60712	0.60712	0.60711	0.60711	0.60711	0.60711	0.60711	0.60711
0.660	0.60784	0.60783	0.60782	0.60776	0.60776	0.60775	0.60773	0.60773	0.60773	0.60772	0.60772	0.60772
0.680	0.60851	0.60850	0.60849	0.60839	0.60839	0.60838	0.60834	0.60834	0.60834	0.60831	0.60831	0.60831
0.700	0.60919	0.60917	0.60916	0.60902	0.60901	0.60901	0.60894	0.60894	0.60893	0.60889	0.60889	0.60888
0.720	0.60986	0.60984	0.60982	0.60963	0.60963	0.60962	0.60952	0.60952	0.60951	0.60944	0.60944	0.60943
0.740	0.61053	0.61049	0.61047	0.61023	0.61022	0.61021	0.61008	0.61007	0.61006	0.60996	0.60996	0.60995

Note: Assumed values of Re_D are used in thus table. These may induce an error greater than 0.01 percent for line sizes less than 4 inches with β ratios greater than 0.60. This table was developed for informational purposes only and is specific to the following conditions: $T_f = 68°F$; $G_r = 0.6$; $\mu = 0.000069$; $k = 1.3$; $P_b = 14.73$; and $T_b = 519.67°R$.

Table 3-B-4—Orifice Slope Factor: F_{sl} From Equations in 3-B.6

	β Ratio													
$Re_D/10^6$	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.44	0.46
0.020	0.00270	0.00294	0.00320	0.00348	0.00379	0.00413	0.00450	0.00492	0.00539	0.00591	0.00650	0.00716	0.00790	0.00873
0.030	0.00205	0.00224	0.00244	0.00266	0.00291	0.00318	0.00348	0.00382	0.00420	0.00463	0.00511	0.00565	0.00626	0.00694
0.040	0.00168	0.00184	0.00201	0.00220	0.00241	0.00264	0.00291	0.00320	0.00353	0.00390	0.00432	0.00480	0.00533	0.00593
0.050	0.00145	0.00159	0.00174	0.00190	0.00209	0.00230	0.00253	0.00279	0.00309	0.00342	0.00380	0.00423	0.00471	0.00525
0.060	0.00128	0.00140	0.00154	0.00169	0.00186	0.00205	0.00226	0.00250	0.00277	0.00308	0.00343	0.00383	0.00427	0.00477
0.070	0.00115	0.00127	0.00139	0.00153	0.00169	0.00186	0.00206	0.00228	0.00254	0.00282	0.00315	0.00352	0.00393	0.00440
0.080	0.00105	0.00116	0.00128	0.00140	0.00155	0.00171	0.00190	0.00211	0.00235	0.00262	0.00292	0.00327	0.00366	0.00410
0.090	0.00097	0.00107	0.00118	0.00130	0.00144	0.00159	0.00177	0.00197	0.00219	0.00245	0.00274	0.00307	0.00344	0.00386
0.100	0.00091	0.00100	0.00110	0.00122	0.00135	0.00149	0.00166	0.00185	0.00206	0.00231	0.00259	0.00290	0.00326	0.00366
0.150	0.00069	0.00076	0.00085	0.00094	0.00105	0.00117	0.00130	0.00146	0.00164	0.00185	0.00208	0.00235	0.00265	0.00299
0.200	0.00057	0.00063	0.00070	0.00078	0.00088	0.00098	0.00110	0.00124	0.00140	0.00158	0.00179	0.00203	0.00230	0.00260
0.250	0.00049	0.00055	0.00061	0.00068	0.00077	0.00086	0.00097	0.00110	0.00124	0.00141	0.00160	0.00181	0.00206	0.00233
0.300	0.00044	0.00049	0.00054	0.00061	0.00069	0.00077	0.00087	0.00099	0.00112	0.00128	0.00145	0.00166	0.00188	0.00214
0.350	0.00039	0.00044	0.00049	0.00055	0.00063	0.00071	0.00080	0.00091	0.00104	0.00118	0.00135	0.00153	0.00175	0.00199
0.400	0.00036	0.00040	0.00045	0.00051	0.00058	0.00065	0.00074	0.00085	0.00097	0.00110	0.00126	0.00144	0.00164	0.00187
0.450	0.00033	0.00038	0.00042	0.00048	0.00054	0.00061	0.00070	0.00079	0.00091	0.00104	0.00119	0.00136	0.00155	0.00177
0.500	0.00031	0.00035	0.00039	0.00045	0.00051	0.00058	0.00066	0.00075	0.00086	0.00098	0.00113	0.00129	0.00148	0.00169
0.600	0.00028	0.00031	0.00035	0.00040	0.00045	0.00052	0.00059	0.00068	0.00078	0.00090	0.00103	0.00119	0.00136	0.00156
0.700	0.00025	0.00028	0.00032	0.00036	0.00042	0.00048	0.00055	0.00063	0.00072	0.00083	0.00096	0.00110	0.00127	0.00145
0.800	0.00023	0.00026	0.00030	0.00034	0.00039	0.00044	0.00051	0.00059	0.00068	0.00078	0.00090	0.00104	0.00119	0.00137
0.900	0.00021	0.00024	0.00028	0.00031	0.00036	0.00041	0.00048	0.00055	0.00064	0.00074	0.00085	0.00098	0.00113	0.00130
1.000	0.00020	0.00023	0.00026	0.00030	0.00034	0.00039	0.00045	0.00052	0.00060	0.00070	0.00081	0.00094	0.00108	0.00124
1.500	0.00015	0.00018	0.00020	0.00023	0.00027	0.00031	0.00036	0.00043	0.00050	0.00058	0.00067	0.00078	0.00090	0.00104
2.000	0.00013	0.00015	0.00017	0.00020	0.00023	0.00027	0.00031	0.00037	0.00043	0.00050	0.00059	0.00069	0.00080	0.00092
2.500	0.00011	0.00013	0.00015	0.00017	0.00020	0.00024	0.00028	0.00033	0.00039	0.00046	0.00053	0.00062	0.00072	0.00084
3.000	0.00010	0.00012	0.00013	0.00016	0.00019	0.00022	0.00026	0.00030	0.00036	0.00042	0.00049	0.00057	0.00067	0.00078
3.500	0.00009	0.00011	0.00012	0.00014	0.00017	0.00020	0.00024	0.00028	0.00033	0.00039	0.00046	0.00054	0.00063	0.00073
4.000	0.00008	0.00010	0.00011	0.00013	0.00016	0.00019	0.00022	0.00026	0.00031	0.00037	0.00043	0.00051	0.00059	0.00069
4.500	0.00008	0.00009	0.00011	0.00013	0.00015	0.00018	0.00021	0.00025	0.00030	0.00035	0.00041	0.00048	0.00057	0.00066
5.000	0.00007	0.00009	0.00010	0.00012	0.00014	0.00017	0.00020	0.00024	0.00028	0.00033	0.00039	0.00046	0.00054	0.00063
5.500	0.00007	0.00008	0.00010	0.00011	0.00013	0.00016	0.00019	0.00023	0.00027	0.00032	0.00038	0.00044	0.00052	0.00061
6.000	0.00007	0.00008	0.00009	0.00011	0.00013	0.00015	0.00018	0.00022	0.00026	0.00031	0.00036	0.00043	0.00050	0.00059
6.500	0.00006	0.00007	0.00009	0.00010	0.00012	0.00015	0.00018	0.00021	0.00025	0.00030	0.00035	0.00041	0.00049	0.00057
7.000	0.00006	0.00007	0.00008	0.00010	0.00012	0.00014	0.00017	0.00020	0.00024	0.00029	0.00034	0.00040	0.00047	0.00055
7.500	0.00006	0.00007	0.00008	0.00010	0.00011	0.00014	0.00017	0.00020	0.00024	0.00028	0.00033	0.00039	0.00046	0.00054
8.000	0.00005	0.00007	0.00008	0.00009	0.00011	0.00013	0.00016	0.00019	0.00023	0.00027	0.00032	0.00038	0.00045	0.00052
8.500	0.00005	0.00006	0.00008	0.00009	0.00011	0.00013	0.00016	0.00019	0.00022	0.00027	0.00031	0.00037	0.00044	0.00051
9.000	0.00005	0.00006	0.00007	0.00009	0.00010	0.00013	0.00015	0.00018	0.00022	0.00026	0.00031	0.00036	0.00043	0.00050
9.500	0.00005	0.00006	0.00007	0.00008	0.00010	0.00012	0.00015	0.00018	0.00021	0.00025	0.00030	0.00035	0.00042	0.00049
10.000	0.00005	0.00006	0.00007	0.00008	0.00010	0.00012	0.00014	0.00017	0.00021	0.00025	0.00029	0.00035	0.00041	0.00048
12.000	0.00004	0.00005	0.00006	0.00008	0.00009	0.00011	0.00013	0.00016	0.00019	0.00023	0.00027	0.00032	0.00038	0.00045
15.000	0.00004	0.00005	0.00006	0.00007	0.00008	0.00010	0.00012	0.00014	0.00017	0.00021	0.00025	0.00030	0.00035	0.00041
18.000	0.00003	0.00004	0.00005	0.00006	0.00007	0.00009	0.00011	0.00013	0.00016	0.00019	0.00023	0.00027	0.00032	0.00038
21.000	0.00003	0.00004	0.00005	0.00006	0.00007	0.00008	0.00010	0.00013	0.00015	0.00018	0.00022	0.00026	0.00031	0.00036
24.000	0.00003	0.00004	0.00004	0.00005	0.00007	0.00008	0.00010	0.00012	0.00014	0.00017	0.00021	0.00025	0.00029	0.00034
27.000	0.00003	0.00003	0.00004	0.00005	0.00006	0.00008	0.00009	0.00011	0.00014	0.00016	0.00020	0.00023	0.00028	0.00033
30.000	0.00003	0.00003	0.00004	0.00005	0.00006	0.00007	0.00009	0.00011	0.00013	0.00016	0.00019	0.00022	0.00027	0.00031

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F, G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-4—(Continued)

	β Ratio													
$Re_D/10^6$	0.48	0.50	0.52	0.54	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.70	0.72	0.74
0.020	0.00966	0.01069	0.01184	0.01312	0.01453	0.01609	0.01782	0.01972	0.02181	0.02409	0.02659	0.02932	0.03229	0.03552
0.030	0.00770	0.00856	0.00951	0.01056	0.01173	0.01302	0.01445	0.01601	0.01774	0.01962	0.02168	0.02393	0.02638	0.02904
0.040	0.00659	0.00734	0.00818	0.00910	0.01013	0.01126	0.01252	0.01389	0.01541	0.01706	0.01887	0.02085	0.02300	0.02533
0.050	0.00586	0.00654	0.00729	0.00813	0.00906	0.01009	0.01123	0.01248	0.01385	0.01536	0.01700	0.01879	0.02074	0.02286
0.060	0.00533	0.00596	0.00665	0.00743	0.00829	0.00925	0.01030	0.01145	0.01272	0.01412	0.01564	0.01729	0.01910	0.02106
0.070	0.00492	0.00551	0.00616	0.00689	0.00770	0.00859	0.00958	0.01066	0.01186	0.01316	0.01459	0.01614	0.01783	0.01967
0.080	0.00460	0.00515	0.00577	0.00646	0.00723	0.00807	0.00901	0.01003	0.01116	0.01239	0.01374	0.01522	0.01682	0.01855
0.090	0.00434	0.00486	0.00545	0.00611	0.00684	0.00764	0.00853	0.00951	0.01059	0.01176	0.01305	0.01445	0.01598	0.01763
0.100	0.00411	0.00462	0.00518	0.00581	0.00651	0.00728	0.00813	0.00907	0.01010	0.01123	0.01246	0.01381	0.01527	0.01686
0.150	0.00337	0.00380	0.00428	0.00482	0.00541	0.00607	0.00679	0.00759	0.00847	0.00943	0.01048	0.01163	0.01287	0.01422
0.200	0.00294	0.00332	0.00375	0.00423	0.00476	0.00535	0.00600	0.00671	0.00750	0.00836	0.00930	0.01032	0.01144	0.01265
0.250	0.00265	0.00300	0.00339	0.00383	0.00432	0.00486	0.00545	0.00611	0.00683	0.00762	0.00848	0.00942	0.01045	0.01156
0.300	0.00243	0.00276	0.00313	0.00354	0.00399	0.00449	0.00505	0.00566	0.00633	0.00707	0.00788	0.00876	0.00971	0.01075
0.350	0.00227	0.00258	0.00292	0.00331	0.00373	0.00421	0.00475	0.00531	0.00595	0.00664	0.00741	0.00824	0.00914	0.01012
0.400	0.00213	0.00243	0.00276	0.00312	0.00353	0.00398	0.00448	0.00503	0.00563	0.00630	0.00702	0.00781	0.00867	0.00960
0.450	0.00202	0.00230	0.00262	0.00297	0.00336	0.00379	0.00427	0.00480	0.00537	0.00601	0.00670	0.00746	0.00828	0.00917
0.500	0.00193	0.00220	0.00250	0.00284	0.00321	0.00363	0.00409	0.00460	0.00515	0.00576	0.00643	0.00716	0.00795	0.00881
0.600	0.00178	0.00203	0.00231	0.00263	0.00298	0.00337	0.00380	0.00427	0.00479	0.00536	0.00599	0.00667	0.00741	0.00821
0.700	0.00166	0.00190	0.00217	0.00247	0.00280	0.00316	0.00357	0.00402	0.00451	0.00505	0.00564	0.00628	0.00698	0.00774
0.800	0.00157	0.00180	0.00205	0.00233	0.00265	0.00300	0.00338	0.00381	0.00428	0.00479	0.00535	0.00597	0.00663	0.00736
0.900	0.00149	0.00171	0.00195	0.00222	0.00252	0.00286	0.00323	0.00364	0.00409	0.00458	0.00512	0.00570	0.00634	0.00703
1.000	0.00143	0.00163	0.00187	0.00213	0.00242	0.00274	0.00310	0.00349	0.00392	0.00439	0.00491	0.00548	0.00609	0.00676
1.500	0.00120	0.00138	0.00158	0.00181	0.00206	0.00233	0.00264	0.00298	0.00335	0.00376	0.00421	0.00470	0.00523	0.00581
2.000	0.00107	0.00123	0.00141	0.00161	0.00184	0.00209	0.00236	0.00267	0.00301	0.00337	0.00378	0.00422	0.00470	0.00522
2.500	0.00097	0.00112	0.00129	0.00147	0.00168	0.00191	0.00217	0.00245	0.00276	0.00310	0.00347	0.00388	0.00432	0.00480
3.000	0.00090	0.00104	0.00120	0.00137	0.00157	0.00178	0.00202	0.00229	0.00258	0.00290	0.00325	0.00363	0.00404	0.00449
3.500	0.00085	0.00098	0.00113	0.00129	0.00148	0.00168	0.00191	0.00216	0.00243	0.00274	0.00307	0.00343	0.00382	0.00425
4.000	0.00080	0.00093	0.00107	0.00123	0.00140	0.00160	0.00181	0.00205	0.00232	0.00260	0.00292	0.00326	0.00364	0.00404
4.500	0.00077	0.00089	0.00102	0.00117	0.00134	0.00153	0.00174	0.00196	0.00222	0.00249	0.00279	0.00312	0.00348	0.00387
5.000	0.00073	0.00085	0.00098	0.00113	0.00129	0.00147	0.00167	0.00189	0.00213	0.00240	0.00269	0.00301	0.00335	0.00373
5.500	0.00071	0.00082	0.00094	0.00109	0.00124	0.00142	0.00161	0.00182	0.00206	0.00231	0.00260	0.00290	0.00324	0.00360
6.000	0.00068	0.00079	0.00091	0.00105	0.00120	0.00137	0.00156	0.00176	0.00199	0.00224	0.00251	0.00281	0.00314	0.00349
6.500	0.00066	0.00077	0.00089	0.00102	0.00117	0.00133	0.00151	0.00171	0.00193	0.00218	0.00244	0.00273	0.00305	0.00339
7.000	0.00064	0.00075	0.00086	0.00099	0.00113	0.00129	0.00147	0.00167	0.00188	0.00212	0.00238	0.00266	0.00296	0.00330
7.500	0.00063	0.00073	0.00084	0.00096	0.00110	0.00126	0.00143	0.00162	0.00183	0.00206	0.00232	0.00259	0.00289	0.00322
8.000	0.00061	0.00071	0.00082	0.00094	0.00108	0.00123	0.00140	0.00159	0.00179	0.00202	0.00226	0.00253	0.00282	0.00314
8.500	0.00060	0.00069	0.00080	0.00092	0.00105	0.00120	0.00137	0.00155	0.00175	0.00197	0.00221	0.00248	0.00276	0.00307
9.000	0.00058	0.00068	0.00078	0.00090	0.00103	0.00118	0.00134	0.00152	0.00172	0.00193	0.00217	0.00243	0.00271	0.00301
9.500	0.00057	0.00066	0.00077	0.00088	0.00101	0.00115	0.00131	0.00149	0.00168	0.00189	0.00213	0.00238	0.00265	0.00295
10.000	0.00056	0.00065	0.00075	0.00086	0.00099	0.00113	0.00129	0.00146	0.00165	0.00186	0.00209	0.00233	0.00260	0.00290
12.000	0.00052	0.00061	0.00070	0.00081	0.00093	0.00106	0.00120	0.00137	0.00154	0.00174	0.00195	0.00219	0.00244	0.00271
15.000	0.00048	0.00056	0.00064	0.00074	0.00085	0.00097	0.00111	0.00126	0.00142	0.00160	0.00180	0.00202	0.00225	0.00251
18.000	0.00045	0.00052	0.00060	0.00069	0.00080	0.00091	0.00104	0.00118	0.00133	0.00150	0.00169	0.00189	0.00211	0.00235
21.000	0.00042	0.00049	0.00057	0.00065	0.00075	0.00086	0.00098	0.00111	0.00126	0.00142	0.00159	0.00179	0.00199	0.00222
24.000	0.00040	0.00047	0.00054	0.00062	0.00072	0.00082	0.00093	0.00106	0.00120	0.00135	0.00152	0.00170	0.00190	0.00212
27.000	0.00038	0.00045	0.00052	0.00060	0.00069	0.00078	0.00089	0.00102	0.00115	0.00130	0.00146	0.00163	0.00182	0.00203
30.000	0.00037	0.00043	0.00050	0.00057	0.00066	0.00076	0.00086	0.00098	0.00111	0.00125	0.00140	0.00157	0.00175	0.00195

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-5—Conversion of $Re_D/10^6$ to $Q_v/1000$ (Q_v in Thousands of Cubic Feet per Hour): $Q_v/1000 = Re_D/1000D/28.2435$

	Nominal Pipe Diameter										
	2 Inches			3 Inches				4 Inches			
$Re_D/10^6$	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.020	1.2	1.4	1.5	1.6	1.9	2.1	2.2	2.2	2.4	2.7	2.9
0.030	1.8	2.1	2.2	2.4	2.8	3.1	3.3	3.3	3.7	4.1	4.3
0.040	2.4	2.7	2.9	3.3	3.7	4.1	4.3	4.5	4.9	5.4	5.7
0.050	3.0	3.4	3.7	4.1	4.6	5.1	5.4	5.6	6.1	6.8	7.1
0.060	3.6	4.1	4.4	4.9	5.6	6.2	6.5	6.7	7.3	8.1	8.6
0.070	4.2	4.8	5.1	5.7	6.5	7.2	7.6	7.8	8.5	9.5	10.0
0.080	4.8	5.5	5.9	6.5	7.4	8.2	8.7	8.9	9.7	10.8	11.4
0.090	5.4	6.2	6.6	7.3	8.4	9.2	9.8	10.0	11.0	12.2	12.8
0.100	6.0	6.9	7.3	8.1	9.3	10.3	10.9	11.2	12.2	13.5	14.3
0.150	9.0	10.3	11.0	12.2	13.9	15.4	16.3	16.7	18.3	20.3	21.4
0.200	11.9	13.7	14.6	16.3	18.6	20.5	21.7	22.3	24.3	27.1	28.5
0.250	14.9	17.2	18.3	20.4	23.2	25.7	27.2	27.9	30.4	33.9	35.6
0.300	17.9	20.6	22.0	24.4	27.9	30.8	32.6	33.5	36.5	40.6	42.8
0.350	20.9	24.0	25.6	28.5	32.5	35.9	38.0	39.1	42.6	47.4	49.9
0.400	23.9	27.5	29.3	32.6	37.2	41.1	43.5	44.6	48.7	54.2	57.0
0.450	26.9	30.9	32.9	36.6	41.8	46.2	48.9	50.2	54.8	61.0	64.1
0.500	29.9	34.3	36.6	40.7	46.5	51.3	54.3	55.8	60.9	67.7	71.3
0.600	35.8	41.2	43.9	48.9	55.7	61.6	65.2	67.0	73.0	81.3	85.5
0.700	41.8	48.1	51.2	57.0	65.0	71.9	76.0	78.1	85.2	94.8	99.8
0.800	47.8	54.9	58.5	65.	74.3	82.1	86.9	89.3	97.4	108	114
0.900	53.8	61.8	65.9	73.3	83.6	92.4	97.8	100	110	122	128
1.000	59.7	68.7	73.2	81.4	92.9	103	109	112	122	135	143
1.500	89.6	103	110	122	139	154	163	167	183	203	214
2.000	119	137	146	163	186	205	217	223	243	271	285
2.500	149	172	183	204	232	257	272	279	304	339	356
3.000	179	206	220	244	279	308	326	335	365	406	428
3.500	209	240	256	285	325	359	380	391	426	474	499
4.000	239	275	293	326	372	411	435	446	487	542	570
4.500	269	309	329	366	418	462	489	502	548	610	641
5.000	299	343	365	407	465	513	543	558	609	677	713
5.500	329	378	403	448	511	565	597	614	670	745	784
6.000	358	412	439	489	557	616	652	670	730	813	855
6.500	388	446	476	529	604	667	706	725	791	881	927
7.000	418	481	512	570	650	719	760	781	852	948	998
7.500	448	515	549	611	697	770	815	837	913	1,016	1,069
8.000	478	549	585	651	743	821	869	893	974	1,084	1,140
8.500	508	584	622	692	790	873	923	949	1,035	1,151	1,212
9.000	538	618	659	733	836	924	978	1,004	1,096	1,219	1,283
9.500	567	652	695	774	883	975	1,032	1,060	1,156	1,287	1,354
10.000	597	687	732	814	929	1,027	1,086	1,116	1,217	1,355	1,425

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6, μ = 0.000069; k = 1.3; P_b = 14.73, and T_b = 519.67°R

Table 3-B-5—Continued

	Nominal Pipe Diameter									
	6 Inches				8 Inches			10 Inches		
$Re_D/10^6$	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.036
0.020	3.5	3.7	4.1	4.3	5.4	5.7	5.7	6.8	7.1	7.1
0.030	5.2	5.5	6.1	6.4	8.1	8.5	8.6	10.2	10.6	10.7
0.040	6.9	7.3	8.2	8.6	10.8	11.3	11.4	13.5	14.2	14.2
0.050	8.7	9.2	10.2	10.7	13.5	14.1	14.3	16.9	17.7	17.8
0.060	10.4	11.0	12.2	12.9	16.2	17.0	17.1	20.3	21.3	21.3
0.070	12.1	12.9	14.3	15.0	18.9	19.8	20.0	23.7	24.8	24.9
0.080	13.9	14.7	16.3	17.2	21.6	22.6	22.9	27.1	28.4	28.4
0.090	15.6	16.5	18.4	19.3	24.3	25.4	25.7	30.5	31.9	32.0
0.100	17.3	18.4	20.4	21.5	27.0	28.3	28.6	33.9	35.5	35.5
0.150	26.0	27.5	30.6	32.2	40.5	42.4	42.9	50.8	53.2	53.3
0.200	34.7	36.7	40.8	42.9	54.0	56.5	57.2	67.7	71.0	71.1
0.250	43.3	45.9	51.0	53.7	67.5	70.6	71.4	84.6	88.7	88.8
0.300	52.0	55.1	61.2	64.4	81.0	84.8	85.7	102	106	107
0.350	60.7	64.3	71.4	75.2	94.5	98.9	100	118	124	124
0.400	69.4	73.5	81.6	85.9	108	113	114	135	142	142
0.450	78.0	82.6	91.8	96.6	121	127	129	152	160	160
0.500	86.7	91.8	102	107	135	141	143	169	177	178
0.600	104	110	122	129	162	170	171	203	213	213
0.700	121	129	143	150	189	198	200	237	248	249
0.800	139	147	163	172	216	226	229	271	284	284
0.900	156	165	184	193	243	254	257	305	319	320
1.000	173	184	204	215	270	283	286	339	355	355
1.500	260	275	306	322	405	424	429	508	532	533
2.000	347	367	408	429	540	565	572	677	710	711
2.500	433	459	510	537	675	706	714	846	887	888
3.000	520	551	612	644	810	848	857	1,016	1,064	1,066
3.500	607	643	714	752	945	989	1,000	1,185	1,242	1,244
4.000	694	735	816	859	1,080	1,130	1,143	1,354	1,419	1,421
4.500	780	826	918	966	1,215	1,272	1,286	1,524	1,596	1,599
5.000	867	918	1,020	1,074	1,350	1,413	1,429	1,693	1,774	1,777
5.500	954	1,010	1,122	1,181	1,485	1,554	1,572	1,862	1,951	1,954
6.000	1,040	1,102	1,224	1,288	1,620	1,695	1,715	2,031	2,129	2,132
6.500	1,127	1,194	1,326	1,396	1,755	1,837	1,857	2,201	2,306	2,310
7.000	1,214	1,286	1,428	1,503	1,890	1,978	2,000	2,370	2,483	2,487
7.500	1,300	1,377	1,530	1,611	2,025	2,119	2,143	2,539	2,661	2,665
8.000	1,387	1,469	1,632	1,718	2,160	2,261	2,286	2,708	2,838	2,843
8.500	1,474	1,561	1,734	1,825	2,295	2,402	2,429	2,878	3,016	3,020
9.000	1,560	1,653	1,836	1,933	2,430	2,543	2,572	3,047	3,193	3,198
9.500	1,647	1,745	1,938	2,040	2,565	2,685	2,715	3,216	3,370	3,376
10.000	1,734	1,837	2,040	2,147	2,700	2,826	2,858	3,386	3,548	3,553

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73, and T_b = 519.67°R

Table 3-B-5—Continued

	Nominal Pipe Diameter														
	12 Inches			16 Inches			20 Inches			24 Inches			30 Inches		
$Re_D/10^6$	11.374	11.938	12.090	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23 000	23.250	28.750	29.000	29.250
0.150	60.4	63.4	64.2	78.0	79.7	81.0	99.9	101	102	120	122	123	153	154	155
0.200	80.5	84.5	85.6	104	106	108	133	135	136	160	163	165	204	205	207
0.250	101	106	107	130	133	135	167	168	170	200	204	206	254	257	259
0.300	121	127	128	156	159	162	200	202	204	240	244	247	305	308	311
0.350	141	148	150	182	186	189	233	235	239	280	285	288	356	359	362
0.400	161	169	171	208	212	216	266	269	273	320	326	329	407	411	414
0.450	181	190	193	234	239	243	300	303	307	360	366	370	458	462	466
0.500	201	211	214	260	266	270	333	336	341	401	407	412	509	513	518
0.600	242	254	257	312	319	324	400	404	409	481	489	494	611	616	621
0.700	282	296	300	364	372	378	466	471	477	561	570	576	713	719	725
0.800	322	338	342	416	425	432	533	538	545	641	651	659	814	821	829
0.900	362	380	385	468	478	486	599	605	613	721	733	741	916	924	932
1.000	403	423	428	520	531	540	666	673	682	801	814	823	1,018	1,027	1,036
1.500	604	634	642	780	797	810	999	1,009	1,022	1,202	1,222	1,235	1,527	1,540	1,553
2.000	805	845	856	1,040	1,062	1,080	1,332	1,345	1,363	1,602	1,629	1,646	2,036	2,054	2,071
2.500	1,007	1,057	1,070	1,300	1,328	1,350	1,665	1,682	1,704	2,003	2,036	2,058	2,545	2,567	2,589
3.000	1,208	1,268	1,284	1,560	1,593	1,620	1,998	2,018	2,045	2,403	2,443	2,470	3,054	3,080	3,107
3.500	1,409	1,479	1,498	1,820	1,859	1,890	2,331	2,355	2,386	2,804	2,850	2,881	3,563	3,594	3,625
4.000	1,611	1,691	1,712	2,080	2.124	2,160	2,664	2,691	2,726	3,204	3,257	3.293	4,072	4,107	4,143
4.500	1,812	1,902	1,926	2,340	2,390	2,430	2,997	3,027	3,067	3,605	3,665	3,704	4,581	4,621	4,660
5.000	2,014	2,113	2,140	2,600	2,655	2,700	3,330	3,364	3,408	4,005	4,072	4,116	5,090	5,134	5,178
5.500	2,215	2,325	2,354	2,860	2,921	2,970	3,663	3,700	3,749	4,406	4,479	4,528	5,599	5,647	5,696
6.000	2,416	2,536	2,568	3,120	3,187	3,240	3,996	4,036	4,089	4,806	4,886	4,939	6,108	6,161	6,214
6.500	2,618	2,747	2,782	3,380	3 452	3,510	4,329	4,373	4,430	5,207	5,293	5.351	6,617	6,674	6,732
7.000	2,819	2,959	2,996	3,640	3.718	3,780	4,662	4,709	4,771	5,607	5,700	5,762	7,126	7,188	7,249
7 500	3,020	3,170	3,210	3,900	3,983	4,050	4,996	5,045	5,112	6,008	6,108	6,174	7,635	7,701	7,767
8.000	3,222	3,381	3,425	4,160	4,249	4,320	5,329	5,382	5,453	6,408	6,515	6,586	8,143	8,214	8,285
8.500	3,423	3,593	3,639	4,420	4,514	4,590	5,662	5,718	5,793	6,809	6,922	6,997	8,652	8,728	8,803
9.000	3,624	3,804	3,853	4,680	4,780	4,860	5,995	6,055	6,134	7,209	7,329	7,409	9,161	9,241	9,321
9.500	3,826	4,015	4,067	4,940	5,045	5,130	6,328	6,391	6,475	7,610	7,736	7,820	9,670	9,754	9,839
10.000	4,027	4,227	4,281	5,201	5,311	5,399	6,661	6,727	6,816	8,010	8,143	8,232	10,179	10,268	10,356
12.000	4,833	5,072	5,137	6,241	6,373	6,479	7,993	8,073	8,179	9,612	9,772	9,878	12,215	12,321	12,428
15.000	6,041	6,340	6,421	7,801	7,966	8,099	9,991	10,091	10,224	12,016	12,215	12,348	15,269	15,402	15,535
18.000	7,249	7,608	7,705	9,361	9,560	9,719	11,989	12,109	12,268	14,419	14,658	14,815	18,323	18,482	18,642
21.000	8,457	8,876	8,989	10,921	11,153	11,339	13,987	14,127	14,313	16,822	17,101	17,287	21,377	21,563	21,748
24.000	9,665	10,144	10,274	12,481	12,746	12,959	15,986	16,145	16,358	19,225	19,544	19,757	24,430	24,643	24,855
27.000	10,873	11,412	11,558	14,041	14,340	14,579	17,984	18,164	18,403	21,628	21,987	22,226	27,484	27,723	27,962
30.000	12,081	12,680	12,842	15,602	15,933	16,198	19,932	20,182	20,447	24,031	24,430	24,696	30,538	30,804	31,069

Note This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6, μ = 0 000069; k = 1.3; P_b = 14 73; and T_b = 519 67°R

Table 3-B-6—Expansion Factors for Flange Taps (Y_1): Static Pressure Taken From Upstream Taps

	$\beta = d/D$												
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60	0.61	0.62
0.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.1	0.9989	0.9989	0.9989	0.9988	0.9988	0.9988	0.9988	0.9988	0.9988	0.9988	0.9987	0.9987	0.9987
0.2	0.9977	0.9977	0.9977	0.9977	0.9976	0.9976	0.9976	0.9976	0.9975	0.9975	0.9975	0.9975	0.9974
0.3	0.9966	0.9966	0.9966	0.9965	0.9965	0.9964	0.9964	0.9963	0.9963	0.9963	0.9962	0.9962	0.9962
0.4	0.9954	0.9954	0.9954	0.9953	0.9953	0.9952	0.9952	0.9951	0.9951	0.9950	0.9949	0.9949	0.9949
0.5	0.9943	0.9943	0.9943	0.9942	0.9941	0.9940	0.9940	0.9939	0.9938	0.9938	0.9937	0.9936	0.9936
0.6	0.9932	0.9932	0.9931	0.9930	0.9929	0.9928	0.9927	0.9927	0.9926	0.9925	0.9924	0.9924	0.9923
0.7	0.9920	0.9920	0.9920	0.9919	0.9918	0.9916	0.9915	0.9915	0.9914	0.9913	0.9912	0.9911	0.9910
0.8	0.9909	0.9909	0.9908	0.9907	0.9906	0.9904	0.9903	0.9902	0.9901	0.9900	0.9899	0.9898	0.9897
0.9	0.9898	0.9897	0.9897	0.9895	0.9894	0.9892	0.9891	0.9890	0.9889	0.9888	0.9886	0.9885	0.9885
1.0	0.9886	0.9886	0.9885	0.9884	0.9882	0.9880	0.9879	0.9878	0.9877	0.9875	0.9874	0.9873	0.9872
1.1	0.9875	0.9875	0.9874	0.9872	0.9870	0.9868	0.9867	0.9866	0.9864	0.9863	0.9861	0.9860	0.9859
1.2	0.9863	0.9863	0.9862	0.9860	0.9859	0.9856	0.9855	0.9853	0.9852	0.9850	0.9848	0.9847	0.9846
1.3	0.9852	0.9852	0.9851	0.9849	0.9847	0.9844	0.9843	0.9841	0.9840	0.9838	0.9836	0.9835	0.9833
1.4	0.9841	0.9840	0.9840	0.9837	0.9835	0.9832	0.9831	0.9829	0.9827	0.9825	0.9823	0.9822	0.9821
1.5	0.9829	0.9829	0.9828	0.9826	0.9823	0.9820	0.9819	0.9817	0.9815	0.9813	0.9810	0.9809	0.9808
1.6	0.9818	0.9818	0.9817	0.9814	0.9811	0.9808	0.9806	0.9805	0.9803	0.9800	0.9798	0.9796	0.9795
1.7	0.9806	0.9806	0.9805	0.9802	0.9800	0.9796	0.9794	0.9792	0.9790	0.9788	0.9785	0.9784	0.9782
1.8	0.9795	0.9795	0.9794	0.9791	0.9788	0.9784	0.9782	0.9780	0.9778	0.9775	0.9772	0.9771	0.9769
1.9	0.9784	0.9783	0.9782	0.9779	0.9776	0.9772	0.9770	0.9768	0.9766	0.9763	0.9760	0.9758	0.9756
2.0	0.9772	0.9772	0.9771	0.9767	0.9764	0.9760	0.9758	0.9756	0.9753	0.9750	0.9747	0.9745	0.9744
2.1	0.9761	0.9761	0.9759	0.9756	0.9753	0.9748	0.9746	0.9744	0.9741	0.9738	0.9734	0.9733	0.9731
2.2	0.9750	0.9749	0.9748	0.9744	0.9741	0.9736	0.9734	0.9731	0.9729	0.9725	0.9722	0.9720	0.9718
2.3	0.9738	0.9738	0.9736	0.9732	0.9729	0.9724	0.9722	0.9719	0.9716	0.9713	0.9709	0.9707	0.9705
2.4	0.9727	0.9726	0.9725	0.9721	0.9717	0.9712	0.9710	0.9707	0.9704	0.9700	0.9697	0.9694	0.9692
2.5	0.9715	0.9715	0.9713	0.9709	0.9705	0.9700	0.9698	0.9695	0.9692	0.9688	0.9684	0.9682	0.9680
2.6	0.9704	0.9704	0.9702	0.9698	0.9694	0.9688	0.9686	0.9683	0.9679	0.9675	0.9671	0.9669	0.9667
2.7	0.9693	0.9692	0.9691	0.9686	0.9682	0.9676	0.9673	0.9670	0.9667	0.9663	0.9659	0.9656	0.9654
2.8	0.9681	0.9681	0.9679	0.9674	0.9670	0.9664	0.9661	0.9658	0.9654	0.9650	0.9646	0.9644	0.9641
2.9	0.9670	0.9669	0.9668	0.9663	0.9658	0.9652	0.9649	0.9646	0.9642	0.9638	0.9633	0.9631	0.9628
3.0	0.9658	0.9658	0.9656	0.9651	0.9647	0.9640	0.9637	0.9634	0.9630	0.9626	0.9621	0.9618	0.9615
3.1	0.9647	0.9647	0.9645	0.9639	0.9635	0.9628	0.9625	0.9622	0.9617	0.9613	0.9608	0.9605	0.9603
3.2	0.9636	0.9635	0.9633	0.9628	0.9623	0.9616	0.9613	0.9609	0.9605	0.9601	0.9595	0.9593	0.9590
3.3	0.9624	0.9624	0.9622	0.9616	0.9611	0.9604	0.9601	0.9597	0.9593	0.9588	0.9583	0.9580	0.9577
3.4	0.9613	0.9612	0.9610	0.9604	0.9599	0.9592	0.9589	0.9585	0.9580	0.9576	0.9570	0.9567	0.9564
3.5	0.9602	0.9601	0.9599	0.9593	0.9588	0.9580	0.9577	0.9573	0.9568	0.9563	0.9558	0.9554	0.9551
3.6	0.9590	0.9590	0.9587	0.9581	0.9576	0.9568	0.9565	0.9560	0.9556	0.9551	0.9545	0.9542	0.9538
3.7	0.9579	0.9578	0.9576	0.9570	0.9564	0.9556	0.9553	0.9548	0.9543	0.9538	0.9532	0.9529	0.9526
3.8	0.9567	0.9567	0.9564	0.9558	0.9552	0.9544	0.9540	0.9536	0.9531	0.9526	0.9520	0.9516	0.9513
3.9	0.9556	0.9555	0.9553	0.9545	0.9540	0.9532	0.9528	0.9524	0.9519	0.9513	0.9507	0.9504	0.9500
4.0	0.9545	0.9544	0.9542	0.9536	0.9529	0.9520	0.9516	0.9512	0.9506	0.9501	0.9494	0.9491	0.9487

Table 3-B-6—Continued

	$\beta = d/D$												
h_w/P_{f_1}	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70	0.71	0.72	0.73	0.74	0.75
0.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.1	0.9987	0.9987	0.9987	0.9987	0.9987	0.9987	0.9986	0.9986	0.9986	0.9986	0.9986	0.9986	0.9986
0.2	0.9974	0.9974	0.9974	0.9974	0.9973	0.9973	0.9973	0.9973	0.9972	0.9972	0.9972	0.9971	0.9971
0.3	0.9961	0.9961	0.9961	0.9960	0.9960	0.9960	0.9959	0.9959	0.9958	0.9958	0.9958	0.9957	0.9957
0.4	0.9948	0.9948	0.9948	0.9947	0.9947	0.9946	0.9946	0.9945	0.9945	0.9944	0.9943	0.9943	0.9942
0.5	0.9935	0.9935	0.9934	0.9934	0.9933	0.9933	0.9932	0.9931	0.9931	0.9930	0.9929	0.9929	0.9928
0.6	0.9923	0.9922	0.9921	0.9921	0.9920	0.9919	0.9918	0.9918	0.9917	0.9916	0.9915	0.9914	0.9913
0.7	0.9910	0.9909	0.9908	0.9907	0.9907	0.9906	0.9905	0.9904	0.9903	0.9902	0.9901	0.9900	0.9899
0.8	0.9897	0.9896	0.9895	0.9894	0.9893	0.9892	0.9891	0.9890	0.9889	0.9888	0.9887	0.9886	0.9884
0.9	0.9884	0.9883	0.9882	0.9881	0.9880	0.9879	0.9878	0.9877	0.9875	0.9874	0.9873	0.9871	0.9870
1.0	0.9871	0.9870	0.9869	0.9868	0.9867	0.9865	0.9864	0.9863	0.9861	0.9860	0.9859	0.9857	0.9855
1.1	0.9858	0.9857	0.9856	0.9854	0.9853	0.9852	0.9851	0.9849	0.9848	0.9846	0.9844	0.9843	0.9841
1.2	0.9845	0.9844	0.9843	0.9841	0.9840	0.9838	0.9837	0.9835	0.9834	0.9832	0.9830	0.9828	0.9826
1.3	0.9832	0.9831	0.9829	0.9828	0.9827	0.9825	0.9823	0.9822	0.9820	0.9818	0.9816	0.9814	0.9812
1.4	0.9819	0.9818	0.9816	0.9815	0.9813	0.9812	0.9810	0.9808	0.9806	0.9804	0.9802	0.9800	0.9798
1.5	0.9806	0.9805	0.9803	0.9802	0.9800	0.9798	0.9796	0.9794	0.9792	0.9790	0.9788	0.9786	0.9783
1.6	0.9793	0.9792	0.9790	0.9788	0.9787	0.9785	0.9783	0.9781	0.9778	0.9776	0.9774	0.9771	0.9769
1.7	0.9780	0.9779	0.9777	0.9775	0.9773	0.9771	0.9769	0.9767	0.9764	0.9762	0.9760	0.9757	0.9754
1.8	0.9768	0.9766	0.9764	0.9762	0.9760	0.9758	0.9755	0.9753	0.9751	0.9748	0.9745	0.9743	0.9740
1.9	0.9755	0.9753	0.9751	0.9749	0.9747	0.9744	0.9742	0.9739	0.9737	0.9734	0.9731	0.9728	0.9725
2.0	0.9742	0.9740	0.9738	0.9735	0.9733	0.9731	0.9728	0.9726	0.9723	0.9720	0.9717	0.9714	0.9711
2.1	0.9729	0.9727	0.9725	0.9722	0.9720	0.9717	0.9715	0.9712	0.9709	0.9706	0.9703	0.9700	0.9696
2.2	0.9716	0.9714	0.9711	0.9709	0.9706	0.9704	0.9701	0.9698	0.9695	0.9692	0.9689	0.9685	0.9682
2.3	0.9703	0.9701	0.9698	0.9696	0.9693	0.9690	0.9688	0.9685	0.9681	0.9678	0.9675	0.9671	0.9667
2.4	0.9690	0.9688	0.9685	0.9683	0.9680	0.9677	0.9674	0.9671	0.9668	0.9664	0.9661	0.9657	0.9653
2.5	0.9677	0.9675	0.9672	0.9669	0.9666	0.9663	0.9660	0.9657	0.9654	0.9650	0.9646	0.9643	0.9639
2.6	0.9664	0.9662	0.9659	0.9656	0.9653	0.9650	0.9647	0.9643	0.9640	0.9636	0.9632	0.9528	0.9624
2.7	0.9651	0.9649	0.9646	0.9643	0.9640	0.9637	0.9633	0.9630	0.9626	0.9622	0.9618	0.9614	0.9610
2.8	0.9638	0.9636	0.9633	0.9630	0.9626	0.9623	0.9620	0.9616	0.9612	0.9608	0.9604	0.9600	0.9595
2.9	0.9625	0.9623	0.9620	0.9616	0.9613	0.9610	0.9606	0.9602	0.9598	0.9594	0.9590	0.9585	0.9581
3.0	0.9613	0.9610	0.9606	0.9603	0.9600	0.9596	0.9592	0.9588	0.9584	0.9580	0.9576	0.9571	0.9566
3.1	0.9600	0.9597	0.9593	0.9590	0.9586	0.9583	0.9579	0.9575	0.9571	0.9566	0.9562	0.9557	0.9552
3.2	0.9587	0.9584	0.9580	0.9577	0.9573	0.9569	0.9567	0.9561	0.9557	0.9552	0.9547	0.9542	0.9537
3.3	0.9574	0.9571	0.9567	0.9564	0.9560	0.9556	0.9552	0.9547	0.9543	0.9538	0.9533	0.9528	0.9525
3.4	0.9561	0.9558	0.9551	0.9550	0.9546	0.9542	0.9538	0.9534	0.9529	0.9524	0.9519	0.9514	0.9508
3.5	0.9548	0.9545	0.9541	0.9537	0.9533	0.9529	0.9524	0.9520	0.9515	0.9510	0.9505	0.9500	0.9494
3.6	0.9535	0.9532	0.9528	0.9524	0.9520	0.9515	0.9511	0.9506	0.9501	0.9496	0.9491	0.9485	0.9480
3.7	0.9522	0.9518	0.9515	0.9511	0.9506	0.9502	0.9497	0.9492	0.9487	0.9482	0.9477	0.9471	0.9465
3.8	0.9509	0.9505	0.9502	0.9497	0.9493	0.9488	0.9484	0.9479	0.9474	0.9468	0.9463	0.9457	0.9451
3.9	0.9496	0.9492	0.9488	0.9484	0.9480	0.9475	0.9470	0.9465	0.9460	0.9454	0.9448	0.9442	0.9436
4.0	0.9483	0.9479	0.9475	0.947	0.9465	0.9462	0.9457	0.9451	0.9446	0.9440	0.9434	0.9428	0.9422

Table 3-B-7—F_{pb} Factors Used to Change From a Pressure Base of 14.73 Pounds Force per Square Inch Absolute to Other Pressure Bases

$$F_{pb} = \frac{14.73}{\text{Contract pressure base, psia}}$$

Pressure Base (pounds force per square inch absolute)	F_{pb}
14.4	1.0229
14.525	1.0141
14.65	1.0055
14.696	1.0023
14.70	1.0020
14.725	1.0003
14.73	1.0000
14.735	0.9997
14.775	0.9970
14.90	0.9886
15.025	0.9804
15.15	0.9723
15.225	0.9675
15.275	0.9643
15.325	0.9612
15.40	0.9565
15.525	0.9488
15.65	0.9412
15.775	0.9338
15.90	0.9264
16.025	0.9192
16.15	0.9121
16.275	0.9051
16.40	0.8982
16.70	0.8820

Table 3-B-8—F_{tb} Factors Used to Change From a Temperature Base of 60°F to Other Temperature Bases

$$F_{tb} = \frac{\text{Base °F} + 459.67}{60 + 459.67}$$

Temperature (°F)	F_{tb}	Temperature (°F)	F_{tb}
40	0.9615	65	1.0096
41	0.9634	66	1.0115
42	0.9654	67	1.0135
43	0.9673	68	1.0154
44	0.9692	69	1.0173
45	0.9711	70	1.0192
46	0.9731	71	1.0212
47	0.9750	72	1.0231
48	0.9769	73	1.0250
49	0.9788	74	1.0269
50	0.9808	75	1.0289
51	0.9827	76	1.0308
52	0.9846	77	1.0327
53	0.9865	78	1.0346
54	0.9885	79	1.0366
55	0.9904	80	1.0385
56	0.9923	81	1.0404
57	0.9942	82	1.0423
58	0.9962	83	1.0443
59	0.9981	84	1.0462
60	1.0000	85	1.0481
61	1.0019	86	1.0500
62	1.0038	87	1.0520
63	1.0058	88	1.0539
64	1.0077	89	1.0558
		90	1.0577

Table 3-B-9—F_{tf} Factors Used to Change From a Flowing Temperature of 60°F to Actual Flowing Temperature

$$F_{tf} = \sqrt{\frac{60 + 459.67}{T_f + 459.67}}$$

Temperature (°F)	F_{tf}	Temperature (°F)	F_{tf}	Temperature (°F)	F_{tf}
–20	1.0872	37	1.0229	94	0.9688
–19	1.0859	38	1.0219	95	0.9679
–18	1.0847	39	1.0208	96	0.9671
–17	1.0835	40	1.0198	97	0.9662
–16	1.0823	41	1.0188	98	0.9653
–15	1.0810	42	1.0178	99	0.9645
–14	1.0798	43	1.0168	100	0.9636
–13	1.0786	44	1.0158	101	0.9627
–12	1.0774	45	1.0148	102	0.9619
–11	1.0762	46	1.0137	103	0.9610
–10	1.0750	47	1.0127	104	0.9602
–9	1.0738	48	1.0117	105	0.9593
–8	1.0726	49	1.0108	106	0.9585
–7	1.0715	50	1.0098	107	0.9576
–6	1.0703	51	1.0088	108	0.9568
–5	1.0691	52	1.0078	109	0.9559
–4	1.0679	53	1.0068	110	0.9551
–3	1.0668	54	1.0058	111	0.9543
–2	1.0656	55	1.0048	112	0.9534
–1	1.0644	56	1.0039	113	0.9526
0	1.0633	57	1.0029	114	0.9518
1	1.0621	58	1.0019	115	0.9509
2	1.0610	59	1.0010	116	0.9501
3	1.0598	60	1.0000	117	0.9493
4	1.0587	61	0.9990	118	0.9485
5	1.0575	62	0.9981	119	0.9477
6	1.0564	63	0.9971	120	0.9468
7	1.0553	64	0.9962	121	0.9460
8	1.0541	65	0.9952	122	0.9452
9	1.0530	66	0.9943	123	0.9444
10	1.0519	67	0.9933	124	0.9436
11	1.0508	68	0.9924	125	0.9428
12	1.0497	69	0.9915	126	0.9420
13	1.0485	70	0.9905	127	0.9412
14	1.0474	71	0.9896	128	0.9404
15	1.0463	72	0.9887	129	0.9396
16	1.0452	73	0.9877	130	0.9388
17	1.0441	74	0.9868	131	0.9380
18	1.0430	75	0.9859	132	0.9372
19	1.0419	76	0.9850	133	0.9364
20	1.0409	77	0.9840	134	0.9356
21	1.0398	78	0.9831	135	0.9348
22	1.0387	79	0.9822	136	0.9340
23	1.0376	80	0.9813	137	0.9332
24	1.0365	81	0.9804	138	0.9325
25	1.0355	82	0.9795	139	0.9317
26	1.0344	83	0.9786	140	0.9309
27	1.0333	84	0.9777	141	0.9301
28	1.0323	85	0.9768	142	0.9294
29	1.0312	86	0.9759	143	0.9286
30	1.0302	87	0.9750	144	0.9278
31	1.0291	88	0.9741	145	0.9271
32	1.0281	89	0.9732	146	0.9263
33	1.0270	90	0.9723	147	0.9255
34	1.0260	91	0.9714	148	0.9248
35	1.0250	92	0.9706	149	0.9240
36	1.0239	93	0.9697	150	0.9232

Table 3-B-10—F_{gr} Factors Used to Adjust for Real Gas Relative Density (G_r): Base Conditions of 60°F and 14.73 Pounds Force per Square Inch Absolute

$$F_{gr} = \sqrt{\frac{1}{G_r}}$$

	F_{gr}									
G_r	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.550	1.3484	1.3472	0.3460	1.3447	1.3435	1.3423	1.3411	1.3399	1.3387	1.3375
0.560	1.3363	1.3351	1.3339	1.3327	1.3316	1.3304	1.3292	1.3280	1.3269	1.3257
0.570	1.3245	1.3234	1.3222	1.3211	1.3199	1.3188	1.3176	1.3165	1.3153	1.3142
0.580	1.3131	1.3119	1.3108	1.3097	1.3086	1.3074	1.3063	1.3052	1.3041	1.3030
0.590	1.3019	1.3008	1.2997	1.2986	1.2975	1.2964	1.2953	1.2942	1.2932	1.2921
0.600	1.2910	1.2899	1.2888	1.2878	1.2867	1.2856	1.2846	1.2835	1.2825	1.2814
0.610	1.2804	1.2793	1.2783	1.2772	1.2762	1.2752	1.2741	1.2731	1.2720	1.2710
0.620	1.2700	1.2690	1.2680	1.2669	1.2659	1.2649	1.2639	1.2629	1.2619	1.2609
0.630	1.2599	1.2589	1.2579	1.2569	1.2559	1.2549	1.2539	1.2529	1.2520	1.2510
0.640	1.2500	1.2490	1.2480	1.2471	1.2461	1.2451	1.2442	1.2432	1.2423	1.2413
0.650	1.2403	1.2394	1.2384	1.2375	1.2365	1.2356	1.2347	1.2337	1.2328	1.2318
0.660	1.2309	1.2300	1.2290	1.2281	1.2272	1.2263	1.2254	1.2244	1.2235	1.2226
0.670	1.2217	1.2208	1.2199	1.2190	1.2181	1.2172	1.2163	1.2154	1.2145	1.2136
0.680	1.2127	1.2118	1.2109	1.2100	1.2091	1.2082	1.2074	1.2065	1.2056	1.2047
0.690	1.2039	1.2030	1.2021	1.2012	1.2004	1.1995	1.1986	1.1978	1.1969	1.1961
0.700	1.1952	1.1944	1.1935	1.1927	1.1918	1.1910	1.1901	1.1893	1.1884	1.1876
0.710	1.1868	1.1859	1.1851	1.1843	1.1834	1.1826	1.1818	1.1810	1.1802	1.1793
0.720	1.1785	1.1777	1.1769	1.1761	1.1752	1.1744	1.1736	1.1728	1.1720	1.1712
0.730	1.1704	1.1696	1.1688	1.1680	1.1672	1.1664	1.1656	1.1648	1.1640	1.1633
0.740	1.1625	1.1617	1.1609	1.1601	1.1593	1.1586	1.1578	1.1570	1.1562	1.1555
0.750	1.1547	1.1539	1.1532	1.1524	1.1516	1.1509	1.1501	1.1493	1.1486	1.1478
0.760	1.1471	1.1463	1.1456	1.1448	1.1441	1.1433	1.1426	1.1418	1.1411	1.1403
0.770	1.1396	1.1389	1.1381	1.1374	1.1366	1.1359	1.1352	1.1345	1.1337	1.1330
0.780	1.1323	1.1316	1.1308	1.1301	1.1294	1.1287	1.1279	1.1272	1.1265	1.1258
0.790	1.1251	1.1244	1.1237	1.1230	1.1222	1.1215	1.1208	1.1201	1.1194	1.1187
0.800	1.1180	1.1173	1.1166	1.1159	1.1152	1.1146	1.1139	1.1132	1.1125	1.1118
0.810	1.1111	1.1104	1.1097	1.1090	1.1084	1.1077	1.1070	1.1063	1.1057	1.1050
0.820	1.1043	1.1036	1.1030	1.1023	1.1016	1.1010	1.1003	1.0996	1.0990	1.0983
0.830	1.0976	1.0970	1.0963	1.0957	1.0950	1.0944	1.0937	1.0930	1.0924	1.0917
0.840	1.0911	1.0904	1.0898	1.0891	1.0885	1.0878	1.0872	1.0866	1.0859	1.0853
0.850	1.0846	1.0840	1.0834	1.0827	1.0821	1.0815	1.0808	1.0802	1.0796	1.0790
0.860	1.0783	1.0777	1.0771	1.0764	1.0758	1.0752	1.0746	1.0740	1.0733	1.0727
0.870	1.0721	1.0715	1.0709	1.0703	1.0696	1.0690	1.0684	1.0678	1.0672	1.0666
0.880	1.0660	1.0654	1.0648	1.0642	1.0636	1.0630	1.0624	1.0618	1.0612	1.0606
0.890	1.0600	1.0594	1.0588	1.0582	1.0576	1.0570	1.0564	1.0558	1.0553	1.0547
0.900	1.0541	1.0535	1.0529	1.0523	1.0518	1.0512	1.0506	1.0500	1.0494	1.0489
0.910	1.0483	1.0477	1.0471	1.0466	1.0460	1.0454	1.0448	1.0443	1.0437	1.0431
0.920	1.0426	1.0420	1.0414	1.0409	1.0403	1.0398	1.0392	1.0386	1.0381	1.0375
0.930	1.0370	1.0364	1.0358	1.0353	1.0347	1.0342	1.0336	1.0331	1.0325	1.0320
0.940	1.0314	1.0309	1.0303	1.0298	1.0292	1.0287	1.0281	1.0276	1.0270	1.0265
0.950	1.0260	1.0254	1.0249	1.0244	1.0238	1.0233	1.0228	1.0222	1.0217	1.0212
0.960	1.0206	1.0201	1.0196	1.0190	1.0185	1.0180	1.0174	1.0169	1.0164	1.0159
0.970	1.0153	1.0148	1.0143	1.0138	1.0132	1.0127	1.0122	1.0117	1.0112	1.0107
0.980	1.0102	1.0096	1.0091	1.0086	1.0081	1.0076	1.0071	1.0066	1.0060	1.0055
0.990	1.0050	1.0045	1.0040	1.0035	1.0030	1.0025	1.0020	1.0015	1.0010	1.0005
1.000	1.0000									

Table 3-B-11—Supercompressibility Factors (F_{pv}) for G_r = 0.6 Without Nitrogen or Carbon Dioxide

Pressure (psia)	Temperature (°F)					
	20	40	60	80	100	120
100	1.00947	1.00807	1.00687	1.00504	1.00496	1.00419
200	1.02058	1.01762	1.01512	1.01294	1.01116	1.00958
300	1.03218	1.02748	1.02355	1.02022	1.01740	1.01497
400	1.04427	1.03764	1.03216	1.02756	1.02367	1.02035
500	1.05688	1.04810	1.04093	1.03497	1.02996	1.02572
600	1.06999	1.05884	1.04983	1.04243	1.03625	1.03104
700	1.08360	1.06983	1.05885	1.04990	1.04251	1.03631
800	1.09766	1.08103	1.06793	1.05737	1.04871	1.04149
900	1.11209	1.09237	1.07703	1.06479	1.05482	1.04656
1000	1.12679	1.10375	1.08608	1.07211	1.06081	1.05150
1100	1.14156	1.11503	1.09501	1.07927	1.06663	1.05628
1200	1.15616	1.12621	1.10372	1.08622	1.07225	1.06087
1300	1.17029	1.13696	1.11211	1.09289	1.07763	1.06524
1400	1.18358	1.14715	1.12007	1.09922	1.08271	1.06935
1500	1.19565	1.15657	1.12749	1.10512	1.08745	1.07318
1600	1.20615	1.16504	1.13425	1.11054	1.09180	1.07669
1700	1.21481	1.17237	1.14025	1.11540	1.09573	1.07986
1800	1.22146	1.17845	1.14541	1.11965	1.09919	1.08267
1900	1.22606	1.18318	1.14965	1.12324	1.10216	1.08509
2000	1.22868	1.18655	1.15294	1.12615	1.10462	1.08710

Note The data in this table were generated using the A.G.A. Gas Measurement Program. Copyright © 1988 American Gas Association. All rights reserved. Gas input data are as follows: % CO_2 = 0; % N_2 = 0; specific gravity = 0.6. This table was developed for informational purposes only and is specific to the gas quality listed. The data in this table are *not* subject to adjustment for nitrogen or carbon dioxide content and, because of their broad range, should not be interpolated. With the A.G.A Program, the user establishes the gas composition parameters and specifies the table range that is consistent with field or measurement conditions

APPENDIX 3-C—FLOW CALCULATION EXAMPLES

3-C.1 General

This appendix presents two methods for calculating the volume flow rate of natural gas through an orifice meter equipped with flange taps. The first method uses the equations presented in 3.3 through 3.5. The second method is based on the more traditional calculation format, which involves the computation of various factors. The equations used for the factor approach are presented in Appendix 3-B.

To assist the user in interpreting the calculation methodology, the data set given below, which is for a single orifice meter, is used consistently throughout the flow calculation examples. The volume flow rate is computed under the assumption that the measurements are absolute and without error. It should be noted that depending on the type of instrumentation used and the calibration methods employed, calibration and correction factors may need to be applied. *For simplicity in using hand calculations and for ease of interpretation in the following examples, intermediate values are rounded to six significant digits. Part 4 should be used for any implementation of the equations.*

3-C.2 Given Data

The orifice meter consists of a carbon steel meter tube equipped with flange taps and a Type 304 stainless steel orifice plate. Static pressure measurements are taken from the upstream tap.

d_r = mean orifice bore diameter at T_r of 68°F, in inches
= 4.000.
D_r = mean meter tube internal diameter at T_r of 68°F, in inches
= 8.071.
G_r = real gas relative density (specific gravity)
= 0.570.
h_w = average differential pressure, in inches of water at 60°F
= 50.0.
P_b = contract base pressure, in pounds force per square inch absolute
= 14.65
P_{f_1} = average upstream absolute static pressure, in pounds force per square inch absolute
= 370.0.
T_b = contract base temperature of 50°F, in degrees Rankine (50°F + 459.67)
= 509.67
T_f = flowing temperature of 65°F, in degrees Rankine (65°F + 459.67)
= 524.67
xc = carbon dioxide content, in mole percent
= 0.00
xn = nitrogen content, in mole percent
= 1.10
k = isentropic exponent (c_p/c_v)
= 1.3
α_1 = linear coefficient of thermal expansion for a stainless steel orifice plate, in inches per inch-°F
= 0.00000925
α_2 = linear coefficient of thermal expansion for a carbon steel meter tube, in inches per inch-°F
= 0.00000620.
μ = dynamic viscosity, in pounds mass per foot-second
= 0.0000069.

3–C.3 Calculation Examples

3–C.3.1 METHOD 1: VOLUME FLOW RATE CALCULATION BASED ON 3.3 THROUGH 3.5

3–C.3.1.1 General

Using the given data set, the volume flow rate of natural gas, in cubic feet per hour at standard conditions, can be calculated using Equation 3-6b:

$$Q_v = 7709.61C_d(\text{FT})E_vY_1d^2\sqrt{\frac{P_{f_1}Z_sh_w}{G_rZ_{f_1}T_f}} \qquad (3\text{-}6b)$$

Note: Since the given data contain values for the contract base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate at standard conditions will require conversion to the flow rate at base conditions of 14.65 pounds force per square inch absolute and 50°F.

The systematic approach to solving the volume flow rate equation above involves the calculation of the intermediate values described 3-C.3.1.2 through 3-C.3.1.7.

3-C.3.1.2 Flange–Tapped Orifice Meter Coefficient of Discharge [C_d(FT)]

The following equations are used to calculate the coefficient of discharge, C_d(FT):

$$C_d(\text{FT}) = C_i(\text{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4C \qquad (3\text{-}11)$$

$$C_i(\text{FT}) = C_i(\text{CT}) + \mathit{Tap\ Term} \qquad (3\text{-}12)$$

$$C_i(\text{CT}) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1 - \beta)M_1 \qquad (3\text{-}13)$$

$$\mathit{Tap\ Term} = \mathit{Upstrm} + \mathit{Dnstrm} \qquad (3\text{-}14)$$

$$\mathit{Upstrm} = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \qquad (3\text{-}15)$$

$$\mathit{Dnstrm} = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \qquad (3\text{-}16)$$

Also,

$$B = \frac{\beta^4}{1 - \beta^4} \qquad (3\text{-}17)$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4},\ 0.0\right) \qquad (3\text{-}18)$$

$$M_2 = \frac{2L_2}{1 - \beta} \qquad (3\text{-}19)$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \qquad (3\text{-}20)$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \qquad (3\text{-}21)$$

Where

C_d(FT) = coefficient of discharge at a specified pipe Reynolds number for a flange-tapped orifice meter

C_i(CT) = coefficient of discharge at an infinite pipe Reynolds number for corner-tapped orifice meter

C_i(FT) = coefficient of discharge at an infinite pipe Reynolds number for a flange-tapped orifice meter.

d = orifice plate bore diameter calculated at T_f, in inches.
D = meter tube internal diameter calculated at T_f, in inches.
e = Napierian constant
= 2.71828.
$L_1 = L_2$
= dimensionless correction for tap location
= N_4/D for flange taps.
N_4 = 1.0 when D is in inches.
Re_D = pipe Reynolds number.
β = diameter ratio
= d/D.

Note: For this example, M_1 is equal to 0.0, since the given meter tube diameter (D) is greater than or equal to 2.8 inches. For meter tube diameters (D) less than 2.8 inches, $M_1 = 2.8 - D$. The solution of the intermediate equations presented above for the flow coefficient calculation follows.

3–C.3.1.3 Meter Tube Diameter, Orifice Plate Bore Diameter, and Diameter Ratio (*D*, *d*, and *β*)

Calculate the values of d, D, and β at a flowing temperature of 65°F from the given diameters d_r and D_r.

$$\begin{aligned} d &= d_r[1 + \alpha_1(T_f - T_r)] \qquad (3\text{-}9) \\ &= 4.000[1 + 0.00000925(524.67 - 527.67)] \\ &= 3.99989 \end{aligned}$$

And

$$\begin{aligned} D &= D_r[1 + \alpha_2(T_f - T_r)] \qquad (3\text{-}10) \\ &= 8.071[1 + 0.00000620(524.67 - 527.67)] \\ &= 8.07085 \end{aligned}$$

Substitute the given values of d and D at 65°F into Equation 3-8:

$$\begin{aligned} \beta &= d / D \qquad (3\text{-}8) \\ &= 3.99989 / 8.07085 \\ &= 0.495597 \end{aligned}$$

3–C.3.1.4 Velocity of Approach Factor (E_v)

The following equation is used to calculate the velocity of approach factor:

$$\begin{aligned} E_v &= \frac{1}{\sqrt{1 - \beta^4}} \qquad (3\text{-}22) \\ &= \frac{1}{\sqrt{1 - 0.495597^4}} \\ &= 1.03160 \end{aligned}$$

3–C.3.1.5 Expansion Factor (*Y*)

The following equation is used to calculate the expansion factor:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \qquad (3\text{-}32)$$

The intermediate value, x_1, is calculated as follows.

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\,P_{f_1}} \qquad (3\text{-}33)$$

Substitute the given values of h_w and P_{f_1} into Equation 3-32:

$$\begin{aligned} x_1 &= \frac{50.0}{(27.707)(370.0)} \\ &= 0.00487729 \end{aligned}$$

Substitute the values for k, x_1, and β into Equation 3-32:

$$\begin{aligned} Y_1 &= 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \qquad (3\text{-}32) \\ &= 1 - [0.41 + 0.35(0.495597)^4]\left(\frac{0.00487729}{1.3}\right) \\ &= 0.998383 \end{aligned}$$

3–C.3.1.6 Compressibility (Z_b, Z_s, and Z_{f_1})

The derivation of the equation for compressibility is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the calculation procedures necessary for determining the compressibility at base conditions (Z_b), standard conditions (Z_s), or flowing conditions (Z_{f_1}). The following values for gas compressibility at the conditions given in the data set were obtained from the A.G.A. computer program that uses the calculation given in A.G.A. Transmission Measurement Committee Report No. 8. At $G_r = 0.57$,

$Z_b = 0.997839$ at 14.65 pounds force per square inch absolute and 509.67°R (50°F)
$Z_s = 0.997971$ at 14.73 pounds force per square inch absolute and 519.67°R (60°F)
$Z_{f_1} = 0.951308$ at 370 pounds force per square inch absolute and 524.67°R (65°F)

3–C.3.1.7 Reynolds Number (Re_D)

The following equation is used to calculate the pipe Reynolds number:

$$Re_D = 0.0114541\left(\frac{Q_b P_b G_r}{\mu D T_b Z_{b_{air}}}\right) \qquad (3\text{-}28)$$

Substituting the calculated value for D, standard conditions for P_b and T_b, a value of 0.999590 for $Z_{b_{air}}$, and the data set values for G_r and μ in Equation 3-28 produce the following:

$$\begin{aligned} Re_D &= (0.0114541)\left(\frac{Q_v(14.73)(0.570)}{(0.0000069)(8.07085)(519.67)(0.999590)}\right) \\ &= 3.32449Q_v \end{aligned}$$

When the flow rate is not known, the Reynolds number can be developed by assuming an initial value for the flange-tapped orifice meter coefficient of discharge, C_d(FT), and iterating for the correct values, as stated in 3.4.5. The following flow rate calculation provides the initial iteration of the Reynolds number. This initial iteration is based on an assumed value for C_d(FT) of 0.60. Based on experience, from three to five iterations should provide results consistent with the requirements of Part 4.

3–C.3.1.8 Volume Flow Rate (Q_v and Q_b)

The volume flow rate can be calculated by substituting the given parameters, the intermediate calculated values, and an assumed value of 0.60 for C_d(FT) in Equation 3-6b and iterating for the final solution:

$$Q_v = 7709.61 C_d(\mathrm{FT}) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \qquad (3\text{-}6b)$$

$$= 7709.61(0.60)(1.03160)(0.998383)(3.99989)^2$$

$$\times \sqrt{\frac{(370.0)(0.997971)(50.0)}{(0.951308)(0.570)(524.67)}}$$

$$= 614{,}033 \text{ cubic feet per hour at standard conditions}$$

[This is an estimate of the initial flow rate based on an assumed $C_d(\mathrm{FT})$ of 0.60.]

Substitute the estimate of initial flow rate into the Reynolds number equation and calculate the estimated initial Reynolds number:

$$Re_D = 3.32449 Q_v$$

$$= 3.32449(614{,}033)$$

$$= 2{,}041{,}347 \text{ (initial estimate of Reynolds number)}$$

Substitute the calculated value of β into Equation 3-17:

$$B = \frac{\beta^4}{1 - \beta^4} \qquad (3\text{-}17)$$

$$= \frac{0.495597^4}{1 - 0.495597^4}$$

$$= 0.0642005$$

Substitute the calculated values of β and D into Equation 3-19:

$$M_2 = \frac{2 L_2}{1 - \beta} \qquad (3\text{-}19)$$

$$= \frac{2}{8.07085(1 - 0.495597)}$$

$$= 0.491284$$

Substitute the calculated values of Re_D and β into Equation 3-20:

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \qquad (3\text{-}20)$$

$$= \left[\frac{19{,}000(0.495597)}{2{,}041{,}347}\right]^{0.8}$$

$$= 0.0135261$$

Substitute the calculated value of Re_D into Equation 3-21:

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \qquad (3\text{-}21)$$

$$= \left(\frac{10^6}{2{,}041{,}347}\right)^{0.35}$$

$$= 0.778985$$

Substitute the appropriate calculated values into Equation 3-13 to determine the $C_i(\mathrm{CT})$ term of the coefficient of discharge, $C_d(\mathrm{FT})$:

$$C_i(\mathrm{CT}) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1 - \beta)M_1 \qquad (3\text{-}13)$$

$$= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8$$

$$+ 0.003(1 - 0.495597)(0.0)$$

$$= 0.602414$$

Substitute the applicable calculated values into Equation 3-15 to compute the *Upstrm* term of the coefficient of discharge, C_d(FT):

$$
\begin{aligned}
Upstrm &= [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \qquad (3\text{-}15)\\
&= [0.0433 + 0.0712e^{-8.5/4.0260} - 0.1145e^{-6.0/4.0260}]\\
&\quad \times [1 - 0.23(0.0135269)](0.0642005)\\
&= 0.000851774
\end{aligned}
$$

Substitute the applicable calculated values into Equation 3-16 to compute the *Dnstrm* term of the coefficient of discharge. C_d(FT):

$$
\begin{aligned}
Dnstrm &= -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \qquad (3\text{-}16)\\
&= -0.0116[0.491284 - 0.52(0.491284)^{1.3}](0.495597)^{1.1}\\
&\quad \times [1 - 0.14(0.0134223)]\\
&= -0.00149777
\end{aligned}
$$

Substitute the applicable calculated values into Equation 3-14 to compute the *Tap Term* of the coefficient of discharge, C_d(FT):

$$
\begin{aligned}
Tap\ Term &= Upstrm + Dnstrm \qquad (3\text{-}14)\\
&= 0.000851774 + (-0.00149777)\\
&= -0.000645999
\end{aligned}
$$

Substitute the applicable calculated values into Equation 3-13 to compute the C_i(FT) term of the coefficient of discharge, C_d(FT):

$$
\begin{aligned}
C_i(\mathrm{FT}) &= C_i(\mathrm{CT}) + Tap\ Term \qquad (3\text{-}12)\\
&= 0.602414 - 0.000645999\\
&= 0.601768
\end{aligned}
$$

Substitute the value for C_i(FT) and the intermediate values into Equation 3-11 to calculate the discharge coefficient, C_d(FT):

$$
\begin{aligned}
C_d(\mathrm{FT}) &= C_i(\mathrm{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4C \qquad (3\text{-}11)\\
&= 0.601768 + 0.000511\left[\frac{10^6(0.495597)}{2,041,347}\right]^{0.7}\\
&\quad + [0.0210 + 0.0049(0.0135261)](0.495597)^4(0.778985)\\
&= 0.602947 \text{ (second estimate of the coefficient of discharge)}
\end{aligned}
$$

By substituting the value of C_d(FT) into the applicable equations, the volume flow rate can be recalculated following the same process outlined in this example. The resulting volume flow rate value is as follows:

$$
\begin{aligned}
Q_v &= 617,049 \text{ cubic feet per hour at standard conditions}\\
&\quad [\text{based on } C_d(\mathrm{FT}) = 0.602947]
\end{aligned}
$$

And

$$
\begin{aligned}
Re_D &= 3.32449Q_v = 3.32449(617,049)\\
&= 2,051,373 \text{ (second estimate of Reynolds number)}
\end{aligned}
$$

Resulting in

$$
C_d(\mathrm{FT}) = 0.602944 \text{ (third estimate of coefficient of discharge)}
$$

On page 57, Equation 3-20 should read as follows:

$$\begin{aligned} A &= \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \\ &= \left[\frac{19{,}000(0.495597)}{2{,}041{,}328}\right]^{0.8} \qquad (3\text{-}20) \\ &= 0.0135262 \end{aligned}$$

On page 57, Equation 3-21 should read as follows:

$$\begin{aligned} C &= \left(\frac{10^6}{Re_D}\right)^{0.35} \\ &= \left(\frac{10^6}{2{,}041{,}328}\right)^{0.35} \qquad (3\text{-}21) \\ &= 0.778988 \end{aligned}$$

On page 58, Equation 3-15 should read as follows:

$$\begin{aligned} Upstrm &= [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \\ &= [0.0433 + 0.0712e^{\text{[illegible]}} - 0.1145e^{\text{[illegible]}}] \qquad (3\text{-}15) \\ &\quad \times [1 - 0.23(0.0135262)](0.0642005) \\ &= 0.000876388 \end{aligned}$$

On page 58, Equation 3-16 should read as follows:

$$\begin{aligned} Dnstrm &= -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \\ &= -0.0116[0.491284 - 0.52(0.491284)^{1.3}](0.495597)^{1.1} \qquad (3\text{-}16) \\ &\quad \times [1 - 0.14(0.0135262)] \\ &= -0.00152379 \end{aligned}$$

On page 58, Equation 3-14 should read as follows:

$$\begin{aligned} Tap\ Term &= Upstrm + Dnstrm \\ &= 0.000876388 + (-0.00152379) \qquad (3\text{-}14) \\ &= -0.000647402 \end{aligned}$$

On page 58, Equation 3-12 should read as follows;

$$\begin{aligned} C(FT) &= C_i(CT) + Tap\ Term \\ &= 0.602414 - 0.000647402 \qquad (3\text{-}12) \\ &= 0.601767 \end{aligned}$$

On page 58, Equation 3-11 should read as follows

$$\begin{aligned} C_d(FT) &= C(FT) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4 C \\ &= 0.601767 + 0.000511\left[\frac{10^6(0.495597)}{2{,}041{,}328}\right]^{0.7} \qquad (3\text{-}11) \\ &\quad + [0.0210 + 0.0049(0.0135262)](0.495597)^4(0.778988) \\ &= 0.602947 \text{ (second estimate of the coefficient of discharge)} \end{aligned}$$

Following the same calculation procedure for iteration of flow rate, the resulting volumetric flow rate is as follows:

$$Q_v = 617{,}046 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(FT) = 0.602944]$$

And

$$Re_D = 3.32449Q_v = 3.32449(617{,}046)$$
$$= 2{,}051{,}363 \text{ (third estimate of Reynolds number)}$$

Resulting in

$$C_d(FT) = 0.602944 \text{ (fourth estimate of coefficient of discharge)}$$

The volume flow rate calculation based on the fourth estimate of C_d(FT) follows. As stated above, three estimates of C_d(FT) should normally provide volume flow rate calculation results that are consistent with the requirements of Part 4.

$$Q_v = 617{,}046 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(FT) = 0.602944]$$

Since the given data contain values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate is the standard volume flow rate. To calculate the flow rate at the given base conditions (P_b = 14.65 pounds force per square inch absolute and T_b = 509.67°R), the standard volume flow rate and the appropriate values for P, T, and Z are substituted into Equation 3-7 as follows:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \tag{3-7}$$

$$= 617{,}046\left(\frac{509.67}{519.67}\right)\left(\frac{14.73}{14.65}\right)\left(\frac{0.997839}{0.997971}\right)$$

$$= 608{,}396 \text{ cubic feet per hour at base conditions}$$

3–C.3.2 METHOD 2: VOLUME FLOW RATE CALCULATION BASED ON THE FACTOR APPROACH PRESENTED IN APPENDIX 3–B

3–C.3.2.1 General

Using the given data, the volume flow rate of natural gas, in cubic feet per hour at standard conditions, can be calculated using Equation 3-B-2, as stated in Appendix 3-B:

$$Q_v = F_n(F_c + F_{sl})Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv}\sqrt{P_{f1} h_w} \tag{3-B-2}$$

Since the given data contain values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate requires conversion to the flow rate at base conditions of 14.65 pounds force per square inch absolute and 60°F.

The systematic approach to solving Equation 3-B-2 involves calculation of the individual factors as shown in 3-C.3.2.2 through 3-C.3.2.10.

3–C.3.2.2 Numeric Conversion Factor (F_n)

Equation 3-B-5b is used to calculate the numeric conversion factor:

$$F_n = 338.196E_v D^2\beta^2 \tag{3-B-5b}$$

Where

$$E_v = \frac{1}{\sqrt{1 - \beta^4}} \qquad (3\text{-}22)$$

Calculate the value of d, D, and β at a flowing temperature of 65°F from the given diameters d_r and D_r:

$$\begin{aligned} d &= d_r[1 + \alpha_1(T_f - T_r)] \qquad (3\text{-}9)\\ &= 4.000[1 + 0.00000925(524.67 - 527.67)]\\ &= 3.99989 \end{aligned}$$

And

$$\begin{aligned} D &= D_r[1 + \alpha_2(T_f - T_r)] \qquad (3\text{-}10)\\ &= 8.071[1 + 0.00000620(524.67 - 527.67)]\\ &= 8.07085 \end{aligned}$$

$$\begin{aligned} \beta &= d / D \qquad (3\text{-}8)\\ &= 3.99989 / 8.07085\\ &= 0.495597 \end{aligned}$$

Substitute the values for β and D into Equation 3-B-5:

$$\begin{aligned} F_n' &= 338.196 E_v D^2\beta^2 \qquad (3\text{-}B\text{-}5)\\ &= 338.196 \frac{1}{\sqrt{1 - \beta^4}} D^2\beta^2\\ &= 338.196 \frac{1}{\sqrt{1 - (0.495597)^4}} (8.07085)^2(0.495597)^2\\ &= 5581.82 \end{aligned}$$

3–C.3.2.3 Flange–Tapped Orifice Meter Coefficient of Discharge [C_d(FT)]

The following equation is used to calculate the coefficient of discharge:

$$C_d(\text{FT}) = F_c + F_{sl} \qquad (3\text{-}B\text{-}6)$$

Where:

$$\begin{aligned} F_c = {} & 0.5961 + 0.0291\beta^2 - 0.2290\beta^8\\ & + \left(0.0433 + 0.0712e^{-8.5/D} - 0.1145e^{-6.0/D}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1 - \beta^4}\\ & - 0.0116\left[\frac{2}{D(1 - \beta)} - 0.52\left(\frac{2}{D(1 - \beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right] \qquad (3\text{-}B\text{-}7) \end{aligned}$$

$$\begin{aligned} F_{sl} = {} & 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7}\\ & + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.35} \qquad (3\text{-}B\text{-}9) \end{aligned}$$

$$Re_D = 0.0114541\left(\frac{Q_b P_b G_i}{\mu D T_b Z_{b_{air}}}\right) \qquad (3\text{-}28)$$

On page 58, the third to the last equation should read as follows:

$$Q_s = 617{,}048 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(\text{FT}) = 0.602947]$$

On page 58, the second to the last equation should read as follows:

$$Re_D = 3.32446Q_s = 3.32446(617{,}048)$$
$$= 2{,}051{,}351 \text{ (second estimate of Reynolds number)}$$

On page 59, the second equation should read as follows.

$$Re_D = 3.32446Q_s = 3.32446(617{,}046)$$
$$= 2{,}051{,}345 \text{ (third estimate of Reynolds number)}$$

On page 59, Equation 3-7 should read as follows:

$$Q_b = Q_s\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right)$$
$$= 617{,}046\left(\frac{14.73}{14.65}\right)\left(\frac{509.67}{519.67}\right)\left(\frac{0.997839}{0.997971}\right) \qquad (3\text{-}7)$$
$$= 608{,}396 \text{ cubic feet per hour at base conditions}$$

On page 60, Equation 3-B-9 should read as follows:

$$F_s = 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7}$$
$$+ \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000}{Re_D}\right)^{0.35} \qquad (3\text{-}B\text{-}9)$$

On page 62, the first equation should read as follows:

$$F_c = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8$$
$$+ (0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1})\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4}$$
$$- 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]$$
$$= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8$$
$$+ (0.0433 + 0.0712e^{\text{[illegible]}} - 0.1145e^{\text{[illegible]}})[1 - 0.23(0.0137493)](0.0642005)$$
$$- 0.0116[0.491284 - 0.52(0.491284^{1.3})](0.495597)^{1.1}[1 - 0.14(0.0137493)]$$
$$= 0.601767$$

$$B = \frac{\beta^4}{1 - \beta^4} \tag{3-17}$$

$$M_2 = \frac{2L_2}{1 - \beta} \tag{3-19}$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \tag{3-20}$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \tag{3-21}$$

Note: In this example, since the given meter tube diameter (D) is greater than 2.8 inches, Equation 3-B-7 is used to calculate the F_c term. For meter tube diameters (D) less than 2.8 inches, Equation 3-B-8 must be used to calculate the F_c term. The solution of the intermediate equations presented above for the flow coefficient calculation follows.

Substituting the calculated values of β and D gives the following:

$$\frac{\beta^4}{1 - \beta^4} = \frac{(0.495597)^4}{1 - (0.495597)^4}$$
$$= 0.0642005$$

$$\frac{2}{D(1 - \beta)} = \frac{2}{8.07085(1 - 0.495597)}$$
$$= 0.491284$$

As discussed in 3.4.5, the Reynolds number (Re_D) for natural gas can be approximated using Equation 3-28. Note that the parameters of this example are within the recommended tolerances for viscosity, temperature, and specific gravity. Furthermore, 3.4.5 states that when the flow rate is not known, a more precise value for the Reynolds number can be determined through iteration of Equation 3-28 and that three to five iterations will provide results that are consistent with the requirements of Part 4. The initial assumption needed for the first iteration can come from assuming a value for C_d(FT) as in the previous example or from assuming an initial Reynolds number for the pipe Reynolds number. Table 3-B-1, Appendix 3-B, provides values for pipe Reynolds numbers versus nominal pipe diameters for the purpose of initiating the iteration process. This example uses Table 3-B-1 for the initial estimate of pipe Reynolds number.

$$Re_D = 2{,}000{,}000 \quad \text{(initial assumption from Table 3-B-1)}$$

Substituting the values of Re_D and β gives the following:

$$\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} = \left[\frac{19{,}000(0.495597)}{2{,}000{,}000}\right]^{0.8}$$
$$= 0.0137493$$

$$\left(\frac{10^6}{Re_D}\right)^{0.35} = \left(\frac{10^6}{2{,}000{,}000}\right)^{0.35}$$
$$= 0.784584$$

Substitute the appropriate calculated values into Equation 3-B-7 to determine the orifice calculation factor, F_c:

$$
\begin{aligned}
F_c &= 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 \\
&\quad + \left(0.0433 + 0.0712e^{-8.5/D} - 0.1145e^{-6.0/D}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4} \\
&\quad - 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right] \\
&= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8 \\
&\quad + \left(0.0433 + 0.0712e^{-8.5/8.07101} - 0.1145e^{-6.0/8.07101}\right)[1 - 0.23(0.0137493)](0.0642005) \\
&\quad - 0.0116[0.491284 - 0.52(0.491284)]^{1.3}(0.495597)^{1.1}[1 - 0.14(0.0137493)] \\
&= 0.601767
\end{aligned}
$$

Substitute the applicable calculated values into Equation 3-B-9 to compute the orifice slope factor, F_{sl}:

$$
\begin{aligned}
F_{sl} &= 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} \\
&\quad + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.35} \qquad (3\text{-B-}9) \\
&= 0.000511\left(\frac{1{,}000{,}000(0.4955972)}{2{,}000{,}000}\right)^{0.7} \\
&\quad + [0.0210 + 0.0049(0.0137493)](0.495597)^4(0.784584) \\
&= 0.00118960
\end{aligned}
$$

Substitute the values for F_c and F_{sl} in Equation 3-B-6 to calculate the discharge coefficient, C_d(FT):

$$
\begin{aligned}
C_d(\text{FT}) &= F_c + F_{sl} \\
&= 0.601767 + 0.00118960 \\
&= 0.602957
\end{aligned}
$$

3-C.3.2.4 Expansion Factor (Y_1)

The following equation is used to calculate the expansion factor:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \qquad (3\text{-}32)$$

The intermediate value, x_1, is calculated as follows:

$$x = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707P_{f_1}} \qquad (3\text{-}33)$$

Substitute the given values of h_w and P_{f_1} into Equation 3-33:

$$
\begin{aligned}
x_1 &= \frac{50.0}{27.707(370.0)} \\
&= 0.00487729
\end{aligned}
$$

Substitute the values for k, x_1, and β into Equation 3-32:

3-C.3.2.8 Flowing Temperature Factor (F_{tf})

The flowing temperature factor is calculated using Equation 3-B-12 as follows:

$$F_{tf} = \sqrt{\frac{519.67}{T_f}} \qquad \text{(3-B-12)}$$

Substitute the given flowing temperature, T_f, into Equation 3-B-12:

$$\begin{aligned} F_{tf} &= \sqrt{\frac{519.67}{T_f}} \\ &= \sqrt{\frac{519.67}{524.67}} \\ &= 0.995224 \end{aligned}$$

3-C.3.2.9 Real Gas Relative Density Factor (F_{gr})

Equation 3-B-13 is used to calculate the real gas relative density factor.

$$F_{gr} = \sqrt{\frac{1}{G_r}} \qquad \text{(3-B-13)}$$

Substitute the given specific gravity, G_r, into Equation 3-B-13:

$$\begin{aligned} F_{gr} &= \sqrt{\frac{1}{G_r}} \\ &= \sqrt{\frac{1}{0.570}} \\ &= 1.32453 \end{aligned}$$

3-C.3.2.10 Supercompressibility Factor (F_{pv})

As stated in the calculations in 3-C.3.1, the derivation of the equation for compressibility is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the procedures necessary for calculating the compressibility at standard conditions (Z_s) or at flowing conditions (Z_{f_1}).

$$\begin{aligned} Z_s &= 0.997971 \\ Z_{f_1} &= 0.951308 \end{aligned}$$

Equation 3-B-14 is used to calculate the supercompressibility factor:

$$\begin{aligned} F_{pv} &= \sqrt{\frac{Z_s}{Z_f}} \\ &= \sqrt{\frac{0.997971}{0.951308}} \\ &= 1.02423 \end{aligned}$$

3-C.3.2.11 Volume Flow Rate (Q_v)

The volume flow rate is calculated by substituting the given parameters and the intermediate calculated factors into Equation 3-B-2.

$$\begin{aligned} Q_v &= F_n (F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \sqrt{P_f h_w} \qquad \text{(3-B-2)} \\ &= 617{,}057 \end{aligned}$$

The calculated flow rate above is based on an initial assumed value for the Reynolds number (Re_D) of 2,000,000. For the second estimate, the value of Re_D is calculated as follows:

$$
\begin{aligned}
Re_D &= 0.0114588\left(\frac{Q_v P_s G_r}{\mu D T_s}\right) \\
&= 3.32449 Q_v \\
&= 3.32449(617{,}057) \\
&= 2{,}051{,}400 \text{ (second iteration)}
\end{aligned}
$$

By substituting the second estimate of Re_D into the applicable equations, the volume flow rate can be recalculated by following the process outlined in 3-C.3.1. The resulting volume flow rate is as follows:

$$Q_v = 617{,}013 \quad \text{(based on the second estimate of } Re_D\text{)}$$

The same calculation procedures are used to obtain the third estimate of Re_D:

$$
\begin{aligned}
Re_D &= 3.32449 Q_v \\
&= 3.32449(617{,}013) \\
&= 2{,}051{,}254 \text{ (third iteration)}
\end{aligned}
$$

The volume flow rate calculation based on the third estimate of Re_D follows. As stated above, three to five estimates of Re_D will provide calculation results that are consistent with the requirements of Part 4.

$$
\begin{aligned}
Q_v &= F_n (F_c - F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \sqrt{P_{f1} h_w} \\
&= (5581.82)(0.601767 + 0.00117736)(0.998383)(1.00000)(1.00000) \\
&\quad \times (0.995224)(1.32453)(1.02423)\sqrt{(370.0)(50.0)} \\
&= 617{,}044 \text{ cubic feet per hour}
\end{aligned}
$$

Note: The calculated volume flow rate is based on the third estimate of Re_D. The small discrepancy between the calculated volume flow rate, Q_v, in Methods 1 and 2 results from the rounding techniques used in the series of equations in the examples

Since the given data included values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differed from the values established in Part 3 for standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate is the standard volume flow rate. To calculate the flow rate at base conditions (P_b = 14.65 pounds force per square inch absolute and T_b = 509.67°R), the standard volume flow rate and the appropriate values for P, T, and Z are substituted into Equation 3-7 as follows:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \qquad (3\text{-}7)$$

$$
\begin{aligned}
&= 617{,}044\left(\frac{509.67}{519.67}\right)\left(\frac{14.73}{14.65}\right)\left(\frac{0.997839}{0.997971}\right) \\
&= 608.394 \text{ cubic feet per hour at base conditions}
\end{aligned}
$$

APPENDIX 3-D—PIPE TAP ORIFICE METERING

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3–D.1 Symbols, Units, and Terminology

3–D.1.1 GENERAL

Some of the symbols listed in 3-D.1.2 are specific to this appendix. Unless otherwise noted, all of these symbols are dimensionless. Symbols that are used in this appendix but not listed in 3-D.1.2 are defined in 3.2.2.

3–D.1.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
C'	Orifice flow constant	—
F_b	Basic orifice factor	—
K_e	Coefficient of discharge when Reynolds number = $(1{,}000{,}000d)/15$	—
K_o	Coefficient of discharge for infinite Reynolds number	—
ρ	Specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F	lbm/ft^3

3–D.2 Scope

3–D.2.1 INTRODUCTION

Recent research work on orifice measurement has been restricted to flange, corner, and radius tap meters. It is recognized that a number of "pipe tap" meters continue in operation in natural gas measurement in the United States. The provisions of the second (1985) edition of Chapter 14, Section 3, that are applicable to pipe tap configurations are included in this appendix. The dimensional information, tolerances, and computation methods in this appendix are only applicable to pipe tap meters.

This appendix provides recommendations and specifications relating to the measurement of natural gas and other related hydrocarbon fluids by means of orifice meters equipped with pipe taps. It includes definitions, construction and installation specifications, and instructions for computing flow rate and volume. Also included are equations and tables that provide factors necessary to apply adjustments to the basic pipe tap orifice flow.

This appendix covers the measurement of natural gas by pipe tap orifice meters, including the primary element and the methods of calculation. It does not cover the equipment used to determine the pressure, temperature, specific gravity, and other variances that must be known for the accurate measurement of natural gas.

3–D.2.2 GENERAL

Unless specifically noted in this appendix, all information and data presented in the body of this standard—including recommendations, specifications, and symbols—are applicable to pipe tap orifice metering.

3–D.2.3 TYPE OF METER

This appendix is limited to orifice meters that have circular orifices located concentrically in the meter tube, having upstream and downstream pressure taps as specified for pipe taps.

3–D.2.4 DEFINITION OF *PIPE TAP PRESSURE MEASUREMENT*

The definition of *pipe tap pressure measurement* is based on the position of the pair of tap holes. The upstream tap center is located 2.5 times the inside pipe diameter upstream from the nearest plate face, and the downstream tap center is located 8 times the inside pipe diameter downstream from the nearest plate face (see 3-D.3.4.1).

3–D.3 Construction and Installation Specifications

3–D.3.1 BETA RATIO LIMITATIONS OF ORIFICE PLATES

The orifice-to-meter-tube (pipe) diameter ratio ($\beta = d/D$) should fall within the range from 0.20 to 0.67 inclusive. These limits, with an uncertainty as high as ±0.75 percent, may be exceeded when additional flow uncertainty is acceptable. Beta ratios that exceed the range from 0.20 to 0.67, with an uncertainty as high as ±1.5 percent, may be used; however, the flow constants for these extreme values of β are subject to higher tolerances, and the use of these extremes should be avoided.

3–D.3.2 METER TUBE SPECIFICATIONS

3–D.3.2.1 Definition

The term *meter tube* refers to the straight upstream pipe of length A or A' on the installation sketches in Part 2 (including the straightening vanes, if used), the orifice flanges or fittings, and the downstream pipe (length B on the installation sketches in Part 2) beyond the orifice. The length of upstream and downstream pipe is specified in Part 2. The tolerances for the diameter and the restrictions on the inside surface of the meter tube are specified in 3-D.3.2.4. There shall be no pipe connections within these distances other than straightening vanes, the thermometer wells specified in Part 2, and the pressure taps specified in 3-D.2.4 and Part 2.

3–D.3.2.2 Inside Surface

The sections of pipe to which the orifice flanges or fittings are attached and the adjacent pipe sections that constitute the meter tube, as defined in 3-D.3.2.1, shall comply with the following:

a. The roughness of the inside pipe walls shall not exceed 300 microinches. Carefully selected smooth commercial pipe may be used. Seamless pipe or cold drawn seamless pressure tubing may be used, provided its inside wall is smooth. Drawn-over-mandrel (DOM), electric-resistance-welded (ERW), straight-seam tubing manufactured to the requirements of ASTM A 513, T-5, may also be used. To improve smoothness inside the meter tube, the inside pipe walls may be machined, ground, or coated.

b. Grooves, scoring, pits, and ridges resulting from seams; distortion caused by welding; offsets; and other irregularities (regardless of their size) that affect the inside diameter at the points identified in Figure 3-D-1 by more than the tolerances shown are not permitted. When these tolerances are exceeded, the irregularities must be corrected.

c. The interior of the meter tube shall be kept clean and free from accumulations of contaminants, such as dirt and liquids, at all times.

3–D.3.2.3 Meter Tube Diameter

The mean inside diameter of the meter tube shall be determined as follows:

a. Measurements shall be made on at least four diameters equally spaced in a plane 1 inch upstream from the upstream face of the orifice plate. The mean (arithmetic average) of these measurements is defined as the mean meter tube diameter to be used in calculating the flow coefficient when minimum uncertainty of this variable is desired.

b. Check measurements of the upstream inside diameter of the meter tube shall be made at two or more additional cross-sections. The actual locations of the check measurements of the diameter, circumferentially and axially along the tube, are not specified. These checks should be taken at points that will indicate the maximum and minimum diameters that exist and should cover at least two pipe diameters from the face of the orifice plate or extend past the flange or fitting weld, whichever distance is greater. Check measurements are used to verify the uniformity of the upstream meter tube but do not become a part of the mean meter tube diameter.

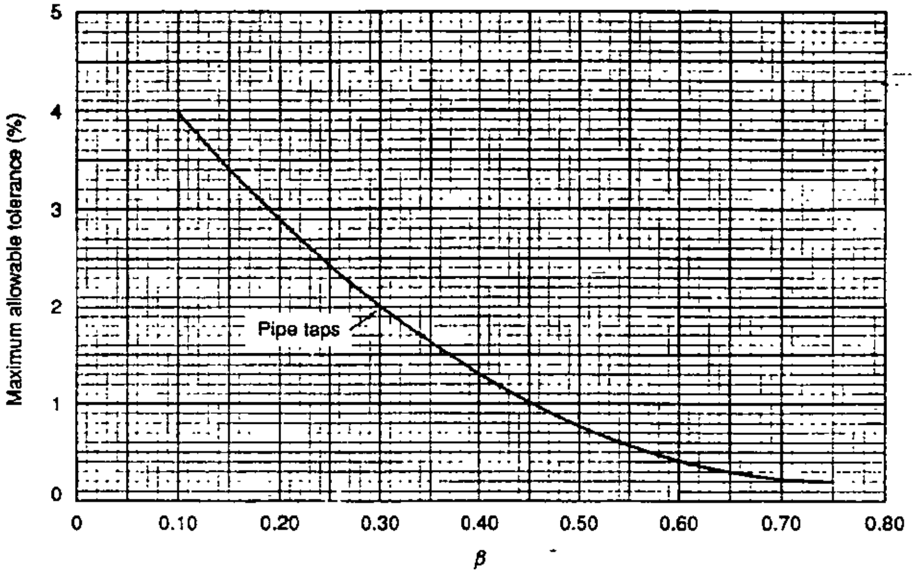


Figure 3-D-1—Maximum Percentage Allowable Meter Tube Tolerance Versus Beta Ratio

c. The inside diameter of the downstream section of the meter tube shall be measured in a plane 1 inch downstream from the downstream face of the orifice plate. Check measurements of the diameter of the downstream section of the meter tube, similar to those described in Item b above, shall be made at two additional cross-sections.

3–D.3.2.4 Tolerances and Restrictions

The tolerances for the diameter and the restrictions on the inside surface of the meter tube are as follows:

a. The difference between the maximum measured diameter and the minimum measured diameter on the inlet section shall not exceed the tolerance shown in Figure 3-D-1 as a percentage of the mean diameter defined in 3-D.3.2.3. The relationship below may be used to calculate the variance of the diameter of the upstream section of the meter tube:

$$\frac{\text{Maximum diameter} - \text{Minimum diameter}}{D} \times 100 \leq \text{Percent tolerance in Figure 3-D-1}$$

b. Abrupt changes in diameter (shoulders, offsets, ridges, and so forth) shall not exist in the meter tube (see 3-D 3.2.3, Item b).

c. When Table 3-D-1 is used for flow measurement estimation, the meter tube diameter, as defined in 3-D 3 2 3, shall agree with the inside diameters listed in the tables within the tolerance shown in Figure 3-D-1.

d. Any diameter measurement in the downstream section shall not vary from the mean diameter of the meter tube, as defined in 3-D.3.2.3, by more than the tolerance shown in Figure 3-D-1. The following relationship may be used to calculate the variance of the diameter of the downstream section of the meter tube.

$$\left|\frac{\text{Any diameter} - D}{D}\right| \times 100 \leq \text{Percent tolerance in Figure 3-D-1}$$

Application of this equation doubles the tolerance for the downstream section of the meter tube.

e. The temperature at which the meter tube measurements are made should be recorded for correction to the operating conditions.

For new installations, in which the beta ratio is likely to be changed, the tolerance permitted for variations in pipe size, as shown in Figure 3-D-1, should be the same as that given for a maximum orifice plate diameter ratio (β) of 0.75.

3–D.3.2.5 Use of Table 3–D–1

If Table 3-D-1 is used for flow estimation, the mean inside diameter of the upstream section of the meter tube should be as nearly the same as the published inside diameter given in Table 3-D-1 as is possible. The inside diameters given in the table were used to calculate the constants in the table. If the mean meter tube diameter differs from the table inside diameter by an amount greater than the tolerance set forth in Figure 3-D-1 or if minimum uncertainty is desired, the mean meter tube diameter should be used to compute the orifice-to-meter-tube diameter ratio, β, as well as the flow coefficient. Other factors should be calculated for this exact value of β.

3–D.3.3 LENGTH OF PIPE PRECEDING AND FOLLOWING THE ORIFICE

The installation sketches and accompanying graphs are not duplicated in this appendix but are available in Part 2, Figures 2-5 through 2-9. The graphs show the minimum lengths of straight pipe required (expressed in nominal pipe diameters) versus beta ratio. It must be noted that when pipe taps are used, lengths *A*, *A'*, and *C* shall be increased by two nominal pipe diameters and length *B* shall be increased by eight nominal pipe diameters. The lengths of straight pipe should be those required for the maximum beta ratio that may be used.

3–D.3.4 PRESSURE TAP HOLES

3–D.3.4.1 Location

Meter tubes that use pipe taps shall have the center of the upstream tap hole located 2.5 times the published or actual inside diameter from the upstream face of the orifice plate.

Table 3-D-1—Basic Orifice Factors (F_b) for Pipe Taps (All Dimensions in Inches)

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 2 Inches			Published Inside Diameters at Nominal Pipe Size of 3 Inches				Published Inside Diameters at Nominal Pipe Size of 4 Inches			
	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.250	12.850	12.813	12.800	12.782	22.765	12.754	12.748	12.745	12.737	12.727	12.723
0.375	29.362	29.098	29.006	28.883	28.772	28.711	28.682	28.670	28.635	26.599	28.585
0.500	53.713	52.817	52.482	52.020	51.594	51.354	51.244	51.197	51.065	50.937	50.887
0.625	87.237	84.920	84.085	82.924	81.802	81.143	80.837	80.704	80.334	79.976	79.837
0.750	132.29	126.87	124.99	122.45	120.08	118.67	118.00	117.70	116.87	116.05	115.73
0.875	192.87	181.02	177.09	171.93	167.26	164.58	163.31	162.76	161.17	159.58	158.94
1.000	275.73	251.17	243.28	233.30	224.61	219.77	217.53	216.55	213.79	211.03	209.92
1.125	392.50	342.99	327.99	309.44	293.87	285.49	281.67	280.03	275.43	270.91	269.10
1.250		466.00	438.00	404.53	377.[illegible]	363.41	357.13	354.45	347.04	339.88	337.06
1.375			583.98	524.69	478.89	455.83	445.75	441.49	429.84	418.80	414.51
1.500				679.12	602.80	565.80	549.95	543.32	525.41	508.77	502.39
1.625					755.89	697.45	672.96	662.83	635.77	611.12	601.81
1.750					917.87	856.39	819.07	803.79	763.53	727.55	714.17
1.875						1,050.4	994.01	971.22	912.00	860.19	841.21
2.000						1,290.7	1,205.6	1,171.9	1,085.5	1,011.7	985.07
2.125							1,465.1	1,415.0	1,289.7	1,185.4	1,148.4
2.250									1,532.0	1,385.4	1,334.5
2.375									1,822.9	1,617.2	1,547.4
2.500										1,887.7	1,792.3
2.625										2,206.1	2,076.0
2.750											2,407.0

Table 3-D-1—Continued

	Published Inside Diameters at Nominal Pipe Size of 6 Inches				Published Inside Diameters at Nominal Pipe Size of 8 Inches			Published Inside Diameters at Nominal Pipe Size of 10 Inches			Published Inside Diameters at Nominal Pipe Size of 12 Inches		
Orifice Diameter	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.136	11.374	11.938	12.090
0.500	50.740	50.707	50.653	50.629									
0.625	79.438	79.351	79.219	79.164									
0.750	114.81	114.62	114.32	114.20									
0.875	157.11	156.72	156.13	155.89	155.11	154.99	154.97						
1.000	206.63	205.92	204.85	204.41	203.01	202.80	202.76	202.16					
1.125	263.71	262.52	260.72	259.99	257.62	257.28	257.20	256.23	256.01	255.96			
1.250	328.73	326.87	324.03	322.87	319.10	318.57	318.44	316.90	316.57	316.49	315.82	315.57	315.51
1.375	402.07	399.32	395.09	393.34	387.63	386.81	386.63	384.30	383.80	383.68	382.67	382.31	382.22
1.500	484.21	480.26	474.21	471.70	463.40	462.20	461.93	458.53	457.80	457.64	456.17	455.65	455.53
1.625	575.75	570.19	561.74	558.25	546.62	544.93	544.54	539.73	538.70	538.47	536.40	535.67	535.49
1.750	677.39	669.69	658.09	653.34	637.52	635.20	634.67	628.05	626.63	626.30	623.46	622.46	622.22
1.875	790.00	779.49	763.79	757.41	736.36	733.25	732.53	723.63	721.72	721.28	717.45	716.12	715.79
2.000	914.59	900.39	879.40	870.95	843.36	839.31	838.37	826.66	824.14	823.56	818.51	816.75	816.32
2.125	1,052.3	1,033.4	1,005.6	994.54	958.80	953.61	952.40	937.31	934.04	933.29	926.74	924.46	923.90
2.250	1,204.7	1,179.6	1,143.2	1,128.9	1,083.0	1,076.4	1,074.9	1,055.8	1,051.6	1,050.7	1,042.3	1,039.4	1,038.7
2.375	1,373.4	1,340.5	1,293.2	1,274.6	1,216.3	1,208.0	1,206.1	1,182.3	1,177.0	1,175.8	1,165.3	1,161.7	1,160.8
2.500	1,560.5	1,517.5	1,456.5	1,432.8	1,359.2	1,348.9	1,346.5	1,316.9	1,310.5	1,309.0	1,296.0	1,291.4	1,290.3
2.625	1,768.3	1,712.6	1,634.4	1,604.3	1,512.1	1,499.3	1,496.4	1,460.1	1,452.2	1,450.4	1,434.4	1,428.8	1,427.4
2.750	1,999.9	1,928.1	1,828.3	1,790.4	1,675.4	1,659.7	1,656.1	1,611.8	1,602.3	1,600.1	1,580.7	1,573.9	1,572.2
2.875	2,258.6	2,166.5	2,040.0	1,992.3	1,849.9	1,830.7	1,826.3	1,771.6	1,761.1	1,758.4	1,735.2	1,727.0	1,725.0
3.000	2,548.6	2,431.0	2,271.2	2,211.6	2,036.1	2,012.7	2,007.4	1,942.6	1,928.8	1,925.6	1,897.9	1,888.2	1,885.8
3.125	2,875.3	2,725.3	2,524.3	2,450.2	2,234.7	2,206.4	2,200.0	2,122.2	2,105.8	2,102.0	2,069.1	2,057.6	2,054.7
3.250	3,244.9	3,054.0	2,801.9	2,710.0	2,446.6	2,412.5	2,404.8	2,311.8	2,292.3	2,287.8	2,249.0	2,235.4	2,232.1
3.375	3,665.7	3,422.4	3,106.9	2,993.4	2,677.6	2,631.7	2,622.4	2,511.7	2,488.7	2,483.4	2,437.8	2,421.9	2,418.0
3.500		3,837.6	3,443.1	3,303.1	2,913.7	2,864.8	2,853.7	2,722.5	2,695.4	2,689.2	2,635.8	2,617.2	2,612.7
3.625		4,308.1	3,814.5	3,642.4	3,171.2	3,112.8	3,099.6	2,944.5	2,912.8	2,905.5	2,843.2	2,821.6	2,816.4
3.750			4,226.4	4,014.9	3,446.1	3,376.7	3,361.1	3,178.4	3,141.3	3,132.8	3,060.3	3,035.4	3,029.3
3.875			4,685.0	4,425.2	3,739.9	3,657.7	3,639.3	3,424.6	3,381.4	3,371.5	3,287.5	3,258.8	3,251.8
4.000			5,197.9	4,878.5	4,054.3	3,957.1	3,935.3	3,683.9	3,633.6	3,622.2	3,525.2	3,492.1	3,484.0
4.250					4,751.6	4,616.7	4,586.7	4,244.2	4,176.9	4,161.7	4,033.1	3,989.6	3,979.1
4.500					5,554.8	5,369.1	5,328.1	4,865.6	4,776.3	4,756.2	4,587.4	4,530.9	4,517.3
4.750					6,485.5	6,231.3	6,175.4	5,555.6	5,438.0	5,411.6	5,191.9	5,119.1	5,101.6
5.000					7,571.6	7,224.5	7,148.8	6,323.1	6,169.4	6,135.0	5,851.1	5,757.9	5,735.6
5.250					8,850.5	8,376.6	8,274.2	7,178.8	6,979.1	6,934.6	6,570.1	6,451.7	6,423.4
5.500						9,724.0	9,585.4	8,135.5	7,877.4	7,820.2	7,354.9	7,205.3	7,169.7
5.750								9,208.8	8,876.6	8,803.3	8,212.4	8,024.4	7,979.8
6.000								10,418	9,991.5	9,898.0	9,150.7	8,915.6	8,860.0
6.250								11,786	11,240	11,121	10,179	9,886.4	9,817.5
6.500								13,344	12,644	12,493	11,309	10,946	10,860
6.750									14,231	14,038	12,552	12,103	11,998
7.000									16,035	15,790	13,925	13,371	13,242
7.250											15,446	14,763	14,605
7.500											17,135	16,295	16,102
7.750											19,021	17,986	17,750
8.000												19,861	19,572
8.250												21,948	21,594

The center of the downstream tap hole shall be located eight times the published or actual inside diameter from the downstream face of the orifice plate. Figure 3-D-2 shows the allowable tolerances. A maximum beta ratio of 0.75 should be used in the design of new installations

3–D.3.4.2 Fabrication

Meter tubes that use pipe taps shall have a hole of the proper size drilled through the pipe wall. Proper hole sizes are listed in Table 3-D-2. The hole shall not be threaded. A fitting

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
1.500	453.93	453.79										
1.625	533.28	533.09	532.94									
1.750	619.20	618.94	618.74									
1.875	711.75	711.41	711.14									
2.000	811.01	810.55	810.21	806.73	806.59	806.42						
2.125	917.03	916.45	916.01	911.54	911.37	911.15						
2.250	1,029.9	1,029.2	1,028.6	1,022.9	1,022.7	1,022.5						
2.375	1,149.7	1,148.8	1,148.1	1,141.0	1,140.7	1,140.4	1,136.8	1,136.5	1,136.3			
2.500	1,276.6	1,275.4	1,274.5	1,265.7	1,265.4	1,265.0	1,260.6	1,260.2	1,260.0			
2.625	1,410.5	1,409.1	1,408.0	1,397.2	1,396.8	1,396.3	1,390.9	1,390.5	1,390.2			
2.750	1,551.7	1,550.0	1,548.6	1,535.5	1,535.0	1,534.4	1,527.9	1,527.4	1,527.0			
2.875	1,700.2	1,698.1	1,696.5	1,680.7	1,680.1	1,679.4	1,671.6	1,670.9	1,670.5	1,663.7		
3.000	1,856.1	1,853.6	1,851.7	1,832.8	1,832.1	1,831.2	1,821.9	1,821.1	1,820.6	1,821.6	1,812.3	1,812.1
3.125	2,019.6	2,016.6	2,014.4	1,991.9	1,991.1	1,990.0	1,979.0	1,978.1	1,977.5	1,968.0	1,967.7	1,967.4
3.250	2,190.7	2,187.2	2,184.6	2,158.1	2,157.1	2,155.8	2,142.9	2,141.8	2,141.1	2,130.0	2,129.7	2,129.3
3.375	2,369.7	2,365.6	2,362.5	2,331.4	2,330.3	2,328.8	2,313.6	2,312.3	2,311.5	2,298.6	2,298.2	2,297.8
3.500	2,556.5	2,551.7	2,548.1	2,512.0	2,510.6	2,508.9	2,491.2	2,489.8	2,488.8	2,473.9	2,473.4	2,472.9
3.625	2,751.5	2,745.9	2,741.7	2,699.8	2,698.3	2,696.3	2,675.8	2,674.1	2,673.0	2,655.8	2,655.2	2,654.7
3.750	2,954.6	2,948.2	2,943.4	2,895.1	2,893.3	2,891.0	2,867.4	2,865.5	2,864.2	2,844.4	2,843.7	2,843.1
3.875	3,166.0	3,158.7	3,153.2	3,097.8	3,095.7	3,093.1	3,066.1	3,063.8	3,062.4	3,039.7	3,039.0	3,038.3
4.000	3,385.8	3,377.5	3,371.3	3,308.1	3,305.7	3,302.7	3,271.9	3,269.3	3,267.7	3,241.8	3,241.0	3,240.2
4.250	3,851.7	3,841.0	3,832.9	3,751.8	3,748.8	3,744.9	3,705.1	3,701.8	3,699.7	3,666.5	3,665.4	3,664.4
4.500	4,353.5	4,339.9	4,329.7	4,226.9	4,223.1	4,218.2	4,167.7	4,163.5	4,160.8	4,118.7	4,117.4	4,116.1
4.750	4,893.0	4,875.9	4,863.0	4,734.3	4,729.5	4,723.4	4,660.2	4,654.9	4,651.5	4,598.9	4,597.2	4,595.5
5.000	5,472.1	5,450.6	5,434.5	5,274.7	5,268.8	5,261.3	5,183.1	5,176.6	5,172.4	5,107.3	5,105.2	5,103.1
5.250	6,092.7	6,066.0	6,046.0	5,849.2	5,842.0	5,832.8	5,737.2	5,729.2	5,724.1	5,644.3	5,641.8	5,639.3
5.500	6,757.2	6,724.3	6,699.6	6,458.8	6,450.1	6,438.8	6,323.1	6,313.4	6,307.2	6,210.4	6,207.3	6,204.3
5.750	7,468.2	7,427.8	7,397.6	7,104.7	7,094.2	7,080.6	6,941.5	6,929.8	6,922.4	6,806.0	6,802.3	6,798.7
6.000	8,228.7	8,179.4	8,142.5	7,778.2	7,775.5	7,759.3	7,593.1	7,579.2	7,570.3	7,431.5	7,427.1	7,422.8
6.250	9,041.9	8,981.9	8,937.2	8,510.8	8,495.6	8,476.2	8,278.6	8,262.2	8,251.7	8,087.5	8,082.2	8,077.1
6.500	9,911.4	9,838.9	9,784.9	9,273.8	9,255.8	9,232.7	8,999.1	8,979.7	8,967.3	8,774.3	8,768.1	8,762.1
6.750	10,842	10,754	10,689	10,079	10,058	10,031	9,755.4	9,732.6	9,718.1	9,492.6	9,485.4	9,478.4
7.000	11,837	11,732	11,654	10,929	10,903	10,871	10,548	10,522	10,505	10,243	10,234	10,226
7.250	12,902	12,777	12,684	11,824	11,795	11,757	11,380	11,349	11,329	11,026	11,016	11,007
7.500	14,044	13,894	13,784	12,768	12,733	12,689	12,250	12,214	12,191	11,841	11,830	11,819
7.750	15,269	15,091	14,959	13,763	13,722	13,671	13,161	13,119	13,093	12,691	12,678	12,666
8.000	16,583	16,372	16,216	14,811	14,764	14,704	14,113	14,065	14,036	13,575	13,560	13,546

should be fastened to the pipe at this point, and great care must be exercised to ensure that the inside of the pipe is not distorted in any way.

The diameter of the tap hole shall not be reduced within a length equal to 2.5 times the tap hole diameter as measured from the inside surface of the meter tube. If the fitting is welded to the pipe used to fabricate the meter tube, the tap hole shall not be drilled until after the welding is done

In Table 3-D-2, the finished tap hole shall be ±1/64 inch from the selected nominal tap hole diameter along the drilled length of the hole.

3-D.4 Computing the Flow of Natural Gas and Other Related Hydrocarbon Fluids Through Orifice Meters Equipped With Pipe Taps

3-D.4.1 GENERAL

The recommendations in 3-D.4.2 through 3-D.4.8 concerning calculations and computations are confined strictly to pipe tap orifice meters installed and operated according to the provisions of this appendix. The equations use inch-pound units and absolute values

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
8.250	17,996	17,746	17,562	15,915	15,861	15,791	15,109	15,055	15,020	14,494	14,477	14,461
8.500	19,517	19,221	19,004	17,079	17,016	16,935	16,150	16,088	16,048	15,448	15,429	15,411
8.750	21,157	20,807	20,551	18,306	18,233	18,140	17,238	17,166	17,121	16,439	16,418	16,398
9.000	22,927	22,515	22,214	19,600	19,515	19,408	18,374	18,293	18,241	17,468	17,444	17,421
9.250	24,842	24,357	24,004	20,964	20,867	20,744	19,561	19,468	19,410	18,535	18,508	18,482
9.500	26,917	26,347	25,932	22,404	22,293	22,151	20,801	20,695	20,629	19,642	19,612	19,582
9.750	29,173	28,502	28,015	23,925	12,797	23,635	22,096	21,976	21,901	20,789	20,755	20,722
10.000	31,630	30,840	30,269	25,531	25,384	25,199	23,448	23,313	23,228	21,977	21,939	21,902
10.250	34,316	33,384	32,714	27,229	27,062	26,850	24,861	24,708	24,612	23,208	23,165	23,124
10.500		36,161	35,373	29,026	28,834	28,593	26,337	26,165	26,057	24,482	24,435	24,389
10.750				30,928	30,710	30,435	27,879	27,686	27,564	25,802	25,749	25,698
11.000				32,944	32,695	32,382	29,492	29,274	29,137	27,168	27,109	27,053
11.250				35,082	34,799	34,444	31,177	30,933	30,780	28,582	28,517	28,454
11.500				37,353	37,031	36,627	32,941	32,667	32,495	30,045	29,973	29,904
11.750				39,766	39,401	38,942	34,786	34,479	34,286	31,559	31,480	31,403
12.000				42,336	41,921	41,400	36,717	36,374	36,158	33,126	33,038	32,953
12.500				47,998	47,462	46,791	40,859	40,430	40,162	36,426	36,319	36,216
13.000				54,472	53,779	52,915	45,410	44,878	44,545	39,960	39,830	39,705
13.500							50,425	49,765	49,353	43,746	43,590	43,438
14.000							55,965	55,148	54,640	47,805	47,617	47,435
14.500							62,106	61,096	60,469	52,159	51,933	51,715
15.000							68,938	67,689	66,917	56,833	56,563	56,303
15.500							76,572	75,027	74,075	61,857	61,535	61,225
16.000								83,233	82,057	67,263	66,879	66,511
16.500										73,087	72,632	72,195
17.000										79,372	78,833	78,315
17.500										86,165	85,227	84,915
18.000										93,522	92,767	92,044
18.500										101,506	100,614	99,761
19.000										110,192	109,137	108,130
19.500										119,667	118,420	117,231
20.000										130,036	128,559	127,153

throughout. Constants and variables that have a subscript of 1 indicate upstream measurements; those that have a subscript of 2 indicate downstream measurements.

3–D.4.2 EQUATION

In the measurement of most gases, especially natural gas, the general practice is to express the flow rate in cubic feet per hour at some specified reference or base conditions of pressure and temperature (that is, in standard cubic feet per hour). To calculate the quantity of gas, the following equation shall be used:

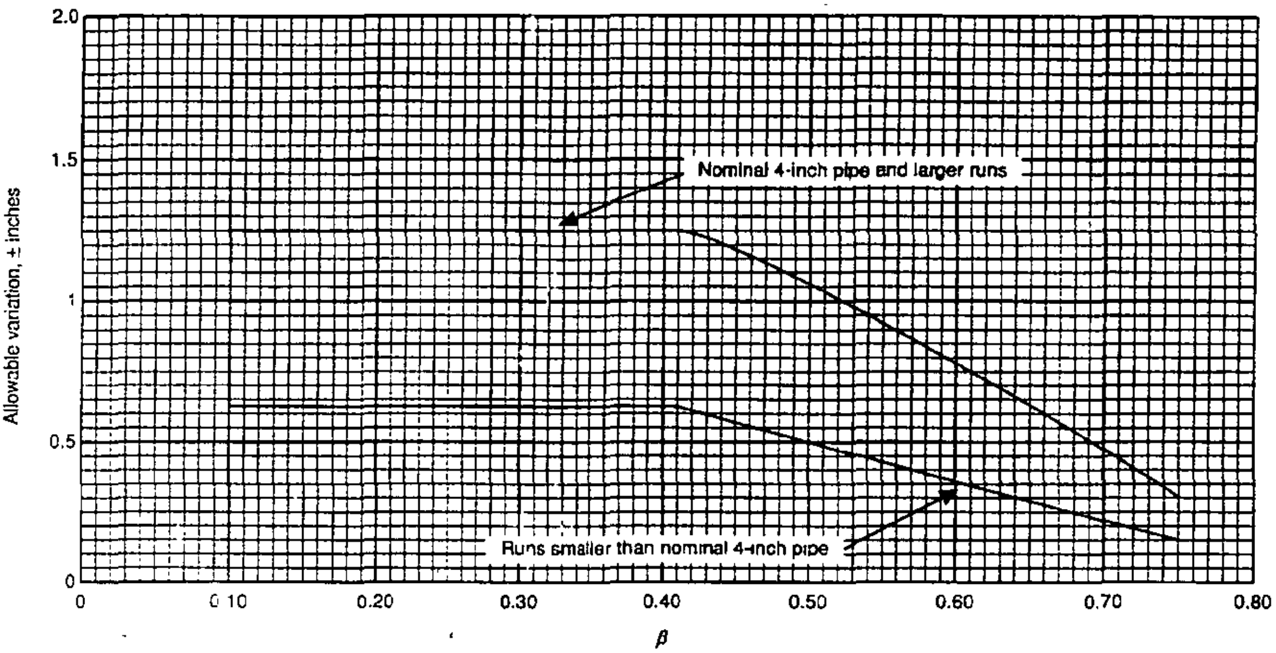
$$Q_s = C'\sqrt{h_w P_f} \qquad (3\text{-D-}1)$$

Where:

C' = orifice flow constant.
h_w = differential pressure at 60°F, in inches of water
P_f = static pressure, in pounds force per square inch absolute.
Q_s = volume flow rate at base conditions, in standard cubic feet per hour.

3–D.4.3 ORIFICE FLOW CONSTANT (C')

The orifice flow constant, C', is defined as the rate of airflow as a real gas, in standard cubic feet per hour, when the extension, $(h_w P_f)^{0.5}$, equals unity. The orifice flow constant



Note A maximum β ratio of 0.75 should be used in the design of new installations.

Figure 3-D-2—Allowable Variations in Pressure Tap Hole Location

should not be confused with the flow coefficient or coefficient of discharge (K). The following equation is used to calculate the orifice flow constant:

$$C' = F_b F_r Y F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \quad (3\text{-}D\text{-}2)$$

Where.

F_b = basic orifice factor
F_g = real specific gravity (relative density) factor.
F_{pb} = base pressure factor.
F_{pv} = supercompressibility factor (from A.G.A. Transmission Measurement Committee Report No. 8).
F_r = Reynolds number factor.
F_{tb} = base temperature factor.
F_{tf} = flowing temperature factor.
Y = expansion factor

Table 3-D-2—Meter Tube Pressure Tap Holes
(Dimensions in Inches)

Meter Tube Nominal Inside Diameter	Nominal Tap Hole Diameter		
	Recommended	Maximum	Minimum
<2	¼	¼	¼
2 or 3	⅜	⅜	¼
≥4	½	½	⅜

Note: The finished tap hole shall be $\pm\frac{1}{64}$ inch from the selected nominal tap hole diameter along the drilled length of the hole.

The sequence of multiplication in Equation 2 is not binding; however, to duplicate the results obtained using Equation 2, the sequence of multiplication and the manner of rounding or truncation should be agreed upon and practiced. Trim factors to compensate for the type of instrumentation used, the calibration methods, and the elements of meter location are treated separately (see Appendix 3-A). These trim factors may be applied as a multiplier to C'.

The values of all the C' factors are detailed in subsequent sections of this appendix. Both equations and tabular data based on the equations are provided. The tables are to be used as an alternative to calculations by equations or to check computed results.

3–D.4.4 COEFFICIENTS OF DISCHARGE (*K*)

To calculate the coefficients of discharge, K, the following empirical equations are used:

$$K_o = \frac{K_e}{1 + \dfrac{15E}{1{,}000{,}000d}} \qquad \text{(3-D-3)}$$

Where

$$K_e = 0.5925 + \frac{0.0182}{D} + \left(0.44 - \frac{0.06}{D}\right)\beta^2 + \left(0.935 + \frac{0.225}{D}\right)\beta^5 + 1.35\beta^{14} + \frac{1.43}{\sqrt{D}}(0.25 - \beta)^{\frac{5}{2}} \qquad \text{(3-D-4)}$$

$$E = d(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + B) \qquad \text{(3-D-5)}$$

$$B = \frac{875}{D} + 75 \qquad \text{(3-D-6)}$$

Note: In Equation 3-D-4, the signs of some of the terms with fractional exponents become negative for some values of β. In such cases, these terms are to be neglected or their value treated as zero, and where these terms are a factor to another term, the whole product is to be treated as zero.

Where:

d = measured orifice diameter, in inches.
D = measured inside meter tube diameter, in inches
K_e = coefficient of discharge when Reynolds number is equal to $(1{,}000{,}000d)/15$.
K_o = coefficient of discharge when Reynolds number equals infinity, which will be the minimum value for any particular orifice and meter tube size.
β = beta ratio
= d/D.

These values will be used in subsequent intermediate calculations of the orifice flow constant factors

3–D.4.5 BASIC ORIFICE FACTOR (F_b)

To calculate the basic orifice factor, F_b, use the following equation and note the standard conditions:

$$F_b = 338.178d^2K_o \qquad \text{(3-D-7)}$$

When

P_b (base pressure) = 14.73 pounds force per square inch absolute
Specific gravity = 1.000
T_b (base temperature) = 60°F (519.67°R)

Table 3-D-1 was developed using Equation 3-D-7 and various combinations of d and D; to use it, however, the measured inside diameter (D) of the meter tube must be within the limits specified in 3-D.3.2 and Figure 3-D-1. Table 3-D-2 may not be interpolated.

3-D.4.6 REYNOLDS NUMBER FACTOR (F_r)

To calculate the Reynolds number factor, F_r, use the following equations:

$$F_r = 1 + \frac{E}{Re_d} \tag{3-D-8}$$

$$Re_d = 220{,}858\, dF_{pv}\sqrt{\rho h_w} \times (0.613408 - 0.152756\beta + 0.803833\beta^2 - 1.701111\beta^3 + 1.569336\beta^4) \tag{3-D-9}$$

$$\rho = \left(\frac{P_f}{14.7}\right)\left(\frac{491.67}{T_f}\right)G \tag{3-D-10}$$

Where:

G = specific gravity.
Re_d = orifice bore Reynolds number.
T_f = absolute flowing temperature, in degrees Rankine.
ρ = specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F.

Table 3-D-3, which may not be interpolated, may be used to determine the value of b; this value may then be applied to Equation 3-D-11:

Table 3-D-3—b Values for Determining Reynolds Number Factor F_r for Pipe Taps (All Dimensions in Inches)

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 2 Inches			Published Inside Diameters at Nominal Pipe Size of 3 Inches				Published Inside Diameters at Nominal Pipe Size of 4 Inches			
	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.250	0.1106	0.1091	0.1087	0.1081	0.1078	0.1078	0.1079	0.1079	0.1081	0.1084	0.1085
0.375	0.0890	0.0878	0.0877	0.0879	0.0888	0.0898	0.0905	0.0908	0.0918	0.0932	0.0939
0.500	0.0758	0.0734	0.0729	0.0728	0.0737	0.0750	0.0758	0.0763	0.0778	0.0800	0.0810
0.625	0.0694	0.0647	0.0635	0.0624	0.0624	0.0634	0.0642	0.0646	0.0662	0.0685	0.0697
0.750	0.0676	0.0608	0.0586	0.0559	0.0546	0.0548	0.0552	0.0555	0.0568	0.0590	0.0602
0.875	0.0684	0.0602	0.0570	0.0528	0.0497	0.0488	0.0488	0.0489	0.0496	0.0513	0.0524
1.000	0.0702	0.0614	0.0576	0.0522	0.0473	0.0452	0.0445	0.0443	0.0443	0.0453	0.0461
1.125	0.0709	0.0635	0.0595	0.0532	0.0469	0.0435	0.0422	0.0417	0.0407	0.0408	0.0412
1.250		0.0650	0.0617	0.0552	0.0478	0.0434	0.0414	0.0406	0.0387	0.0376	0.0377
1.375			0.0629	0.0575	0.0496	0.0443	0.0418	0.0408	0.0379	0.0358	0.0353
1.500				0.0590	0.0518	0.0461	0.0431	0.0418	0.0382	0.0350	0.0341
1.625					0.0539	0.0482	0.0450	0.0435	0.0392	0.0351	0.0336
1.750					0.0554	0.0504	0.0471	0.0456	0.0408	0.0359	0.0340
1.875						0.0521	0.0492	0.0477	0.0427	0.0372	0.0349
2.000						0.0532	0.0508	0.0495	0.0448	0.0388	0.0363
2.125							0.0519	0.0509	0.0467	0.0407	0.0380
2.250									0.0483	0.0427	0.0398
2.375									0.0494	0.0445	0.0417
2.500										0.0461	0.0435
2.625										0.0472	0.0450
2.750											0.0462

Note: The b values are calculated from the following equation:

$$b = \frac{E}{12{,}835\, dK}$$

Where:

d = mean orifice diameter, in inches.
E = value from Equation 3-D-5.
K = value approximated from Table 3-D-4.

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}} \tag{3-D-11}$$

$$b = \frac{E}{12{,}835dK} \tag{3-D-12}$$

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 6 Inches				Published Inside Diameters at Nominal Pipe Size of 8 Inches			Published Inside Diameters at Nominal Pipe Size of 10 Inches			Published Inside Diameters at Nominal Pipe Size of 12 Inches		
	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.136	11.374	11.938	12.090
0.500	0.0850	0.0862	0.0883	0.0893									
0.625	0.0747	0.0762	0.0789	0.0802									
0.750	0.0655	0.0672	0.0703	0.0719									
0.875	0.0575	0.0592	0.0625	0.0642	0.0716	0.0730	0.0734						
1.000	0.0506	0.0523	0.0556	0.0573	0.0652	0.0668	0.0672	0.0728					
1.125	0.0448	0.0464	0.0495	0.0512	0.0593	0.0609	0.0613	0.0674	0.0691	0.0695			
1.250	0.0401	0.0414	0.0442	0.0458	0.0538	0.0555	0.0560	0.0624	0.0641	0.0646	0.0687	0.0704	0.0708
1.375	0.0363	0.0373	0.0397	0.0412	0.0489	0.0506	0.0511	0.0576	0.0594	0.0599	0.0643	0.0661	0.0666
1.500	0.0334	0.0341	0.0360	0.0372	0.0445	0.0462	0.0466	0.0532	0.0550	0.0555	0.0601	0.0620	0.0625
1.625	0.0313	0.0315	0.0329	0.0339	0.0405	0.0421	0.0425	0.0490	0.0509	0.0514	0.0561	0.0580	0.0585
1.750	0.0300	0.0298	0.0304	0.0311	0.0369	0.0384	0.0388	0.0452	0.0471	0.0476	0.0523	0.0543	0.0548
1.875	0.0293	0.0287	0.0285	0.0290	0.0338	0.0352	0.0355	0.0417	0.0436	0.0440	0.0488	0.0508	0.0513
2.000	0.0292	0.0281	0.0273	0.0273	0.0311	0.0323	0.0327	0.0385	0.0403	0.0407	0.0454	0.0475	0.0480
2.125	0.0297	0.0281	0.0265	0.0262	0.0288	0.0299	0.0301	0.0355	0.0373	0.0377	0.0423	0.0443	0.0449
2.250	0.0305	0.0285	0.0261	0.0256	0.0268	0.0277	0.0280	0.0329	0.0345	0.0349	0.0394	0.0414	0.0419
2.375	0.0316	0.0293	0.0262	0.0253	0.0252	0.0259	0.0261	0.0305	0.0320	0.0324	0.0367	0.0387	0.0392
2.500	0.0330	0.0304	0.0267	0.0254	0.0239	0.0244	0.0246	0.0283	0.0298	0.0301	0.0342	0.0361	0.0366
2.625	0.0345	0.0317	0.0274	0.0258	0.0230	0.0232	0.0233	0.0265	0.0277	0.0281	0.0319	0.0337	0.0342
2.750	0.0362	0.0332	0.0284	0.0265	0.0224	0.0224	0.0224	0.0248	0.0260	0.0263	0.0298	0.0316	0.0320
2.875	0.0379	0.0348	0.0295	0.0274	0.0220	0.0218	0.0218	0.0234	0.0244	0.0246	0.0279	0.0295	0.0300
3.000	0.0395	0.0364	0.0308	0.0285	0.0219	0.0214	0.0213	0.0222	0.0230	0.0233	0.0262	0.0277	0.0281
3.125	0.0410	0.0380	0.0323	0.0297	0.0220	0.0213	0.0211	0.0212	0.0218	0.0220	0.0246	0.0260	0.0264
3.250	0.0422	0.0394	0.0338	0.0311	0.0223	0.0214	0.0212	0.0205	0.0209	0.0210	0.0232	0.0245	0.0249
3.375	0.0433	0.0408	0.0353	0.0325	0.0228	0.0217	0.0214	0.0199	0.0201	0.0202	0.0220	0.0232	0.0235
3.500		0.0419	0.0367	0.0339	0.0235	0.0221	0.0218	0.0195	0.0195	0.0196	0.0210	0.0220	0.0223
3.625		0.0428	0.0381	0.0354	0.0243	0.0227	0.0224	0.0193	0.0191	0.0191	0.0200	0.0209	0.0212
3.750			0.0393	0.0367	0.0252	0.0234	0.0230	0.0192	0.0188	0.0188	0.0193	0.0200	0.0202
3.875			0.0404	0.0380	0.0262	0.0243	0.0238	0.0193	0.0187	0.0186	0.0187	0.0192	0.0194
4.000			0.0413	0.0391	0.0273	0.0252	0.0248	0.0195	0.0187	0.0186	0.0182	0.0185	0.0187
4.250					0.0297	0.0273	0.0268	0.0203	0.0192	0.0189	0.0176	0.0176	0.0177
4.500					0.0321	0.0296	0.0290	0.0215	0.0200	0.0197	0.0175	0.0172	0.0171
4.750					0.0344	0.0320	0.0314	0.0230	0.0212	0.0208	0.0178	0.0171	0.0170
5.000					0.0364	0.0342	0.0336	0.0248	0.0228	0.0223	0.0185	0.0175	0.0172
5.250					0.0381	0.0361	0.0356	0.0267	0.0245	0.0239	0.0195	0.0181	0.0178
5.500						0.0377	0.0373	0.0287	0.0263	0.0257	0.0207	0.0190	0.0186
5.750								0.0307	0.0282	0.0276	0.0221	0.0202	0.0197
6.000								0.0326	0.0302	0.0295	0.0236	0.0215	0.0210
6.250								0.0343	0.0320	0.0314	0.0253	0.0230	0.0224
6.500								0.0358	0.0336	0.0331	0.0270	0.0246	0.0240
6.750									0.0351	0.0346	0.0288	0.0262	0.0256
7.000									0.0363	0.0359	0.0304	0.0279	0.0272
7.250											0.0320	0.0295	0.0288
7.500											0.0334	0.0310	0.0304
7.750											0.0347	0.0325	0.0318
8.000												0.0338	0.0332
8.250												0.0349	0.0344

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
1.500	0.0697	0.0705										
1.625	0.0662	0.0670	0.0676									
1.750	0.0628	0.0636	0.0642									
1.875	0.0595	0.0603	0.0610									
2.000	0.0563	0.0571	0.0578	0.0663	0.0667	0.0672						
2.125	0.0532	0.0541	0.0548	0.0635	0.0639	0.0645						
2.250	0.0503	0.0512	0.0519	0.0609	0.0613	0.0618						
2.375	0.0475	0.0485	0.0492	0.0583	0.0588	0.0593	0.0658	0.0665	0.0669			
2.500	0.0449	0.0458	0.0466	0.0558	0.0562	0.0568	0.0635	0.0642	0.0646			
2.625	0.0424	0.0433	0.0441	0.0534	0.0538	0.0544	0.0613	0.0620	0.0624			
2.750	0.0400	0.0409	0.0417	0.0510	0.0515	0.0520	0.0591	0.0598	0.0603			
2.875	0.0378	0.0387	0.0394	0.0488	0.0492	0.0498	0.0570	0.0577	0.0582	0.0669		
3.000	0.0356	0.0365	0.0372	0.0466	0.0470	0.0476	0.0549	0.0556	0.0561	0.0650	0.0654	0.0657
3.125	0.0336	0.0345	0.0352	0.0445	0.0449	0.0455	0.0529	0.0536	0.0541	0.0632	0.0636	0.0639
3.250	0.0317	0.0326	0.0333	0.0425	0.0429	0.0435	0.0509	0.0517	0.0521	0.0615	0.0618	0.0622
3.375	0.0300	0.0308	0.0314	0.0405	0.0410	0.0416	0.0490	0.0497	0.0502	0.0597	0.0601	0.0604
3.500	0.0283	0.0291	0.0297	0.0387	0.0391	0.0397	0.0471	0.0479	0.0484	0.0580	0.0584	0.0587
3.625	0.0268	0.0275	0.0281	0.0369	0.0373	0.0379	0.0453	0.0461	0.0466	0.0563	0.0567	0.0571
3.750	0.0254	0.0261	0.0267	0.0352	0.0356	0.0362	0.0436	0.0444	0.0449	0.0547	0.0551	0.0554
3.875	0.0240	0.0247	0.0253	0.0336	0.0340	0.0346	0.0419	0.0427	0.0432	0.0530	0.0534	0.0538
4.000	0.0228	0.0235	0.0240	0.0320	0.0324	0.0330	0.0403	0.0411	0.0416	0.0515	0.0519	0.0523
4.250	0.0207	0.0213	0.0217	0.0291	0.0295	0.0301	0.0372	0.0380	0.0385	0.0484	0.0488	0.0492
4.500	0.0190	0.0194	0.0198	0.0265	0.0269	0.0274	0.0343	0.0351	0.0356	0.0455	0.0459	0.0463
4.750	0.0176	0.0180	0.0183	0.0242	0.0246	0.0250	0.0316	0.0324	0.0329	0.0427	0.0431	0.0435
5.000	0.0166	0.0168	0.0171	0.0221	0.0225	0.0229	0.0292	0.0299	0.0303	0.0401	0.0405	0.0409
5.250	0.0160	0.0161	0.0162	0.0203	0.0206	0.0210	0.0269	0.0276	0.0280	0.0376	0.0380	0.0384
5.500	0.0156	0.0156	0.0156	0.0188	0.0190	0.0194	0.0248	0.0255	0.0259	0.0352	0.0356	0.0360
5.750	0.0155	0.0154	0.0153	0.0175	0.0177	0.0180	0.0230	0.0236	0.0240	0.0330	0.0334	0.0338
6.000	0.0157	0.0154	0.0153	0.0164	0.0165	0.0168	0.0213	0.0218	0.0222	0.0309	0.0313	0.0317
6.250	0.0161	0.0157	0.0154	0.0155	0.0156	0.0158	0.0197	0.0203	0.0206	0.0289	0.0293	0.0297
6.500	0.0167	0.0162	0.0159	0.0148	0.0149	0.0151	0.0184	0.0189	0.0192	0.0271	0.0274	0.0278
6.750	0.0175	0.0169	0.0164	0.0144	0.0144	0.0145	0.0172	0.0176	0.0179	0.0253	0.0257	0.0261
7.000	0.0184	0.0177	0.0172	0.0141	0.0141	0.0142	0.0162	0.0166	0.0168	0.0237	0.0241	0.0244
7.250	0.0195	0.0187	0.0181	0.0140	0.0140	0.0139	0.0153	0.0156	0.0159	0.0223	0.0226	0.0229
7.500	0.0206	0.0198	0.019	0.0140	0.0140	0.0139	0.0146	0.0149	0.0150	0.0209	0.0212	0.0215
7.750	0.0219	0.0209	0.0202	0.0143	0.0141	0.0140	0.0140	0.0142	0.0144	0.0196	0.0199	0.0202
8.000	0.0232	0.0222	0.0214	0.0146	0.0144	0.0142	0.0136	0.0138	0.0139	0.0185	0.0187	0.0190

Table 3-D-4 must be used to determine the value of K in Equation 3-D-12. First-order linear interpolation of Table 3-D-4 is permissible. In calculating the extension for determinations of F_r, average or estimated values may be used.

3–D.4.7 EXPANSION FACTOR (Y)

3–D.4.7.1 Expansion Factor Based on Upstream Static Pressure (Y_1)

If the static pressure is measured at the upstream pressure tap, the calculations for the expansion factor, Y_1, use the following equations.

$$Y_1 = 1 - [0.333 + 1.145(\beta^2 + 0.7\beta^5 + 12\beta^{13})]\frac{x_1}{k} \qquad \text{(3-D-13)}$$

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
8.250	0.0246	0.0235	0.0227	0.0151	0.0149	0.0146	0.0133	0.0134	0.0135	0.0174	0.0177	0.0179
8.500	0.0260	0.0249	0.0240	0.0157	0.0154	0.0151	0.0132	0.0132	0.0132	0.0165	0.0167	0.0170
8.750	0.0273	0.0262	0.0253	0.0163	0.0160	0.0157	0.0131	0.0130	0.0130	0.0156	0.0158	0.0161
9.000	0.0286	0.0276	0.0267	0.0171	0.0168	0.0163	0.0131	0.0130	0.0130	0.0149	0.0151	0.0153
9.250	0.0299	0.0288	0.0280	0.0180	0.0176	0.0171	0.0133	0.0131	0.0130	0.0142	0.0144	0.0146
9.500	0.0311	0.0301	0.0292	0.0189	0.0185	0.0180	0.0136	0.0133	0.0132	0.0137	0.0138	0.0140
9.750	0.0322	0.0312	0.0304	0.0198	0.0194	0.0189	0.0139	0.0136	0.0134	0.0132	0.0133	0.0135
10.000	0.0332	0.0323	0.0315	0.0239	0.0204	0.0198	0.0143	0.0140	0.0138	0.0129	0.0129	0.0130
10.250	0.0341	0.0333	0.0326	0.0219	0.0214	0.0208	0.0149	0.0144	0.0142	0.0126	0.0126	0.0127
10.500		0.0341	0.0335	0.0230	0.0225	0.0219	0.0154	0.0150	0.0147	0.0123	0.0124	0.0124
10.750				0.0241	0.0236	0.0229	0.0161	0.0155	0.0152	0.0122	0.0122	0.0122
11.000				0.0252	0.0247	0.0240	0.0168	0.0162	0.0158	0.0121	0.0121	0.0121
11.250				0.0263	0.0258	0.0251	0.0175	0.0169	0.0165	0.0121	0.0121	0.0121
11.500				0.0273	0.0268	0.0261	0.0183	0.0176	0.0172	0.0122	0.0122	0.0121
11.750				0.0284	0.0278	0.0272	0.0191	0.0184	0.0180	0.0124	0.0123	0.0122
12.000				0.0293	0.0288	0.0282	0.0200	0.0192	0.0188	0.0126	0.0124	0.0123
12.500				0.0312	0.0307	0.0301	0.0218	0.0210	0.0205	0.0131	0.0130	0.0128
13.000				0.0327	0.0323	0.0318	0.0236	0.0228	0.0222	0.0139	0.0137	0.0135
13.500							0.0255	0.0246	0.0240	0.0148	0.0146	0.0143
14.000							0.0272	0.0264	0.0258	0.0159	0.0156	0.0153
14.500							0.0289	0.0280	0.0275	0.0172	0.0168	0.0165
15.000							0.0304	0.0296	0.0291	0.0185	0.0181	0.0177
15.500							0.0318	0.0311	0.0306	0.0199	0.0194	0.0191
16.000								0.0323	0.0319	0.0213	0.0209	0.0205
16.500										0.0228	0.0223	0.0219
17.000										0.0242	0.0238	0.0233
17.500										0.0257	0.0252	0.0248
18.000										0.0270	0.0266	0.0261
18.500										0.0283	0.0279	0.0275
19.000										0.0296	0.0292	0.0288
19.500										0.0307	0.0303	0.0299
20.000										0.0317	0.0313	0.0310

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707 P_{f_1}} \qquad (3\text{-D-}14)$$

Where:

k = ratio of specific heats, c_p/c_v (that is, the ratio of the specific heat of a gas at constant pressure to the specific heat of the gas at constant volume at standard conditions).

x_1/k = acoustic ratio.

Table 3-D-5 was developed using Equations 3-D-13 and 3-D-14 with a value of $k = 1.3$. First- or second-order linear interpolation of Table 3-D-5 is permissible.

The values of Y_1 are subject to an uncertainty varying from 0 when $x_1 = 0$ to ±0.5 percent when $x_1 = 0.2$. For larger values of x_1, a somewhat larger uncertainity can be expected. Equation 3-D-13 may be used over a range of $0.1 \leq \beta \leq 0.7$.

Table 3-D-4—Values of K to Be Used in Determining R_d for Calculation of F_r Factor

β	K (pipe)
0.100	0.607
0.125	0.608
0.150	0.611
0.175	0.614
0.200	0.618
0.225	0.623
0.250	0.628
0.275	0.634
0.300	0.641
0.325	0.650
0.350	0.658
0.375	0.668
0.400	0.680
0.425	0.692
0.450	0.707
0.475	0.724
0.500	0.742
0.525	0.763
0.550	0.785
0.575	0.810
0.600	0.837
0.625	0.869
0.650	0.904
0.675	0.943
0.700	0.988

3–D.4.7.2 Expansion Factor Based on Downstream Static Pressure (Y_2)

If the static pressure is measured at the downstream pressure tap, the calculations for the expansion factor, Y_2, use the following equations:

$$Y_2 = \sqrt{1 + x_2} - [0.333 + 1.145(\beta^2 - 0.7\beta^5 + 12\beta^{13})]\frac{x_2}{k\sqrt{1 + x_2}} \quad (3\text{-D-}15)$$

$$x_2 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\,P_{f_2}} \quad (3\text{-D-}16)$$

Table 3-D-6 was developed using Equations 3-D-15 and 3-D-16 with a value of $k = 1.3$. First- or second-order linear interpolation of Table 3-D-6 is permissible.

3–D.4.8 OTHER C' FACTORS

The remaining orifice flow constant C' factors (namely, F_{pb}, F_{tb}, F_{tf}, F_{gr}, and F_{pv}) are calculated exactly as described in the body of this standard. Computations using equations or tables are permissible with these factors when calculating the flow of natural gas through orifice meters equipped with pipe taps.

3–D.4.9 EXAMPLES

3–D.4.9.1 Example 1

Given the following physical parameters and flowing conditions, calculate the flow rate for a pipe tap orifice meter through one meter tube:

Tube diameter	2.067 in
Orifice diameter	1 in
Static pressure	500 psig (measured upstream)
Differential pressure	50 inches of water at 60°F

Base pressure	14.73 psia
Atmospheric pressure	14.7 psia (barometric)
Flowing temperature	100°F
Base temperature	60°F
Relative density (specific gravity)	0.600
Carbon dioxide	0.5 mole percent
Nitrogen	0.5 mole percent
Differential pressure device	Bellows (recorder, dry)

The solution is calculated as follows:

Diameter ratio (β) = 0.483793

Extension = 160.421

Basic orifice factor (F_b) = 243.279

(from Equations 3-D-3, 3-D-4, 3-D-5, 3-D-6, and 3-D-7; or Table 3-D-2)

Table 3-D-5—Expansion Factors for Pipe Taps (Y_1): Static Pressure Taken From Upstream Taps

	$\beta = d/D$										
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9990	0.9989	0.9988	0.9985	0.9984	0.9982	0.9981	0.9980	0.9979	0.9978	0.9977
0.2	0.9981	0.9979	0.9976	0.9971	0.9968	0.9964	0.9962	0.9961	0.9959	0.9957	0.9954
0.3	0.9971	0.9968	0.9964	0.9956	0.9952	0.9946	0.9944	0.9941	0.9938	0.9935	0.9931
0.4	0.9962	0.9958	0.9951	0.9942	0.9936	0.9928	0.9925	0.9921	0.9917	0.9913	0.9908
0.5	0.9952	0.9947	0.9939	0.9927	0.9919	0.9910	0.9906	0.9902	0.9897	0.9891	0.9885
0.6	0.9943	0.9937	0.9927	0.9913	0.9903	0.9892	0.9887	0.9882	0.9876	0.9870	0.9862
0.7	0.9933	0.9926	0.9915	0.9898	0.9887	0.9874	0.9869	0.9862	0.9856	0.9848	0.9840
0.8	0.9923	0.9916	0.9903	0.9883	0.9871	0.9857	0.9850	0.9843	0.9835	0.9826	0.9817
0.9	0.9914	0.9905	0.9891	0.9869	0.9855	0.9839	0.9831	0.9823	0.9814	0.9805	0.9794
1.0	0.9904	0.9895	0.9878	0.9854	0.9839	0.9821	0.9812	0.9803	0.9794	0.9783	0.9771
1.1	0.9895	0.9884	0.9866	0.9840	0.9823	0.9803	0.9794	0.9784	0.9773	0.9761	0.9748
1.2	0.9885	0.9874	0.9854	0.9825	0.9807	0.9785	0.9775	0.9764	0.9752	0.9739	0.9725
1.3	0.9876	0.9863	0.9842	0.9811	0.9791	0.9767	0.9756	0.9744	0.9732	0.9718	0.9702
1.4	0.9866	0.9853	0.9830	0.9796	0.9775	0.9749	0.9737	0.9725	0.9711	0.9696	0.9679
1.5	0.9857	0.9842	0.9818	0.9782	0.9758	0.9731	0.9718	0.9705	0.9690	0.9674	0.9656
1.6	0.9847	0.9832	0.9805	0.9767	0.9742	0.9713	0.9700	0.9685	0.9670	0.9652	0.9633
1.7	0.9837	0.9821	0.9793	0.9752	0.9726	0.9695	0.9681	0.9666	0.9649	0.9631	0.9610
1.8	0.9828	0.9811	0.9781	0.9738	0.9710	0.9677	0.9662	0.9646	0.9628	0.9609	0.9587
1.9	0.9818	0.9800	0.9769	0.9723	0.9694	0.9659	0.9643	0.9626	0.9608	0.9587	0.9565
2.0	0.9809	0.9790	0.9757	0.9709	0.9678	0.9641	0.9625	0.9607	0.9587	0.9566	0.9542
2.1	0.9799	0.9779	0.9745	0.9694	0.9662	0.9623	0.9606	0.9587	0.9566	0.9544	0.9519
2.2	0.9790	0.9768	0.9732	0.9680	0.9646	0.9605	0.9587	0.9567	0.9546	0.9522	0.9496
2.3	0.9780	0.9758	0.9720	0.9665	0.9630	0.9587	0.9568	0.9548	0.9525	0.9500	0.9473
2.4	0.9770	0.9747	0.9708	0.9650	0.9613	0.9570	0.9550	0.9528	0.9505	0.9479	0.9450
2.5	0.9761	0.9737	0.9696	0.9636	0.9597	0.9552	0.9531	0.9508	0.9484	0.9457	0.9427
2.6	0.9751	0.9726	0.9681	0.9621	0.9581	0.9534	0.9512	0.9489	0.9463	0.9435	0.9404
2.7	0.9742	0.9716	0.9672	0.9607	0.9565	0.9516	0.9493	0.9469	0.9443	0.9414	0.9381
2.8	0.9732	0.9705	0.9659	0.9592	0.9549	0.9498	0.9475	0.9449	0.9422	0.9392	0.9358
2.9	0.9723	0.9695	0.9647	0.9578	0.9533	0.9480	0.9456	0.9430	0.9401	0.9370	0.9335
3.0	0.9713	0.9684	0.9635	0.9563	0.9517	0.9462	0.9437	0.9410	0.9381	0.9348	0.9312
3.1	0.9704	0.9674	0.9623	0.9549	0.9501	0.9444	0.9418	0.9390	0.9360	0.9327	0.9290
3.2	0.9694	0.9663	0.9611	0.9534	0.9485	0.9426	0.9400	0.9371	0.9339	0.9305	0.9267
3.3	0.9684	0.9653	0.9599	0.9519	0.9469	0.9408	0.9381	0.9351	0.9319	0.9283	0.9244
3.4	0.9675	0.9642	0.9587	0.9505	0.9452	0.9390	0.9362	0.9331	0.9298	0.9261	0.9221
3.5	0.9665	0.9632	0.9574	0.9490	0.9436	0.9372	0.9343	0.9312	0.9277	0.9240	0.9198
3.6	0.9656	0.9621	0.9562	0.9476	0.9420	0.9354	0.9324	0.9292	0.9257	0.9218	0.9175
3.7	0.9646	0.9611	0.9550	0.9461	0.9404	0.9336	0.9306	0.9272	0.9236	0.9196	0.9152
3.8	0.9637	0.9600	0.9538	0.9447	0.9388	0.9318	0.9287	0.9253	0.9216	0.9175	0.9129
3.9	0.9627	0.9590	0.9526	0.9432	0.9372	0.9301	0.9263	0.9233	0.9195	0.9153	0.9106
4.0	0.9617	0.9579	0.9514	0.9417	0.9356	0.9283	0.9249	0.9213	0.9174	0.9131	0.9083

Table 3-D-5—Continued

	$\beta = d/D$									
h_w/P_f	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9976	0.9976	0.9975	0.9974	0.9973	0.9972	0.9971	0.9970	0.9969	0.9968
0.2	0.9953	0.9951	0.9950	0.9948	0.9947	0.9945	0.9943	0.9941	0.9938	0.9935
0.3	0.9929	0.9927	0.9925	0.9923	0.9920	0.9917	0.9914	0.9911	0.9907	0.9903
0.4	0.9906	0.9903	0.9900	0.9897	0.9893	0.9890	0.9986	0.9881	0.9876	0.9871
0.5	0.9882	0.9879	0.9875	0.9871	0.9867	0.9862	0.9857	0.9851	0.9845	0.9389
0.6	0.9859	0.9854	0.9850	0.9845	0.9840	0.9834	0.9828	0.9822	0.9814	0.9806
0.7	0.9835	0.9830	0.9825	0.9819	0.9813	0.9807	0.9800	0.9792	0.9784	0.9774
0.8	0.9811	0.9806	0.9800	0.9794	0.9787	0.9779	0.9771	0.9762	0.9753	0.9742
0.9	0.9788	0.9782	0.9775	0.9768	0.9760	0.9752	0.9742	0.9733	0.9722	0.9710
1.0	0.9764	0.9757	0.9750	0.9742	0.9733	0.9724	0.9714	0.9703	0.9691	0.9677
1.1	0.9741	0.9733	0.9725	0.9716	0.9707	0.9696	0.9685	0.9673	0.9660	0.9645
1.2	0.9717	0.9709	0.9700	0.9690	0.9680	0.9669	0.9657	0.9643	0.9629	0.9613
1.3	0.9694	0.9685	0.9675	0.9664	0.9653	0.9641	0.9628	0.9614	0.9598	0.9581
1.4	0.9670	0.9660	0.9650	0.9639	0.9627	0.9614	0.9599	0.9584	0.9567	0.9548
1.5	0.9646	0.9636	0.9625	0.9613	0.9600	0.9586	0.9571	0.9554	0.9536	0.9516
1.6	0.9623	0.9612	0.9600	0.9587	0.9573	0.9558	0.9542	0.9525	0.9505	0.9484
1.7	0.9599	0.9587	0.9575	0.9561	0.9547	0.9531	0.9514	0.9495	0.9474	0.9452
1.8	0.9576	0.9563	0.9550	0.9535	0.9520	0.9503	0.9485	0.9465	0.9443	0.9419
1.9	0.9552	0.9539	0.9525	0.9510	0.9493	0.9476	0.9456	0.9435	0.9412	0.9387
2.0	0.9529	0.9515	0.9500	0.9484	0.9467	0.9448	0.9428	0.9406	0.9381	0.9355
2.1	0.9505	0.9490	0.9475	0.9458	0.9440	0.9420	0.9399	0.9376	0.9351	0.9323
2.2	0.9481	0.9466	0.9450	0.9432	0.9413	0.9393	0.9371	0.9346	0.9320	0.9290
2.3	0.9458	0.9442	0.9425	0.9406	0.9387	0.9365	0.9342	0.9317	0.9289	0.9258
2.4	0.9434	0.9418	0.9400	0.9381	0.9360	0.9338	0.9313	0.9287	0.9258	0.9226
2.5	0.9411	0.9393	0.9375	0.9355	0.9333	0.9310	0.9285	0.9257	0.9227	0.9194
2.6	0.9387	0.9369	0.9350	0.9329	0.9307	0.9282	0.9256	0.9227	0.9196	0.9161
2.7	0.9364	0.9345	0.9325	0.9303	0.9280	0.9255	0.9227	0.9198	0.9165	0.9129
2.8	0.9340	0.9321	0.9300	0.9277	0.9253	0.9227	0.9199	0.9168	0.9134	0.9097
2.9	0.9316	0.9296	0.9275	0.9252	0.9227	0.9200	0.9170	0.9138	0.9103	0.9064
3.0	0.9293	0.9272	0.9250	0.9226	0.9200	0.9172	0.9142	0.9108	0.9072	0.9032
3.1	0.9269	0.9248	0.9225	0.9200	0.9173	0.9144	0.9113	0.9079	0.9041	0.9000
3.2	0.9246	0.9223	0.9200	0.9174	0.9147	0.9117	0.9084	0.9049	0.9010	0.8968
3.3	0.9222	0.9199	0.9175	0.9148	0.9120	0.9089	0.9056	0.9019	0.8979	0.8935
3.4	0.9199	0.9175	0.9150	0.9122	0.9093	0.9062	0.9027	0.8990	0.8948	0.8903
3.5	0.9175	0.9151	0.9125	0.9097	0.9067	0.9034	0.8999	0.8960	0.8918	0.8817
3.6	0.9151	0.9126	0.9100	0.9071	0.9040	0.9006	0.8970	0.8930	0.8887	0.8839
3.7	0.9128	0.9102	0.9075	0.9045	0.9013	0.8979	0.8941	0.8900	0.8856	0.8806
3.8	0.9104	0.9078	0.9050	0.9019	0.8987	0.8951	0.8913	0.8871	0.8825	0.8774
3.9	0.9081	0.9054	0.9025	0.8993	0.8960	0.8924	0.8884	0.8841	0.8794	0.8742
4.0	0.9057	0.9029	0.9000	0.8968	0.8933	0.8896	0.8856	0.8811	0.8763	0.8710

Reynolds number factor (F_r) = 1.0004
(from Equations 3-D-5, 3-D-8, 3-D-9, and 3-D-10; or Table 3-D-1 and Equation 3-D-11; or Table 3-D-3 and Equations 3-D-5, 3-D-11, and 3-D-12)
Expansion factor (Y_1) = 0.9983
(from Equations 3-D-13 and 3-D-14 or Table 3-D-4)
Base pressure factor (F_{pb}) = 1.0000
Base temperature factor (F_{tb}) = 1.0000
Flowing temperature factor (F_{tf}) = 0.9636
Relative density factor (F_{gr}) = 1.2910
Supercompressibility factor (F_{pv}) = 1.0299
Orifice flow constant (C') = 311.284
(from Equation 3-D-2)

Flow rate (Q_v) = 49.9367 MSCFH
= 1.19848 MMSCFD
(from Equation 3-D-1)

3–D.4.9.2 Example 2

Given the following physical parameters and flowing conditions, calculate the flow rate from a pipe tap orifice meter through one meter tube:

Tube diameter	10.020 in
Orifice diameter	4.5 in
Static pressure	350 psig (measured upstream)
Differential pressure	40 inches of water at 60°F
Base pressure	14.73 psia
Atmospheric pressure	14.7 psia (barometric)

Table 3-D-6—Expansion Factors for Pipe Taps (Y_2): Static Pressure Taken From Downstream Taps

	$\beta = d/D$										
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	1.0008	1.0008	1.0006	1.0003	1.0002	1.0000	0.9999	0.9998	0.9997	0.9996	0.9995
0.2	1.0017	1.0015	1.0012	1.0007	1.0004	1.0000	0.9999	0.9997	0.9995	0.9993	0.9990
0.3	1.0025	1.0023	1.0018	1.0010	1.0006	1.0000	0.9998	0.9995	0.9992	0.9989	0.9986
0.4	1.0034	1.0030	1.0024	1.0014	1.0008	1.0001	0.9997	0.9994	0.9990	0.9986	0.9981
0.5	1.0042	1.0038	1.0030	1.0018	1.0010	1.0001	0.9997	0.9992	0.9988	0.9982	0.9976
0.6	1.0051	1.0045	1.0036	1.0021	1.0012	1.0001	0.9996	0.9991	0.9985	0.9979	0.9972
0.7	1.0059	1.0053	1.0041	1.0025	1.0014	1.0002	0.9996	0.9990	0.9983	0.9975	0.9967
0.8	1.0068	1.0060	1.0047	1.0028	1.0016	1.0002	0.9995	0.9988	0.9980	0.9972	0.9962
0.9	1.0076	1.0068	1.0053	1.0032	1.0018	1.0002	0.9995	0.9987	0.9978	0.9969	0.9958
1.0	1.0085	1.0075	1.0059	1.0036	1.0021	1.0003	0.9994	0.9986	0.9976	0.9965	0.9954
1.1	1.0093	1.0083	1.0065	1.0039	1.0023	1.0003	0.9994	0.9984	0.9974	0.9962	0.9949
1.2	1.0102	1.0091	1.0071	1.0043	1.0025	1.0004	0.9994	0.9983	0.9972	0.9959	0.9945
1.3	1.0110	1.0098	1.0077	1.0047	1.0027	1.0004	0.9994	0.9982	0.9970	0.9956	0.9941
1.4	1.0119	1.0106	1.0083	1.0051	1.0030	1.0004	0.9993	0.9981	0.9968	0.9953	0.9936
1.5	1.0127	1.0113	1.0089	1.0054	1.0032	1.0005	0.9993	0.9980	0.9966	0.9950	0.9932
1.6	1.0136	1.0121	1.0096	1.0058	1.0034	1.0006	0.9993	0.9979	0.9964	0.9947	0.9928
1.7	1.0144	1.0128	1.0102	1.0062	1.0036	1.0006	0.9992	0.9978	0.9962	0.9944	0.9924
1.8	1.0153	1.0136	1.0108	1.0066	1.0039	1.0007	0.9992	0.9977	0.9960	0.9941	0.9920
1.9	1.0161	1.0144	1.0114	1.0070	1.0041	1.0008	0.9992	0.9976	0.9958	0.9938	0.9916
2.0	1.0170	1.0151	1.0120	1.0073	1.0044	1.0008	0.9992	0.9975	0.9956	0.9935	0.9912
2.1	1.0178	1.0159	1.0126	1.0077	1.0046	1.0009	0.9992	0.9974	0.9954	0.9932	0.9908
2.2	1.0187	1.0167	1.0132	1.0081	1.0048	1.0010	0.9992	0.9973	0.9952	0.9929	0.9904
2.3	1.0195	1.0174	1.0138	1.0085	1.0051	1.0010	0.9992	0.9972	0.9950	0.9927	0.9900
2.4	1.0204	1.0182	1.0144	1.0089	1.0053	1.0011	0.9992	0.9971	0.9949	0.9924	0.9896
2.5	1.0212	1.0189	1.0150	1.0093	1.0056	1.0012	0.9992	0.9971	0.9947	0.9921	0.9893
2.6	1.0221	1.0197	1.0156	1.0097	1.0058	1.0013	0.9992	0.9970	0.9945	0.9919	0.9889
2.7	1.0229	1.0205	1.0162	1.0101	1.0061	1.0014	0.9992	0.9969	0.9944	0.9916	0.9885
2.8	1.0238	1.0212	1.0169	1.0104	1.0063	1.0014	0.9992	0.9968	0.9942	0.9914	0.9882
2.9	1.0246	1.0220	1.0175	1.0108	1.0066	1.0015	0.9992	0.9968	0.9941	0.9911	0.9878
3.0	1.0255	1.0228	1.0181	1.0112	1.0068	1.0016	0.9993	0.9967	0.9939	0.9908	0.9874
3.1	1.0264	1.0235	1.0187	1.0116	1.0071	1.0017	0.9993	0.9966	0.9938	0.9906	0.9871
3.2	1.0272	1.0243	1.0193	1.0120	1.0074	1.0018	0.9993	0.9966	0.9936	0.9904	0.9867
3.3	1.0280	1.0250	1.0199	1.0124	1.0076	1.0019	0.9993	0.9965	0.9935	0.9901	0.9864
3.4	1.0289	1.0258	1.0206	1.0128	1.0079	1.0020	0.9994	0.9965	0.9933	0.9899	0.9860
3.5	1.0298	1.0266	1.0212	1.0133	1.0082	1.0021	0.9994	0.9964	0.9932	0.9896	0.9857
3.6	1.0306	1.0273	1.0218	1.0137	1.0084	1.0022	0.9994	0.9964	0.9931	0.9894	0.9854
3.7	1.0314	1.0281	1.0224	1.0141	1.0087	1.0024	0.9994	0.9963	0.9929	0.9892	0.9850
3.8	1.0323	1.0289	1.0230	1.0145	1.0090	1.0025	0.9995	0.9963	0.9928	0.9890	0.9847
3.9	1.0332	1.0296	1.0237	1.0149	1.0093	1.0026	0.9995	0.9963	0.9927	0.9888	0.9844
4.0	1.0340	1.0304	1.0243	1.0153	1.0095	1.0027	0.9996	0.9962	0.9926	0.9885	0.9840

Table 3-D-6—Continued

	$\beta = d/D$									
h_w/P_{f_1}	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9994	0.9994	0.9993	0.9992	0.9991	0.9990	0.9989	0.9988	0.9987	0.9986
0.2	0.9989	0.9988	0.9986	0.9985	0.9983	0.9981	0.9979	0.9977	0.9974	0.9972
0.3	0.9984	0.9982	0.9979	0.9977	0.9974	0.9972	0.9969	0.9965	0.9962	0.9958
0.4	0.9978	0.9976	0.9972	0.9969	0.9966	0.9962	0.9958	0.9954	0.9949	0.9944
0.5	0.9973	0.9970	0.9966	0.9962	0.9958	0.9953	0.9948	0.9942	0.9936	0.9930
0.6	0.9968	0.9964	0.9959	0.9954	0.9949	0.9944	0.9938	0.9931	0.9924	0.9916
0.7	0.9962	0.9958	0.9953	0.9947	0.9941	0.9935	0.9928	0.9920	0.9912	0.9902
0.8	0.9957	0.9952	0.9946	0.9940	0.9933	0.9926	0.9918	0.9909	0.9899	0.9889
0.9	0.9952	0.9946	0.9940	0.9932	0.9925	0.9917	0.9908	0.9898	0.9887	0.9875
1.0	0.9947	0.9940	0.9933	0.9925	0.9917	0.9908	0.9898	0.9887	0.9875	0.9862
1.1	0.9942	0.9935	0.9927	0.9918	0.9909	0.9899	0.9888	0.9876	0.9863	0.9848
1.2	0.9937	0.9929	0.9920	0.9911	0.9901	0.9890	0.9878	0.9865	0.9851	0.9835
1.3	0.9932	0.9924	0.9914	0.9904	0.9893	0.9881	0.9868	0.9854	0.9839	0.9822
1.4	0.9928	0.9918	0.9908	0.9897	0.9885	0.9872	0.9859	0.9844	0.9827	0.9809
1.5	0.9923	0.9912	0.9902	0.9890	0.9877	0.9864	0.9849	0.9833	0.9815	0.9796
1.6	0.9918	0.9907	0.9896	0.9883	0.9870	0.9855	0.9840	0.9822	0.9804	0.9783
1.7	0.9913	0.9902	0.9889	0.9876	0.9862	0.9847	0.9830	0.9812	0.9792	0.9770
1.8	0.9908	0.9896	0.9883	0.9870	0.9854	0.9838	0.9821	0.9801	0.9780	0.9757
1.9	0.9904	0.9891	0.9877	0.9863	0.9847	0.9830	0.9811	0.9791	0.9769	0.9744
2.0	0.9899	0.9886	0.9872	0.9856	0.9840	0.9822	0.9802	0.9781	0.9757	0.9732
2.1	0.9895	0.9881	0.9866	0.9849	0.9832	0.9813	0.9793	0.9770	0.9746	0.9719
2.2	0.9890	0.9876	0.9860	0.9843	0.9825	0.9805	0.9784	0.9760	0.9734	0.9706
2.3	0.9886	0.9870	0.9854	0.9836	0.9817	0.9797	0.9774	0.9750	0.9723	0.9694
2.4	0.9881	0.9865	0.9948	0.9830	0.9810	0.9789	0.9765	0.9740	0.9712	0.9681
2.5	0.9877	0.9860	0.9842	0.9823	0.9803	0.9780	0.9756	0.9730	0.9701	0.9669
2.6	0.9873	0.9855	0.9837	0.9817	0.9796	0.9772	0.9747	0.9720	0.9690	0.9657
2.7	0.9868	0.9850	0.9831	0.9811	0.9788	0.9764	0.9738	0.9710	0.9679	0.9644
2.8	0.9864	0.9846	0.9826	0.9804	0.9781	0.9757	0.9730	0.9700	0.9668	0.9632
2.9	0.9860	0.9841	0.9820	0.9798	0.9774	0.9749	0.9721	0.9690	0.9657	0.9620
3.0	0.9856	0.9836	0.9815	0.9792	0.9767	0.9741	0.9712	0.9681	0.9646	0.9608
3.1	0.9852	0.9831	0.9809	0.9786	0.9760	0.9733	0.9703	0.9671	0.9635	0.9596
3.2	0.9848	0.9826	0.9804	0.9780	0.9754	0.9725	0.9695	0.9661	0.9625	0.9584
3.3	0.9843	0.9822	0.9798	0.9774	0.9747	0.9718	0.9686	0.9652	0.9614	0.9572
3.4	0.9839	0.9817	0.9793	0.9768	0.9740	0.9710	0.9678	0.9642	0.9603	0.9561
3.5	0.9835	0.9812	0.9788	0.9762	0.9733	0.9702	0.9669	0.9633	0.9593	0.9549
3.6	0.9832	0.9808	0.9783	0.9756	0.9727	0.9695	0.9661	0.9623	0.9582	0.9537
3.7	0.9828	0.9803	0.9778	0.9750	0.9720	0.9688	0.9652	0.9614	0.9572	0.9526
3.8	0.9824	0.9799	0.9772	0.9744	0.9713	0.9680	0.9644	0.9605	0.9562	0.9514
3.9	0.9820	0.9794	0.9767	0.9738	0.9707	0.9673	0.9636	0.9596	0.9551	0.9503
4.0	0.9816	0.9790	0.9762	0.9732	0.9700	0.9665	0.9628	0.9586	0.9541	0.9491

Flowing temperature	60°F
Base temperature	60°F
Relative density (specific gravity)	0.620
Carbon dioxide	2 mole percent
Nitrogen	3 mole percent
Differential pressure device	Bellows (recorder, dry)

The solution is calculated as follows:

Diameter ratio (β) = 0.449102
Extension = 120.781
Basic orifice factor (F_b) = 4776.30
Reynolds number factor (F_r) = 1.0002
Expansion factor (Y_1) = 0.9982
Base pressure factor (F_{pb}) = 1.0000

Base temperature factor (F_{pb}) = 1.0000
Flowing temperature factor (F_{tf}) = 1.0000
Relative density factor (F_{gr}) = 1.2700
Supercompressibility factor (F_{pv}) = 1.0273
Orifice flow constant (C') = 6221.53
Flow rate (Q_v) = 751.441 MSCFH
= 18.0346 MMSCFD

3–D.4.10 ADJUSTMENTS FOR INSTRUMENTATION CALIBRATION AND USE

Other multiplying factors may be applied to the orifice flow constant, C', as a function of the type of instrumentation applied, the method of calibration, the meter environment, or any combination of these. These factors are discussed in the body of the standard and in other appendixes to the standard. These factors are calculated and applied independently of tap type. With these factors, the orifice flow rate is calculated using the following equation:

$$Q_v = C' F_{hg} F_a F_{am} F_{wl} F_{wt} F_{pwl} F_{hgm} F_{hgt} \sqrt{h_w P_f} \qquad (3\text{-D-17})$$

Where:

F_{hg} = mercury manometer factor (formerly F_m).
F_a = orifice thermal expansion factor.
F_{am} = correction for air over water in a water manometer during differential instrument calibration.
F_{wl} = local gravitational correction for water column calibration.
F_{wt} = water density correction (temperature or composition) for water column calibration.
F_{pwl} = local gravitational correction for deadweight tester static pressure calibration.
F_{hgm} = correction for gas column in a mercury manometer.
F_{hgt} = mercury manometer span correction for instrument temperature change after calibration.

APPENDIX 3-E—SI CONVERSIONS

This appendix contains tables of SI conversions that are pertinent to the information in this part of Chapter 14, Section 3. For additional information on SI units, refer to Chapter 15.

Table 3-E-1—Volume Reference Conditions for Custody Transfer Operations: Natural Gas Volume

Common Reference Conditions (ft³) Pressure (psia)	Temperature (°F)	To Convert From ft³ to m³, Multiply by	m³ to ft³, Multiply by
14.4	60	0.02769321	36.10994
14.65	60	0.02817399	35.49373
14.696	60	0.02826245	35.38263
14.7	60	0.02827015	35.37300
14.73	60	0.02832784	35.30096
14.7347	60	0.02833688	35.28970
14.735	60	0.02833746	35.28898
14.9	60	0.02865478	34.89819
15.025	60	0.02889517	34.60786

Note: The following standard conditions were used for inch-pound units—a temperature of 60°F and a pressure of 14.73 pounds per square inch absolute. The following standard conditions were used for SI units—a temperature of 15°C and an absolute pressure of 101.325 kPa. The following values were assumed: 1 ft = 0.3048 m, 1 psi = 6.894757 kPa. The following methodology was used to obtain the conversion factors:

$$\left(\frac{\text{ft}^3}{\text{m}^3}\right)\left(\frac{T_{imp}}{T_{SI}}\right)\left(\frac{P_{SI}}{P_{imp}}\right) = \text{factor}$$

Table 3-E-2—Energy Reference Conditions

Unit	Used in	Definition	To Convert Btu to J, Multiply by
Btu_{IT}	International steam tables	1 Btu/lbm = 2326 J/kg	1055.056

Table 3-E-3—Heating Value Reference Conditions

Reference Conditions (ft³) Pressure (psia)	Temperature (°F)	To Convert From Btu_{IT}/ft³ to MJ/m³, Multiply by
14.4	60	0.03809801
14.65	60	0.03744787
14.696	60	0.03733066
14.7	60	0.03732050
14.73	60	0.03724449
14.7347	60	0.03723261
14.735	60	0.03723185
14.9	60	0.03681955
15.025	60	0.03651323

Note: The following standard conditions were used for inch-pound units—a temperature of 60°F and a pressure of 14.73 pounds per square inch absolute. The following standard conditions were used for SI units—a temperature of 15°C and an absolute pressure of 101.325 kPa. The following values were assumed: 1 ft = 0.3048 m; 1 psi = 6.894757 kPa. 1 Btu_{IT} = 1055.056 J. The following methodology was used to obtain the conversion factors:

$$\left(\frac{\text{J}}{\text{Btu}}\right)\left(\frac{\text{MJ}}{1 \times 10^6\ \text{J}}\right)\left(\frac{\text{ft}^3}{\text{m}^3}\right)\left(\frac{T_{imp}}{T_{SI}}\right)\left(\frac{P_{SI}}{P_{imp}}\right) = \text{factor}$$

APPENDIX F—HEATING VALUE CALCULATION

3–F.1 General

Heating value is a gas property evaluated on a per-unit mass basis (H_m). This property is technically termed an "ideal property" (H_m^{id}). From a practical standpoint, in mass measurement there is no difference between the "ideal" and the "real." The value is converted to a heating value per cubic foot (*HV*) using the following relationships. The more common convention has been applied in this appendix.

$$HV = H_m \frac{\rho_b^{id}}{Z_b} = H_m \rho_b \qquad (3\text{-F-1})$$

The value of *HV* is used as a factor in calculating the energy flow rate, or the total energy passing through the flow meter *HV* is also used for product specifications.

It is also convenient to define the following:

$$HV = \frac{H_v^{id}}{Z_b} \qquad (3\text{-F-2})$$

3–F.2 Heating Value Symbols

Symbol	Description	Units
H_m	Heating value per pound mass	Btu/lbm
H_m^{id}	Ideal heating value per pound mass	Btu/lbm
H_v^{id}	Ideal heating value per cubic foot	Btu/ft³
HV	Gross heating value	Btu/ft³
Mr	Molar mass of component	lbm/lb-mol
P_b	Base pressure	lbf/in² (abs)
P_{f1}	Flowing pressure (upstream tap)	lbf/in² (abs)
P_v	Vapor pressure of water	lbf/in² (abs)
°R	Absolute temperature	—
T_b	Base temperature	°R
Z_b	Gas compressibility at base conditions (P_b, T_b)	—
ρ_b	Density at base conditions (P_b, T_b)	lbm/ft³
ρ_b^{id}	Ideal density at base conditions	lbm/ft³
x	Mole fraction	%/100
x_w	Mole fraction water	%/100

3–F.3 Heating Value

The gross heating value is an ideal gas property based on the ideal reaction:

$$\text{Fuel}^{id} + O_2^{id} \rightarrow CO_2^{id} + H_2O_l + SO_2^{id} \qquad (3\text{-F-3})$$

Where.

Superscript id = ideal gas.
Subscript l = liquid.

(Each fuel requires different stoichiometric coefficients.) This gross ideal heating value includes the energy obtained from the condensation of the water vapor (formed by the ideal reaction expressed in the equation) to the liquid phase.

It should be noted that the gross heating value is expressed per unit (pound mass or cubic foot) of dry gas. Although water is a product of combustion, it is not indicated on the left-hand side of Equation 3-F-3 in either the fuel or the oxygen; water is a result, not a part, of the reaction

Heating value may be determined directly by a calorimeter, either on line or from a sample cylinder. Heating value may also be calculated from gas analysis.

3–F.4 Physical Properties

Table 3-F-1 lists physical properties of many of the compounds present in natural gas in various hydrocarbon mixtures. The data in Table 3-F-1 have been adjusted to base or standard conditions, as defined in 3.2.3.4.

Table 3-F-1 provides the best currently available data on physical properties and is taken from GPA 2145-91. These data are subject to modification yearly as additional research is accomplished. Future revisions to GPA 2145 may include updated values. The values of the most recent edition of GPA 2145 should be used. The user of the GPA tables is cautioned that the information presented in them is calculated from different base conditions and that conversion is required when the information is used with Part 3 (see 3.5.2).

3–F.5 Heating Value Determined on a Volume Basis

A calculation of a mixture's gross ideal heating value, using H_v values from Table 3-F-1 and using mole fractions of the gas composition, involves determining the heating value per unit volume of real gas. *HV* can be determined by using Equation 3-F-2 and the following relationship:

Table 3-F-1—Physical Properties of Gases at Exactly 14.73 Pounds Force per Square Inch Absolute and 60°F (See Note 1)

								Thermal Energy	
Compound	Formula	*Mr* (Note 2)	P_c (psia) (Note 3)	T_c (°R) (Note 3)	G_i (Note 4)	Ideal Density (lbm/ft³) (Note 5)	Viscosity (cp) (Note 6)	H_m^{id} (Btu/lbm) (Note 7)	H_v^{id} (Btu/ft³) (Note 7)
Hydrogen	H_2	2.0159	187.5	59.36	0.06960	0.00532	0.00871	61,025	324.9
Helium	He	4.0026	32.9	9.34	0.13820	0.01057	0.01927	0	0
Water	H_2O	18.0153	3,200.1	1,164.85	0.62202	0.04758		1,059.8	50.4
Carbon monoxide	CO	28.010	507.5	239.26	0.96711	0.07398	0.01725	4,342.4	321.3
Nitrogen	N_2	28.0134	493.1	227.16	0.96723	0.07399	0.01735	0	0
Oxygen	O_2	31.9988	731.4	278.24	1.10484	0.08452	0.02006	0	0
Hydrogen sulfide	H_2S	34.08	1306	672.12	1.17669	0.09001	0.01240	7,094.2	638.6
Argon	Ar	39.948	710.4	271.55	1.37930	0.10551	0.02201	0	0
Carbon dioxide	CO_2	44.010	1,071.0	547.42	1.51955	0.11624	0.01439	0	0
Air (Note 8)		28.9625	546.9	238.36	1.00000	0.07650	0.01790	0	0
Methane	CH_4	16.043	667.0	343.00	0.55392	0.04237	0.01078	23,891	1,012.3
Ethane	C_2H_6	30.070	707.8	549.76	1.03824	0.07942	0.00901	22,333	1,773.7
Propane	C_3H_8	44.097	615.0	665.64	1.52256	0.11647	0.00788	21,653	2,521.9
iso-Butane	C_4H_{10}	58.123	527.9	734.13	2.00684	0.15351	0.00732	21,232	3,259.4
n-Butane	C_4H_{10}	58.123	548.8	765.25	2.00684	0.15351	0.00724	21,300	3,269.8
iso-Pentane	C_5H_{12}	72.150	490.4	828.70	2.49115	0.19057		21,043	4,010.2
n-Pentane	C_5H_{12}	72.150	488.1	845.44	2.49115	0.19057		21,085	4,018.2
n-Hexane	C_6H_{14}	86.177	439.5	911.47	2.97547	0.22762		20,943	4,766.9
n-Heptane	C_7H_{16}	100.204	397.4	970.57	3.45978	0.26466		20,839	5,515.2
n-Octane	C_8H_{18}	114.231	361.1	1,017.67	3.94410	0.30172		20,759	6,263.4
n-Nonane	C_9H_{20}	128.258	330.7	1,070.57	4.42842	0.33876		20,701	7,012.7
n-Decane	$C_{10}H_{22}$	142.285	304.6	1,111.87	4.91273	0.37581		20,651	7,760.8

Notes

1. The source for the data in this table is Gas Processors Association 2145-91. The accuracy of the experimental numbers is estimated to be 1 in 1000; the additional figures are for calculation consistency.
2. The following molecular weights were used: C = 12.011; H = 1.00794; O = 15.9994; N = 14.0067; and S = 32.06 (1979).
3. The data in these columns come from the Thermodynamics Research Center, Texas A&M University, IUPAC and National Bureau of Standards selections.
4. The ideal relative density is the ratio of the molecular weight of the gas to that of air (Mr/Mr_a).
5. Ideal density = 0.0026413*Mr* at 60°F and 14.73 pounds force per square inch absolute.
6. The data in this column are from N. B. Vargaftik, *Tables on Thermodynamic Properties of Liquids and Gases* (2nd ed.), New York, Wiley, 1975.
7. See Equation 3-F-3. Depending on the fuel, the reaction has various stoichiometric coefficients. The H_m^{id} column comes from data, whereas the H_v^{id} comes from multiplying H_m^{id} by the ideal gas density. The ideal energy released as heat is H_m^{id} multiplied by the real gas flow rate (in cubic feet per hour) divided by Z. Water has gross values for H_m^{id} and H_v^{id} (the ideal enthalpy of condensation).
8. The data in this row are from F. E. Jones, *National Bureau of Standards Journal of Research*, 1978, Volume 83, p. 491.

$$H_v^{id} = \phi_1 (H_{vi}^{id})_1 + \phi_2 (H_{vi}^{id})_2 + \ldots + \phi_n (H_{vi}^{id})_n \tag{3-F-4}$$

Or

$$H_v^{id} = \sum_{i=1}^{n} \phi_i (H_{vi}^{id})_i \tag{3-F-5}$$

When

$$HV = \frac{H_v^{id}}{Z_b} \tag{3-F-2}$$

Where:

ϕ = mole fraction (percent/100).

3–F.6 Heating Value Determined on a Mass Basis

The question of compressibility factor disappears when the ideal heating value per pound mass is used with the mass flow rate. The following equation is applicable for using H_m and Mr values from Table 3-F-1 to calculate the heating value:

$$H_m^{id} = \frac{\phi_1 Mr_1 (H_{mi}^{id})_1 + \phi_2 Mr_2 (H_{mi}^{id})_2 + \ldots + \phi_n Mr_n (H_{mi}^{id})_n}{\phi_1 Mr_1 + \phi_2 Mr_2 + \ldots + \phi_n Mr_n} \tag{3-F-6}$$

Or

$$H_m^{id} = \frac{\sum_{i=1}^{n} \phi_i Mr_i (H_{mi}^{id})_i}{\sum_{i=1}^{n} \phi_i Mr_i} \tag{3-F-7}$$

The result from Equation 3-F-7 can be converted to the gross heating value per cubic foot of real gas at base conditions by using Equation 3-F-1:

$$HV = H_{m}^{id} \frac{\rho_b^{id}}{Z_b} = H_{m}^{id} \rho_b$$

3–F.7 Heating Value of a Natural Gas Mixture Containing Water

To define heating value on a dry basis for gas containing water, the relationships in Equations 3-F-1 and 3-F-2 are valid if the mole fractions of the components are corrected for water content by using Equation 3-F-8 and the compressibility (Z) reflects the water content:

$$\phi_{i,wet} = \phi_i (1 - \phi_w) \tag{3-F-8}$$

Where the gas is water saturated under flowing conditions, Raoult's law may be used to estimate the mole fraction of water:

$$\phi_w = \frac{P_v}{P_f} \tag{3-F-9}$$

Where:

P_v = absolute vapor pressure of water at flowing conditions or T_f

Therefore,

$$\phi_{i,wet} = \phi_i \left(1 - \frac{P_v}{P_f}\right) \tag{3-F-10}$$

APPENDIX G—DEVELOPMENT OF CONSTANTS FOR FLOW EQUATIONS

3–G.1 General

The practical orifice flow equation used in Part 3 is given in Part 1 of this standard as Equation 1-2:

$$q_m = N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P} \qquad (1\text{-}2)$$

Where:

$C_d(FT)$ = coefficient of discharge at a specific pipe Reynolds number for a flange-tapped orifice meter.
d = orifice plate bore diameter calculated at flowing temperature.
ΔP = orifice differential pressure.
E = velocity of approach factor.
q_m = mass flow rate.
$\rho_{t,p}$ = density of fluid at flowing conditions (P_f, T_f).

And

N_1 = factor that incorporates the "constants" from Equation 1-1 and the required numeric conversions, including the following:

$\frac{3.14159}{4}$ = constant in Equation 1-1.

$\sqrt{2(32.1740)}$ = constant in Equation 1-1.

$\sqrt{\frac{62.3663}{12}}$ = converts differential pressure (ΔP) from pounds force per square foot to inches of water at 60°F.

$\frac{1}{12^2}$ = converts the diameter of the orifice bore (d) from feet to inches

Therefore,

$$\begin{aligned} N_1 &= \left(\frac{3.14159}{4}\right)\sqrt{2(32.1740)}\sqrt{\frac{62.3663}{12}}\left(\frac{1}{12^2}\right) \\ &= 0.0997424 \end{aligned}$$

(This is shown as the factor for U.S. units in Part 1, Table 1-2.)

Note: Some numeric constants do not have absolute values (for example, π and e). To express six significant digits accurately, the values were computed using double precision (16 significant digits). The results were then rounded to the values shown. In this appendix, for ease of understanding, the computations are shown to only six significant digits.

Mass flow can be modified to provide volume units by dividing the mass by the density at base conditions:

$$q_v = \frac{q_m}{\rho_b}$$

Where:

q_m = mass flow rate, in pounds mass per second.
q_v = volume flow rate at base conditions, in cubic feet per second.
ρ_b = density at base conditions, in pounds mass per cubic foot.

3–G.2 Symbols and Units

3–G.2.1 GENERAL

Some of the symbols and units listed below are specific to Appendix 3-B and were developed based on the customary inch-pound system of units. Regular conversion factors can

be used where applicable; however, if SI units are used, the more generic equations in Part 1 should be used for consistent results.

3–G.2.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
$C_d(FT)$	Coefficient of discharge at a specified pipe Reynolds number for flanged-tapped orifice meter	—
d	Orifice plate bore diameter calculated at flowing temperature, T_f	in
D	Meter tube internal diameter calculated at flowing temperature, T_f	in
E_v	Velocity of approach factor	—
°F	Temperature, in degrees Fahrenheit	—
°R	Temperature, in degrees Rankine	459.67 + °F
F_n	Numeric conversion factor (see Appendix 3-B)	—
g_c	Gravitational constant	32.1740 (lbm-ft)/(lbf-sec^2)
G_i	Ideal gas relative density (specific gravity)	—
G_r	Real gas relative density (specific gravity)	—
h_w	Orifice differential pressure	inches of water column at 60°F
N_1	Numeric conversion factor (see Part 1)	—
P	Pressure	lbf/in^2 (abs)
P_b	Base pressure	lbf/in^2 (abs)
P_{f_1}	Flowing pressure (upstream tap)	lbf/in^2 (abs)
P_s	Standard pressure	14.73 lbf/in^2 (abs)
Q_m	Mass flow rate per hour	lbm/hr
Q_v	Volume flow rate per hour at standard (base) conditions	ft^3/hr
R	Universal gas constant	1545.35 (lbf-ft)/(lb-mol-°R)
T	Temperature	°R
T_b	Base temperature	°R
T_f	Flowing temperature	°R
T_s	Standard temperature	519.67°R
Y_1	Expansion factor (upstream tap)	—
Z_b	Compressibility at base conditions	—
Z_{air}	Compressibility of air at 14.73 psia and 60°F	0.999590
Z_{f_1}	Compressibility at upstream flowing conditions	—
Z_s	Compressibility at standard conditions (P_s, T_s)	—
β	Ratio of orifice plate bore diameter to meter tube internal diameter (d/D) calculated at flowing temperature, T_f	—
π	Universal constant	3.14159
ρ_b	Gas density at base conditions (P_b, T_b, and Z_b)	lbm/ft^3
$\rho_{b,air}$	Density of air at base conditions (P_b, T_b, and Z_b)	lbm/ft^3
$\rho_{t,p}$	Density at flowing conditions (P_f, T_f, and Z_f)	lbm/ft^3
ρ_{t,p_1}	Density at flowing conditions (P_{f_1}, T_f, and Z_{f_1})	lbm/ft^3

3–G.3 General Numeric Constant for Mass Flow

Equation 3-1 expresses flow in pounds mass per hour (Q_m) rather than pounds mass per second (q_m) and requires an additional factor, 3600, to convert from seconds to hours.

Therefore, in Equation 3-1,

$$N_1 = 0.0997424(3600)$$
$$= 359.072$$

And

$$Q_m = 359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w} \qquad (3\text{-}1)$$

Equation 3-4a is Equation 3-1 divided by ρ_b, as described above. The numeric constant is the same.

$$Q_b = \frac{359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_b} \qquad (3\text{-}4a)$$

3–G.4 Numeric Constant for Mass Flow Developed From Ideal Gas Relative Density

Equation 3-2 substitutes Equation 3-55 for ρ_{t,p_1} in Equation 3-1.

$$Q_m = 359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} G_i (28.9625)(144) h_w}{Z_{f_1} R T_f}}$$

Where:

28.9625 = molecular weight of dry air.
1545.35 = universal gas constant (R).
144 = factor to convert pressure from pounds force per square foot to pounds force per square inch.

In Equation 3-2, therefore,

$$N_1 = 359.072 \sqrt{28.9625\left(\frac{144}{1545.35}\right)}$$
$$= 589.885$$

And

$$Q_m = 589.885 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{G_i P_{f_1} h_w}{Z_{f_1} T_f}} \qquad (3\text{-}2)$$

3–G.5 Numeric Constant for Mass Flow Developed From Real Gas Relative Density

Equation 3-3 substitutes G_r for G_i in Equation 3-2 through the use of Equation 3-48:

$$Q_m = 589\ 885 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{Z_b G_r P_{f_1} h_w}{Z_{b_{air}} Z_{f_1} T_f}}$$

And for standard conditions,

$$Z_b = Z_{b_{air}} = 0.999590 \text{ at } 14.73 \text{ psia and } 519.67°\text{R } (60°\text{F})$$

In Equation 3-3, therefore,

$$N_1 = \frac{589.885}{\sqrt{0.999590}}$$
$$= 590.006$$

And

$$Q_m = 590.006 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{Z_i G_r P_{f_1} h_w}{Z_{f_1} T_f}} \qquad (3\text{-}3)$$

3–G.6 Numeric Constant for Base Volume Developed From Ideal Gas Relative Density

The constant 359.072 in Equation 3-4a was developed in 3-G.3. Equation 3-5a substitutes Equation 3-55 for ρ_{t,P_1} and Equation 3-56 for ρ_b in Equation 3-4a.

$$Q_b = \frac{359.072 C_d (FT) E_v Y_1 d^2 \sqrt{\rho_{t,P_1} h_w}}{\rho_b} \qquad (3\text{-}4a)$$

$$Q_b = 359.072 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} G_i (28.9625)(144) h_w}{Z_{f_1} R T_f}} \sqrt{\frac{Z_b R T_b}{P_b G_i (28.9625)(144)}}$$

Where:

1545.35 = universal gas constant (R).
28.9625 = molecular weight of dry air.
144 = factor to convert flowing pressure (P_{f_1}) from pounds force per square foot to pounds force per square inch.
144 = factor to convert base pressure (P_b) from pounds force per square foot to pounds force per square inch.

In Equation 3-5a, therefore,

$$N_1 = \frac{359.072 \sqrt{1545.35 \left(\frac{144}{28.9625} \right)}}{144} = 218.573$$

And

$$Q_b = 218.573 C_d (FT) E_v Y_1 d^2 \frac{T_b Z_b}{P_b} \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}} \qquad (3\text{-}5a)$$

For the following standard conditions:

$P_b = P_s$
$= 14.73$ lbf/in^2 (abs)
$T_b = T_s$
$= 519.67°R$ (60°F)
$Z_b = Z_s$
= compressibility of the gas at P_s and T_s

In Equation 3-5b,

$$N_1 = 218.573 \left(\frac{519.67}{14.73} \right) = 7711.19$$

Therefore,

$$Q_b = 7711.19 C_d (FT) E_v Y_1 d^2 Z_s \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}} \qquad (3\text{-}5b)$$

3–G.7 Numeric Constant for Base Volume Developed From Real Gas Relative Density

Equation 3-6a substitutes G_r for G_i in Equation 3-5a through the use of Equation 3-48. The inclusion of ρ_b moves this correction to the numerator:

$$Q_b = 218.573 C_d (FT) E_v Y_1 d^2 \frac{T_b}{P_b} \sqrt{\frac{Z_b Z_{b_{air}} P_{f_1} h_w}{G_r Z_{f_1} T_f}}$$

In Equation 3-6a, therefore,

$$N_1 = 218.573$$

For the following standard conditions:

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ lbf/in}^2 \text{ (abs)} \\ T_b &= T_s \\ &= 519.67°\text{R (60°F)} \\ Z_{b_{air}} &= Z_{s_{air}} \\ &= 0.999590 \end{aligned}$$

In Equation 3-6b,

$$\begin{aligned} N_1 &= 218.573\left(\frac{519.67}{14.73}\right)\sqrt{0.999590} \\ &= 7709.61 \end{aligned}$$

$$Q_v = 7709.61 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \qquad (3\text{-}6b)$$

3–G.8 Numeric Constant for Standard Volume Developed From Real Gas Relative Density

In Appendix 3-B, F_n, as expressed in Equation 3-B-5, includes additional numeric ratios, as stated in Equation 3-B-1, including the following:

519.67 = base temperature at 60°F, expressed in degrees Rankine.

$\frac{1}{14.73}$ = base pressure of 14.73 pounds force per square inch absolute.

$\sqrt{\frac{1}{519.67}}$ = flowing temperature at 60°F, expressed in degrees Rankine.

$\sqrt{0.999590}$ = compressibility of air at the base pressure of 14.73 pounds force per square inch absolute and the base temperature of 519.57°R.

In Equation 3-B-5, therefore,

$$\begin{aligned} N_1 &= 218.573\left(\frac{519.67}{14.73}\right)\sqrt{\frac{1}{519.67}} \\ &= 338.196 \end{aligned}$$

And

$$F_n = 338.196 E_v d^2 \qquad (3\text{-}B\text{-}5a)$$

Or

$$F_n = 338.196 E_v D^2 \beta^2 \qquad (3\text{-}B\text{-}5b)$$

Manual of Petroleum Measurement Standards Chapter 14—Natural Gas Fluids Measurement

Section 8—Liquefied Petroleum Gas Measurement

Measurement Coordination Department

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Chapter 14—Natural Gas Fluids Measurement

SECTION 8—LIQUEFIED PETROLEUM GAS MEASUREMENT

14.8.0 Scope and Purpose

This publication describes dynamic and static metering systems used to measure liquefied petroleum gas in the density range of 0.30 to 0.70 grams per cubic centimetre. The physical properties of the components to be measured and the mixture composition of liquefied petroleum gas should be reviewed to determine the measurement system to be used. Various systems and methods can be used in metering the product, and mutual agreement on the system and method between the contracting parties is required.

This publication does not endorse or advocate the preferential use of any specific type of meter or metering system. Further, this publication is not intended to restrict the future development of meters or measuring devices nor to in any way affect metering equipment already installed and in operation.

This publication serves as a guide in the selection, installation, operation, and maintenance of measuring systems applicable to liquefied petroleum gases and includes functional descriptions for individual systems.

14.8.1 Application

This publication does not set tolerances or accuracy limits. The application of the information here should be adequate to achieve acceptable measurement performance using good measurement practices, while in addition considering user requirements and applicable codes and regulations.

Systems for measuring liquefied petroleum gases use either volumetric or mass determination methods, and both methods apply to either static or dynamic conditions.

Volumetric methods of measurement are generally used where physical property changes in temperature and pressure are known and correction factors can be applied to correct the measurement to standard conditions.[1] Volumetric measurement is applicable to most pure components and many commercial product grades.

Mass determination methods of measurement are most commonly used where conditions in addition to temperature and pressure will affect the measurement. Such conditions include compositional changes, intermolecular adhesion, and volumetric changes caused by solution mixing. Mass measurement is applicable to liquefied petroleum gas mixtures where accurate physical correction factors have not been determined and in some manufacturing processes for a mass balance.

Many of the measurement procedures pertaining to the measurement of other products are applicable to the measurement of liquefied petroleum gases. However, certain characteristics of liquefied petroleum gas require extra precautions to improve measurement accuracy.

Liquefied petroleum gas will remain in the liquid state only if a pressure sufficiently greater than the equilibrium vapor pressure is maintained (see Chapters 5.3 and 6.6). In liquid meter systems, adequate pressure must be maintained to prevent vaporization caused by pressure drops attributed to piping, valves, and meter tubes. When liquefied

---

[1] Standard temperature is 60°F in the English (or customary) system and 15°C in the International System of Units (SI). Standard pressure is the vapor pressure at 60°F (15°C) or 14.696 pounds per square inch absolute (101.325 kilopascals), whichever is higher. This is not the same pressure base standard as that used for gas.

petroleum gas is stored in tanks or containers, a portion of the liquid will vaporize and fill the space above the liquid. The amount vaporized will be related to the temperature and the equilibrium constant for the mixture of components.

Liquefied petroleum gas is more compressible and has a greater coefficient of thermal expansion than the heavier hydrocarbons. The application of appropriate compressibility and temperature correction factors is required to correct measurements to standard conditions, except when measurement for mass determination is from density and volume at metering temperatures and pressures.

Meters should be proven on each product at or near the normal operating temperature and pressure. Should the product or operating conditions change so that a significant change in the meter factor occurs, the meter should be proven again according to Chapters 4 and 5.

14.8.2 Referenced Publications

To the extent specified in the text, the latest edition or revision of the following standards and publications form a part of this publication

API

Manual of Petroleum Measurement Standards

Chapter 2, "Tank Calibration" (in preparation)
Chapter 4, "Proving Systems"
Chapter 5.2, "Measurement of Liquid Hydrocarbons by Positive Displacement Meter"
Chapter 5.3, "Turbine Meters"
Chapter 5.4, "Instrumentation or Accessory Equipment for Liquid Hydrocarbon Metering Systems"
Chapter 6.6, "Pipeline Metering Systems"
Chapter 9.1, "Hydrometer Test Method for Density, Relative Density, or API Gravity of Crude Petroleum and Liquid Petroleum Products"
Chapter 11.1, "Volume Correction Factors"
Chapter 12.2, "Calculation of Liquid Petroleum Quantities Measured by Turbine or Displacement Meters"
Chapter 14.1, "Measuring, Sampling, Testing, and Base Conditions for Natural Gas Fluids"
Chapter 14.3, "Orifice Metering of Natural Gas"
Chapter 14.4, (in preparation)
Chapter 14.6, "Installing and Proving Density Meters"
Chapter 14.7, (in preparation)

ASTM[2]

DS 4A	*Physical Constants of Hydrocarbons* C_1 *to* C_{10}

GPA[3]

2140	*Liquefied Petroleum Gas Specifications and Test Methods* (ASTM D 1265, ANSI Z11 91)
2145	*Physical Constants for the Paraffin Hydrocarbons and Other Components of Natural Gas*
2165	*Method for Analysis of Natural Gas Liquid Mixtures by Gas Chromatography*
2174	*Method for Obtaining Hydrocarbon Fluid Samples Using a Floating Piston Cylinder*

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[2] American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103
[3] Gas Processors Association, 1812 First Place, Tulsa, Oklahoma 74103

2177	*Tentative Method for the Analysis of Demethanized Hydrocarbon Liquid Mixtures Containing Nitrogen and Carbon Dioxide by Gas Chromatography*
2261	*Method of Analysis for Natural Gas and Similar Gaseous Mixtures by Gas Chromatography*
8173	*A Standard for Converting Natural Gas Liquids and Vapors to Equivalent Liquid Volumes*

GPSA[4]
Engineering Data Book

14.8.3 Requirements for All Measurement Methods

The following general requirements apply to dynamic measurement systems using either volumetric or mass determination methods of measuring liquefied petroleum gases.

14.8.3.1 PROVISIONS TO ENSURE THAT FLUIDS ARE IN THE LIQUID PHASE

Provisions shall be made to ensure that liquefied petroleum gas measurement conditions of temperature and pressure will be adequate to keep the fluid totally in the liquid phase. Measurement in the liquid phase must occur at a pressure at least 1.25 times the equilibrium vapor pressure at measurement temperature, plus twice the pressure drop across the meter at maximum operating flow rate, or at a pressure 125 pounds per square inch higher than the vapor pressure at a maximum operating temperature, whichever is lower (see Chapters 5.3 and 6.6)

14.8.3.2 ELIMINATION OF SWIRL

To prevent swirl through the measuring device when using turbine or orifice meters, straightening vanes or adequate unrestricted straight lengths of piping should be used in the upstream and downstream metering tube.

14.8.3.3 TEMPERATURE MEASUREMENT

Temperature measurements, where required, should be made at a point that indicates conditions in the measuring device. The accuracy of instruments and the type of measurement used are specified in Chapters 5.2, 5.3, 5.4, and 14.6.

14.8.3.4 PRESSURE MEASUREMENT

Pressure measurements, where required, should be made at a point that will be responsive to varying pressure conditions in the measuring device. The accuracy of instruments and the type of measurement used should be as described in Chapters 5.2 and 14 6.

14.8.3.5 DENSITY OR RELATIVE DENSITY MEASUREMENT

The point for measurement of density or relative density (specific gravity) of the liquid should be sensitive to varying conditions in the measuring device. Densities to be used for mass measurement determination must be obtained at the same flowing conditions that exist at the meter. The accuracy of instruments and the type of measurement used should be as described in Chapters 9 and 14.6.

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[4] Gas Processors Suppliers Association; Order from Gas Processors Association, 1812 First Place, Tulsa, Oklahoma 74103

14.8.3.6 LOCATION OF MEASURING AND SAMPLING EQUIPMENT

Measuring and sampling equipment must be located to minimize or eliminate the influence of pulsation or mechanical vibration caused by pump or control valve generated noise. Special precautions should be taken to minimize or eliminate the effects of electrical interference that may be induced in the flow meter pick-up coil circuit.

14.8.4 Volumetric Determination in Dynamic Systems

Measurement of liquefied petroleum gas (liquid phase) in a dynamic condition can be performed using several measurement devices. The use of a specific type of measuring device is dependent upon mutual agreement between the contracting parties.

14.8.4.1 MEASUREMENT BY ORIFICE METER

Measurement of liquefied petroleum gases by orifice meter shall conform to Chapter 14.3, using orifice and line internal diameter ratios and appropriate coefficients for flow as agreed upon between the parties. Location factors, F_l, and orifice thermal expansion factor, F_a, should be used where applicable according to the procedure in Chapter 14.3, Appendix B.14 and B.15 respectively. Manometer factors, F_m, must be calculated according to the procedure in this section for recorders utilizing mercury manometers. (F_m = 1 000 for bellows type differential pressure instruments.)

Measurement of liquefied petroleum gas having a high vapor pressure is simplified where deliveries are obtained in mass units, by multiplying the volume at flowing conditions times the density or relative density (measured within prescribed limits at the same flowing temperature and pressure that exists at the meter) times an appropriate constant. Calculation of the volume at standard conditions can then be made using 14.8.6 or GPA Standard 8173.

The following equations can be used to determine flow rate:

1. Flow rate in cubic feet per hour at flowing conditions

$$Q_f = 0.134452\, F_b F_r Y\, F_m F_a F_l \sqrt{\frac{h_w}{G_f}}$$

$$Q_f = 1.0618\, F_b F_r Y\, F_m F_a F_l \sqrt{\frac{h_w}{\rho_f}}$$

2. Flow rate in pounds mass per hour.

$$Q_m = 8.3853\ F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, G_f}$$

$$Q_m = 1.0618\ F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, \rho_f}$$

3. Flow rate in cubic feet per hour at base conditions.

$$Q_b = \frac{0.134452}{G_b} F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, G_f}$$

$$Q_b = \frac{1.0618}{\rho_b} F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, \rho_f}$$

Where:

F_b = basic orifice factor from Chapter 14.3 (F_b = 338.17 d^2K_o).

F_m = manometer factor for mercury manometers only.
Y = expansion factor, calculated using a specific heat ratio for flowing conditions as determined from data or an equation of state.
F_r = Reynolds number factor.

The Reynolds number factor may be calculated using b values from Table 5 or Table 9 of Chapter 14.3. CAUTION: Do not use the equations for F_r in Tables 5 or 9, but use the b values only in the following equations to obtain the Reynolds number factor.

$$F_r = 1 + \frac{b\ 8{,}423\mu_{pfs}}{\sqrt{h_w\ \rho_f}} = 1 + \frac{b\ 1{,}067\mu_{pfs}}{\sqrt{h_w\ G_f}}$$

$$F_r = 1 + \frac{b\ 271{,}000\mu_e}{\sqrt{h_w\ \rho_f}} = 1 + \frac{b\ 34{,}316\mu_e}{\sqrt{h_w\ G_f}}$$

$$F_r = 1 + \frac{b\ 5.66\mu_{cp}}{\sqrt{h_w\ \rho_f}} = 1 + \frac{b\ 0.7167\mu_{cp}}{\sqrt{h_w\ G_f}}$$

$$b = \frac{E}{12{,}835dK}$$

The Reynolds number factor also may be calculated from the following:

$$F_r = 1 + E/R_d$$

Where.

$$R_d = \frac{V_f d\rho}{12\mu_{pfs}}$$

d = diameter of orifice, in inches.
ρ = density, in pounds per cubic foot.
V_f = velocity of jet in orifice, in feet per second.
μ_{pfs} = absolute viscosity, in pounds per foot per second.

$$R_d = \frac{2{,}267.8\ dK\sqrt{h_w\rho_f}}{\mu_{cp}} - \frac{17{,}909\ dK\sqrt{h_w\ G_f}}{\mu_{cp}}$$

$$R_d = \frac{0.04736\ dK\sqrt{h_w\rho_f}}{\mu_e} = \frac{0.37405\ dK\sqrt{h_w\ G_f}}{\mu_e}$$

$$R_d = \frac{1.5238\ dK\sqrt{h_w\rho_f}}{\mu_{pfs}} = \frac{12.034\ dK\sqrt{h_w\ G_f}}{\mu_{pfs}}$$

R_d can also be determined by trial and error as follows: Set F_r = 1.000 in the flow equation to get an approximate Q_m or Q_b, and use this result to calculate F_r. With this calculated value of F_r, obtain a new value of F_r and of Q_m or Q_b. Repeat this process until the value of Q_m or Q_b is within the limits desired.

$$R_d - R_D/\beta$$

$$R_D = \frac{6.30\ Q_m}{D\mu_{cp}} = \frac{294\ 30\ Q_bG_b}{D\mu_{cp}}$$

$$R_D = \frac{0.0001519\ Q_m}{D\mu_e} = \frac{0.004244\ Q_m}{D\mu_{pfs}}$$

$$F_r = 1 + \frac{0.1582\beta\, E\, D\mu_{cp}}{Q_m} = 1 + \frac{0.002539\beta\, E\, D\mu_{cp}}{Q_b G_b}$$

$$F_r = 1 + \frac{7581.5\beta\, E\, D\mu_{cp}}{Q_m} = 1 + \frac{235.63\beta\, E\, D\mu_{pfs}}{Q_m}$$

Where:

μ_{pfs} = absolute viscosity, in pounds per foot per second. = $g\mu_r$

μ_e = absolute viscosity, in pounds per square foot per second.

μ_{cp} = absolute viscosity, in centipoises.

μ_r = $0.03108\mu_{pfs} = 0.00002089\mu_{cp}$.

ρ_b = density of liquid, in pounds per cubic foot at base conditions.

ρ_f = density of liquid, in pounds per cubic foot at flowing temperature and pressure.

D = diameter (inside) of meter tube, in inches.

d = diameter of orifice bore, in inches.

β = d/D (commonly called the beta ratio).

G_f = relative density at flowing conditions. Ratio of the density of the liquid at flowing conditions to the density of water at 60°F. (The U.S. National Bureau of Standards has established 0.999012 gram per cubic centimetre as the density of air-free pure water in a vacuum at a temperature of 60°F and a pressure of 14.696 pounds per square inch and standard gravitational acceleration of 980.665 centimetres per second per second.)

G_b = relative density of liquid at base conditions.

K = coefficient of discharge for a sharp edge orifice.

$K = K_o\,(1 + E/R_d)$

$$K_o = \frac{K_e}{1 + \dfrac{15E}{1{,}000{,}000d}}$$

Where:

K_o = coefficient of discharge for infinite Reynolds number.

K_e = coefficient of discharge when the Reynolds number is equal to

$$\frac{1{,}000{,}000d}{15}.$$

$$E = d(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + \frac{520}{\sqrt{D}}), \quad \text{for flange taps.}$$

$$E = d(905 - 5000\beta + 9000\beta^2 - 4200\beta^3 + \frac{875}{D}), \quad \text{for pipe taps.}$$

For flange taps

$$K_e = 0.5993 + \left[0.364 - \frac{0.076}{\sqrt{D}}\right]\beta^4 + 0.4\left[1.6 - \frac{1}{D}\right]^5 \left[(0.07 + \frac{0.5}{D}) - \beta\right]^{2.5}$$

$$- \left[0.009 + \frac{0.034}{D}\right]\left[0.5 - \beta\right]^{1.5} + \left[\frac{65}{D^2} + 3\right]\left[\beta - 0.7\right]^{2.5} + \frac{0.007}{D}$$

For pipe taps

$$K_e = 0.5925 + \frac{0.0182}{D} + \left[0.440 - \frac{0.06}{D}\right]\beta^2 + \left[0.935 + \frac{0.225}{D}\right]\beta^5$$

$$+ 1.35\ \beta^{14} + \frac{1.43}{\sqrt{D}}\ (0.25 - \beta)^{2.5}$$

NOTE: When any of the terms in K_e is negative, that term is set equal to zero.

F_l = location factor.

The location factor is used to correct for the change in specific weight of (a) the mercury in mercury manometer type differential gages, (b) the calibrating liquid in the test manometer, and (c) the weights for a deadweight gage used in calibrating the instruments. See Chapter 14.3, Appendix B, B. 34 for equations.

F_m = manometer factor

The manometer factor is required only in mercury manometer type gages to correct for the error in differential pressure indication caused by the weight of the liquid column above the mercury and the change in the density of the mercury at temperatures other than the base temperature of 60°F.

$$F_m = 0.034374 \sqrt{\rho_m - \rho_l}$$

Where:

ρ_m = density of mercury at ambient temperature, in pounds per cubic foot.

ρ_m = 846.324 [1 − 0.000101(T_a − 60)]

T_a = ambient temperature, in degrees Fahrenheit.

ρ_l = density of liquid on mercury at ambient temperature, in pounds per cubic foot. See Chapter 11.1, Tables 6, for density correction.

F_a = orifice thermal expansion factor.

This factor is used to correct for the error resulting from the expansion or contraction of the orifice bore at operating temperatures different from the temperature of the plate when bored, usually assumed to be 68°F.

F_a = 1 + 0.0000185 (°F − 68) for Type 304 and 316 stainless steels.

F_a = 1 + 0.0000159 (°F − 68) for Monel.

14.8.4.2 MEASUREMENT BY POSITIVE DISPLACEMENT METER

The manufacturer's recommendations should be carefully considered in sizing turbine and positive displacement meters (see Chapters 5.2 and 5.3).

Air eliminators should be used with caution, particularly where the line in which they are installed could be shut-in occasionally, and where complete vaporization could occur

Vapor formation, resulting from the effects of ambient temperature or heat tracing on the line ahead of the meter, could cause inaccuracies and damage, which are most likely to be encountered during startup Caution must be exercised.

14.8.4.2.1 Volume at Standard or Base Conditions

Liquid measurement by positive displacement meters should conform to the procedures in Chapter 5.2. Appropriate correction factors should be used to adjust the measured volume to standard conditions by correcting for temperature, pressure, and meter factor. Factors to be applied will be found in Chapters 11 and 12.

The positive displacement measurement equation is:

$$V_b = V_f \times \text{M.F.} \times C_{tl} \times C_{pl}$$

Where:

V_b = volume at base or standard conditions.
V_f = volume at flowing conditions, indicated by a measuring device.
M.F. = meter factor, obtained by proving the meter according to Chapters 4 and 12.2.
C_{tl} = correction factor for temperature to correct the volume at flowing temperature to standard temperature. See Chapter 11.1, Tables 24, or other agreed-upon tables.
C_{pl} = correction factor for pressure to correct the volume at flowing pressure to standard conditions. See Chapter 11.1, Tables 24, or other agreed-upon tables.

14.8.4.2.2 Volume at Flowing Conditions for Mass Determination

The volume measured at flowing conditions (V_m) times the meter factor equals the volume at flowing conditions. Displacement meters used for volumetric measurement in deriving total mass shall conform to the standards described in Chapter 5.2 for the service intended. Temperature or pressure compensation devices are not to be used on these meters and the accessories used shall conform to Chapter 5.4.

14.8.4.3 MEASUREMENT BY TURBINE METER

See 14.8.4.2 for cautions about air eliminators and vapor formation in lines. Also carefully consider the manufacturer's recommendations about sizing of meters.

Liquid measurement by turbine meter should conform to the procedures described in Chapter 5.3. Appropriate correction factors should be used that will adjust the measured volume to standard conditions by correcting for temperature, pressure, and meter factor. Factors to be applied will be found in Chapters 4, 11, and 12

The following equation is used when measuring by turbine meter.

$$V_b = V_f \times \text{M.F.} \times C_{tl} \times C_{pl}$$

Where:

V_b = volume at base or standard conditions
V_f = volume at flowing conditions, indicated by a measuring device.
M.F = meter factor, obtained by proving the meter according to Chapters 4 and 12.2.
C_{tl} = correction factor for temperature to correct the volume at flowing temperature to standard temperature. See Chapter 11.1, Tables 24, or other agreed-upon tables
C_{pl} = correction factor for pressure to correct the volume at flowing pressure to standard conditions. See Chapter 11.1, Tables 24, or other agreed-upon tables

Turbine meters used for volumetric measurement in deriving total mass shall conform to Chapter 5.3 for the service intended. Temperature or pressure compensating devices shall not be used on these meters and accessories shall conform to Chapter 5.4. The mass delivered and the volume of each component at standard conditions may be determined according to Chapter 14.7.

14.8.4.4 MEASUREMENT BY OTHER DEVICES

Dynamic measurement of liquefied petroleum gas can be accomplished using other types of equipment by mutual agreement of the contracting parties.

14.8.4.5 METER PROVING

The primary measuring device must be compared to a known standard. Comparison to a standard is accomplished by proving displacement and turbine meters using a pipe prover calibrated in accordance with Chapter 4. Tank-type provers are not recommended because liquefied petroleum gas may vaporize in the tank, making accountability for these vapors difficult. When a meter is used to measure more than one product, the meter shall be proved at the operating rates of flow, pressure, and temperature and the specification of the liquid that it will measure in routine operation. Several meter factors may be required where normal operations change significantly. The proving device should be installed so that the temperature and pressure within the prover and meter coincide as closely as possible. Should meter and prover temperatures or pressures vary, the prover volume shall be corrected to meter operating conditions according to Chapters 4, 11, and 12 or as agreed to by the contracting parties. Factors shall be adjusted as required between proving dates as a result of significant changes in metering pressure and/or temperature since the last proving.

14.8.4.6 SAMPLING

Sampling shall be accomplished to yield a sample that is proportional to, and representative of, the flowing stream during the measuring interval. Proportional samplers take small samples of the flowing stream proportional to the flow rate. Time incremental sampling may be used only when the flow rate is constant.

The sample collecting system shall be designed to contain the collected sample in the liquid state. This may be done using a piston cylinder or a cylinder with a bladder. Both the piston cylinder and bladder cylinder normally use inert gas vapor, hydraulic oil, or pipeline fluid to oppose the liquid injection and maintain a pressure level above the vapor pressure of the sample. A typical proportional sampler is described in the appendix to this publication.

Precautions shall be taken to avoid vaporization in sample loop lines when operating near the product vapor pressure. In some instances, insulating sample lines and sample containers or controlling the pressure or temperature of sample containers containing volatile materials may be necessary.

Sample loops should be short and of small diameter, sampling from the center of the stream. Adequate sample loop flow rates should be maintained to keep fresh product at the sample valve and to reduce the time lag between the meter and the sampler to a minimum.

All sample lines, pumps, and related equipment should be purged or bled down when sample collection cylinders are emptied to avoid contamination or distortion of the flowing sample. Sampler systems should be designed to minimize dead product areas, which could distort samples.

Obtaining a representative sample for transport to the laboratory shall be in accordance with GPA 2174, Appendix B of Chapter 14.1, or other recognized safety procedures. Sample containers must be adequately sized. If samples are to be shipped by common carrier, containers must comply with the latest hazardous materials regulations of the United States Department of Transportation.

Products or mixtures that have equilibrium vapor pressures above atmospheric pressure shall be maintained at a pressure where vaporization cannot occur within the on-line sample system or transfer containers.

Use of sample collection and transportation containers equipped with floating pistons or bladders (and equipped to maintain sample storage pressures above vapor pressure) is one effective way to avoid liquid-vapor separation. When using this type of equipment, adequate precautions must be observed to allow for thermal expansion of the product so that excessive pressure or release of product does not occur. Procedures described in the appendix of this publication may be used.

Sample handling procedures outlined in API Chapter 14.1, Appendix B, using immiscible fluid outage cylinders, may also be used. Water used with this method may result in removal of carbon dioxide or other water-soluble components from the sample.

Sample injection pumps or devices that inject the sample into containers shall be designed to deliver a constant volume per stroke over their normal operating pressure range. Procedures as outlined in Chapter 14.1, the appendix to this publication, and GPA Publication 2174 shall be followed, as applicable.

Samples taken over a period of time using a proportional sampler must be mixed to be truly representative before they are transferred to portable sample containers. Product mixing should not be attempted until the sampler has been isolated from the source. Procedures for thorough mixing of samples shall be provided to ensure that samples transferred to transportation cylinders and the analysis obtained are representative of the flowing stream during the measured interval.

After mixing, the sampled product is transferred to a portable piston cylinder or a double valved sample cylinder, using the immiscible fluid displacement method. Transfer the sampler to the portable cylinder using the same procedure used to take spot samples. When the required number of portable cylinders has been filled, the remaining product in the sampler must be vented back into the pipeline or disposed of before the sampler is returned to service.

Obtaining a representative sample of the stream liquid for transport to the laboratory shall be in accordance with GPA Publication 2174 or Appendix B of Chapter 14.1. Provisions shall be made for thermal expansion. Department of Transportation approved containers shall be used.

14.8.4.7 SAMPLE ANALYSIS

Depending upon the composition of the stream, liquid sample analysis shall follow the chromatographic procedures described in GPA Publications 2165, 2177, and 2261, or other methods agreed upon by the contracting parties.

Where applicable, such as with liquefied petroleum gas mixtures, special efforts shall be made to accurately determine the molecular weight and the density of the heptanes plus fraction (or of the last significant fraction determined by agreement).

14.8.5 Mass Determination in Dynamic Systems (Density Range 0.30 to 0.70 g/cm^3)

Mass measurement is applicable to liquefied petroleum gas mixtures and to components that are affected by compositional changes, intermolecular adhesions, solution mixing, or extreme pressure and temperature conditions where accurate physical correction factors have not been determined.

Mass measurement in a dynamic state normally utilizes (1) a volumetric measuring device at flowing conditions, (2) a density or relative density (specific gravity) measuring device for determining density or relative density at the same flowing conditions as the measuring device, and (3) a representative sample of the fluid flowing through the measuring system, collected proportional to flow, as presented in Chapter 14.7.

Mass measurement is accomplished by multiplying the measured volume at flowing conditions times flowing density measured at the same conditions, using consistent units. The equivalent volume at standard conditions of each component in the mixture may be

obtained by using a compositional analysis of the representative sample and the density of each component at 60°F and the equilibrium pressure at 60°F.

Liquids with densities below 0.3 and above 0.7 grams per cubic centimetre and cryogenic fluids are excluded from the scope of this document. However, the principles can apply to these fluids with modified application techniques.

Equipment exists which uses diverse principles for measuring volume, sampling the product, and determining the composition and density of the product. This publication does not advocate the preferential use of any particular type of equipment. It is not the intention of this publication to restrict future development or improvement of equipment.

14.8.5.1 BASE CONDITIONS

Density is defined as mass per unit volume:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

Mass is an absolute measure of the quantity of matter. Weight is the force resulting from an acceleration due to gravity acting upon a mass. Changes of gravity acceleration from one locality to another will affect the resulting weight force observed. Therefore, quantities determined in accordance with Chapter 14.7 shall be *mass* rather than weight. This may be accomplished through procedures in Chapter 14.6 by referral to weighing devices used to calibrate density meters to test weights of known mass. This referral or calibration is done at or near the densitometer location, eliminating the need for further correction for local gravitational force variances.

Weight observations to determine fluid density shall be corrected for air bouyancy (commonly called "weighed in vacuum") and for local gravity, as necessary. Such observations can be used in conjunction with the calibration of density meters or for checking the performance of equation of state correlations. Procedures are outlined in Chapter 14.6.

Volumes and densities for mass measurement shall be determined at operating temperature and pressure to eliminate temperature and compressibility corrections However, equivalent volumes of components are often computed for the determined mass flow These volumes will be stated as follows· temperature, 15°C (or 60°F); pressure, 101.325 kilopascals (14.696 pounds per square inch absolute), or the product equilibrium vapor pressure at 15°C (or 60°F), whichever is higher.

14.8.5.2 MASS MEASUREMENT USING DISPLACEMENT TYPE OR TURBINE METERS

The equation for determining mass using displacement-type or turbine meters is:

$$\text{Mass} = \begin{bmatrix}\text{Metered volume}\\ \text{at meter}\\ \text{operating}\\ \text{conditions}\end{bmatrix} \times \begin{bmatrix}\text{Meter factor}\\ \text{at meter}\\ \text{operating}\\ \text{conditions}\end{bmatrix} \times \begin{bmatrix}\text{Density per}\\ \text{unit volume at}\\ \text{meter operating}\\ \text{conditions}\end{bmatrix} \times \begin{bmatrix}\text{Densitometer}\\ \text{correction}\\ \text{factor (if}\\ \text{applicable)}\end{bmatrix}$$

14.8.5.3 MASS MEASUREMENT USING ORIFICE METERS

The equation for determining mass using orifice meters is:

$$Q_m = C' \sqrt{h_w \rho_f} = \text{flow rate expressed in units of mass/units of time.}$$

The terms for this equation are defined and discussed in 14.8.5.1.

14.8.5.4 DENSITY DETERMINATION

14.8.5.4.1 Empirical Density

Liquid density may be calculated as a function of composition, temperature, and pressure. It is preferred that the calculated or measured density be applied in real time to the flow meter. This provides for the maximum mass measurement precision, that is, the incremental volume of measured liquid is always in direct time relation to the density measured or calculated. However, it is common practice to use the composition of a sample taken continuously during the delivery period proportional to the volume delivered, and to use the average temperature and pressure for the delivery period.

Calculations may be made by means of empirical correlations or by generalized equations of state. The empirical correlations are derived from fitting experimental data covering specific ranges of compositions, temperatures, and pressures and can be inaccurate outside these ranges. Gas Processors Association procedure TP-1 for ethane/propane mix and TP-2 for high ethane raw make streams are examples. TP-3 is a more theoretical procedure for application to liquefied natural gas.

Generalized equations of state do not have strict limitations on ranges of compositions and conditions and can be applied to a wide variety of systems; however, empirical correlations are much more accurate when applied to the specific systems for which they were derived. The Rackett equation, the Starling-Han modification of the BWR equation of state, and several modified Redlich-Kwong equations of state (Soave, Mark V, Peng-Robinson) are examples.

It is the responsibility of the contracting parties to verify the validity and limits of the accuracy of methods considered for empirical density determination on the particular fluids to be measured.

Significant errors can occur from inaccuracies in temperature and pressure measurement, recording, or integration. Products with a density of less than 0.6 grams per cubic metre are particularly susceptible to errors and require a higher level of precision. See Chapter 14.6 for recommended precision levels of temperature and pressure.

14.8.5.4.2 Measured Density

Measured density of products between 0.3 and 0.7 grams per cubic centimetre shall be determined using density meters installed and calibrated in accordance with Chapter 14.6 or as otherwise agreed between the contracting parties.

Density instruments or probes shall be installed as follows:

1. No interaction that would adversely affect the flow or density measurement shall exist between the flow meter and the density transducer or probe.
2. Temperature and pressure differences among the fluid in the flow meter, the density measuring device, and the calibrating devices must be minimized and must be within specified limits for the fluid being measured and the mass measurement accuracy expected or required.
3. Density meters may be installed either upstream or downstream of primary flow devices in accordance with Chapter 14.6 but should not be located between flow straightening devices and meters and must not bypass the primary flow measurement device.

Densitometer accuracy will be seriously affected by the accumulation of foreign material from the flowing stream. The possibility of accumulation should be considered in selecting density measurement equipment and in determining the frequency of density equipment calibration and maintenance. Accuracy of the data recording, transmission, and computation equipment and methods should also be considered in system selection. See Chapter 14.6 for further comments.

14.8.5.5 CONVERSION OF MEASURED MASS TO VOLUME

Conversion from mass determined into equivalent volumes of components shall be in accordance with the latest revision of GPA Publication 8173, as described below. In this procedure, a chromatographic analysis representative of the delivered product is used to determine the mass of each individual component that comprised the total mass. The individual component masses are then converted to their respective equivalent liquid volumes at 15°C (or 60°F) and equilibrium vapor pressure at 15°C (or 60°F), using component density values from GPA Publication 2145.

The calculation of total mass flowing must be performed continuously on-line by a suitable device or by off-line integration of charts on which metered volume and density are continuously recorded so that at all times the density corresponds to the volume measured.

Conversion of the determined mass into an equivalent volume of each component at base or standard conditions at equilibrium vapor pressure at 15°C (60°F) or 101.325 kilopascals (14.696 pounds per square inch absolute), whichever is higher, shall be in accordance with Chapter 14.4. In this procedure a chromatographic analysis, representative of the delivered product, is used to determine the mass of each individual component comprising the total mass. The individual component masses are then converted to their respective equivalent liquid volumes at 15°C (or 60°F) and the equilibrium vapor pressure at 15°C (or 60°F) using component density values in vacuum from Chapter 11 or GPA Publication 2145. Example calculations, repeated from Chapter 14.4, are provided in 14.8.5.6

14.8.5.6 CALCULATIONS FOR LIQUID-VAPOR CONVERSION

The density of pure hydrocarbons in pounds mass per gallon (weight in vacuum) shall be as stated in GPA Standard 2145. Should constants be required for a hydrocarbon component that is not presented in GPA Standard 2145, the constants contained in the GPSA *Engineering Data Book*, Section 16, "Physical Properties," shall be used. If the required constants are not contained in the GPSA *Engineering Data Book*, the ASTM Data Series Publication, DS 4A, constants shall be used. The steps described in Figure 1 are required.

14.8.5.7 SPECIAL PRECAUTIONS FOR MASS MEASUREMENT

Volume measurement must be made at flowing conditions. The measuring device must be proven at flowing conditions.

Density or relative density (specific gravity) measurements must be made at the same flowing conditions as the volume measurements.

Temperature compensated metering devices shall not be used in the mass measurement method.

14.8.6 Volumetric Measurement in Static Systems

The liquid volume of liquefied petroleum gas consists of the sum of the liquid volume and the volume of the vapor above the liquid converted to its liquid equivalent.

Volumetric measurement is accomplished by using calibrated vessels or tanks with gaging devices that can be read at the vessel operating pressures to determine the liquid level. The volume of vapor above the liquid is determined by using the ideal gas law ($PV = NRT$) corrected by the gas compressibility factor. The liquid and vapor are corrected for temperature and pressure to standard or base conditions of temperature and the vapor pressure of the product at standard or base temperature. The vapor volume can be converted to equivalent liquid volume by using the appropriate factors.

Step 1—Convert to mass analysis. Given: 825,300 = Total pounds mass.

Component	Mole Percent	Mole Weight	Mole Percent × Mole Weight	Weight of Fraction of Component
CO_2	0.11	44.01	4.84	0.001107
C_1	2.14	16.043	34.33	0.007852
C_2	38.97	30.069	1171.79	0.268010
C_3	36.48	44.096	1608.62	0.367921
IC_4	2.94	58.123	170.88	0.039083
nC_4	8.77	58.123	509.74	0.116587
iC_5	1.71	72.15	123.38	0.028219
nC_5	1.82	72 15	131.31	0.030033
C_6+	7.06	87.436	617.30	0.141188
	100.00		4372.19	1.000000

Step 2—Calculate the mass of each component as follows: Weight fraction times total pounds mass equals pounds mass each component:

Component	Weight Fraction of Component	Total Pounds Mass	Pounds Mass of Component
CO_2	0.001107	825,300	914
C_1	0.007852	825,300	6,480
C_2	0.268010	825,300	221,189
C_3	0.367920	825,300	303,645
IC_4	0.0339083	825,300	32,255
nC_4	0.116587	825,300	96,219
IC_5	0.028219	825,300	23,289
nC_5	0.030033	825,300	24,786
C_6+	0.141188	825,300	116,523
			825,300

Step 3—Calculate the volume of each component at equilibrium pressure and 60°F as follows:

Component	Component Pounds Mass	Density Pounds/Gallon (In vacuum)	U.S. Gallons
CO_2	914	6.817	134
C_1	6,480	2.50	2,592
C_2	221,189	2.97	74,474
C_3	303,645	4.231	71,767
IC_4	32,255	4.694	6,872
nC_4	96,219	4.871	19,785
IC_5	23,289	5.206	4,473
nC_5	24,786	5.262	4,710
C_6+	116,523	5.951*	19,580
			204,355

*From analysis.

Figure 1—Calculations for Liquid Vapor Conversion

A pressure vessel or container must be able to safely withstand the vapor pressures of the contained product at the maximum operating temperature.

14.8.6.1 TANK CALIBRATION

Procedures for calibrating tanks and vessels are presented in Chapter 2.

14.8.6.2 TANK GAGING OF LIQUEFIED PETROLEUM GAS

Procedures for gaging liquefied petroleum gas in storage tanks are presented in Chapter 3. Special precautions are necessary to accurately account for the vapors above the liquid.

The composition and volume of the vapors are dependent upon the temperature and pressure conditions of the liquid.

14.8.6.3 TEMPERATURE MEASUREMENT

Chapter 5.4 contains general requirements for temperature measurement. Procedures for measuring the temperature of liquefied petroleum gas in storage vessels under static conditions are presented in Chapter 7.

14.8.6.4 RELATIVE DENSITY MEASUREMENT

Procedures for determining relative density of liquefied petroleum gas are presented in Chapters 9, 11, 12, 14.6, and 14.7. Observed relative densities (specific gravities) are corrected to standard or base conditions by using tables in Chapter 11.1.

14.8.6.5 WATER AND FOREIGN MATERIAL

Water and sediment content is not as serious a problem with liquefied petroleum gases as with crude oil Product specifications in contracts for custody transfer should contain a section on product quality to provide for testing propane by the freeze valve method (ANSI/ASTM D 2713-76), the cobal bromide method, or the Bureau of Mines method. Other mutually acceptable methods for determining dryness may be used for other liquefied petroleum gases having a high vapor pressure.

14.8.6.6 SAMPLING

The scope of Chapter 8 does not include sampling of liquefied petroleum gases; however, GPA Publication 2140 contains a section on sampling this type of product. GPA Publication 2140 is also designated as ASTM D 1265. Its scope covers the procedure for obtaining representative samples of liquefied petroleum gases, such as propane, butane, or mixtures thereof, in containers other than those used in laboratory testing apparatus. A liquid sample is transferred from the source into a sample container by purging the container and filling it with liquid to 80 percent of capacity.

Considerable effort may be required to obtain a representative sample, especially if the material being sampled is a mixture of liquefied petroleum gases. The following factors must be considered:

1. Samples must be obtained in the liquid phase.
2. When it is definitely known that the material being sampled is composed predominantly of only one liquefied petroleum gas, a liquid sample may be taken from any part of the vessel.
3. When the material being sampled has been agitated until uniformity is assured, a liquid sample may be taken from any part of the vessel.
4. Because of wide variations in the construction details of containers for liquefied petroleum gases, it is difficul to specify a uniform method for obtaining representative samples of heterogeneous mixtures. If it is not practicable to agitate a mixture for homogeneity, obtain liquid samples by a procedure that has been agreed upon by the contracting parties

Directions for sampling cannot be explicit enough to cover all cases. They must be supplemented by judgment, skill, and sampling experience. Extreme care and good judgment are necessary to ensure that samples represent the general character and average condition of the material. Because of the hazards involved, liquefied petroleum gases should be sampled by, or under the supervision of, persons familiar with the necessary safety precautions

14.8.6.7 VOLUMETRIC CALCULATION

When product is removed from or added to a tank, the beginning and ending liquid levels are obtained along with corresponding temperatures and pressures. The volumes of liquid and vapor are calculated for the beginning and ending conditions, and the difference between the beginning and ending calculations of the total volume of the vapor and liquid is the volume change in the vessel.

$$\begin{bmatrix}\text{Total volume}\\ \text{at standard}\\ \text{conditions}\end{bmatrix} = \begin{bmatrix}\text{Volume of liquid}\\ \text{at standard}\\ \text{conditions}\end{bmatrix} + \begin{bmatrix}\text{Volume of vapor}\\ \text{above the liquid}\\ \text{in equivalent}\\ \text{liquid units at}\\ \text{standard conditions}\end{bmatrix}$$

$$\begin{bmatrix}\text{Volume of}\\ \text{liquid at}\\ \text{standard}\\ \text{conditions}\end{bmatrix} = \begin{bmatrix}\text{Liquid volume}\\ \text{at tank}\\ \text{conditions}\end{bmatrix} \times \begin{bmatrix}\text{Volume correction}\\ \text{factor for}\\ \text{temperature and}\\ \text{gravity}\end{bmatrix}$$

$$\begin{bmatrix}\text{Volume of vapor}\\ \text{above liquid in}\\ \text{equivalent liquid}\\ \text{units at base}\\ \text{conditions}\end{bmatrix} = \begin{bmatrix}\text{Volume of}\\ \text{vapor above}\\ \text{the liquid}\end{bmatrix} \times \frac{P_o}{P_s} \times \frac{T_s}{T_o} \times \begin{bmatrix}\text{Factor for liquid}\\ \text{volume per vapor}\\ \text{volume}\end{bmatrix}$$

Where·

Total volume = (volume of product in the vessel as a liquid) + (vapor above the liquid converted to its liquid volume equivalent). Volume measured at standard conditions.

Volume of liquid at standard conditions = volume measured at standard temperature and vapor pressure of the liquid at standard temperature.

Volume of liquid at tank conditions = volume of vessel at liquid level determined by tank calibration and gaging device

Volume of vapor above the liquid = volume of vessel above the liquid level determined by tank calibration and gaging device.

Volume correction factor = factor used to correct the liquid volume to standard temperature Refer to tables in Chapters 11 and 12.

P_o = observed pressure, in absolute units.

P_s = standard pressure, in absolute units.

T_o = observed temperature, in kelvins (K) or degrees Rankine (°R).

T_s = standard temperature in kelvins (K) or degrees Rankine (°R).

Factor for liquid volume per vapor volume = standard conversion unit for product being measured

14.8.6.8 MIXTURE CALCULATION

When mixtures are measured, the composition of the liquid and vapor will be different for varying conditions of temperature and pressure. The composition of each phase can be determined by sampling and analysis of each. Refer to Chapter 14.4 for the procedure for calculating liquid equivalent of the vapor volume above stored natural gas liquid mixtures.

14.8.7 Mass Measurement in Static Systems

Mass is determined by weighing the container or vessel before and after product has been added to, or removed from, the vessel. The difference in weight provides the basis

for total mass of the product contained in the vessel.

To calculate the volume using mass units:

$$V_b = \frac{\text{Mass}}{\text{Density}}$$

Where:

V_b = volume at standard temperature and vapor pressure of the product at standard temperature.
Mass = difference between before and after mass determination.
Density = density in vacuum of liquid product at standard conditions in same units as mass.

Refer to Chapter 11 to determine relative density at standard conditions.

APPENDIX—INSTALLATION AND OPERATION OF FLOATING PISTON SAMPLERS

The procedures included here are presented to supplement other existing procedures, specifications, and standards in sampling higher than atmospheric vapor pressure products where flashing of lighter components within the container may cause distortion of the sample composition.

All samples should be obtained using some type of probe from the center of the flowing stream. A bypass around a device that causes a differential pressure, such as an orifice plate or small pump, is used to supply fresh product to bypass-type sample injection valves. See Figures A-1 and A-2. Bypass lines must not bypass primary volume measurement devices.

Figure A-3 provides an example of a typical proportional sampler.

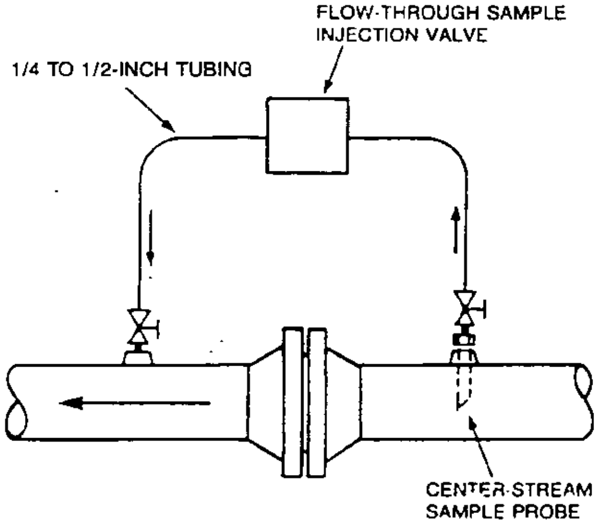

Figure A-1—Typical Sample Probe Installation on an Orifice Flange

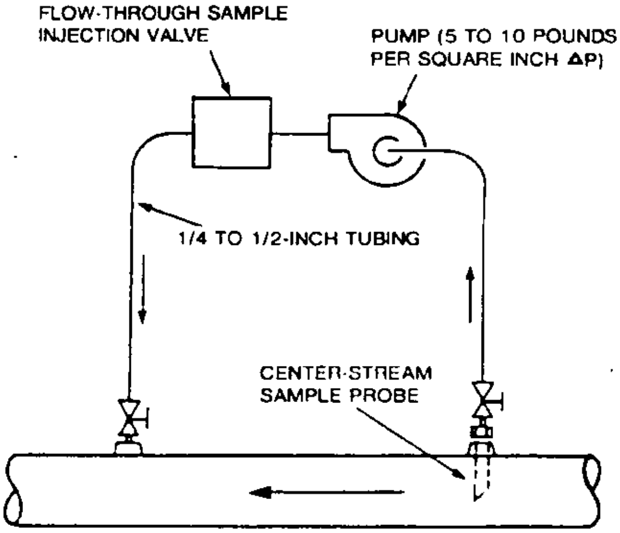

Figure A-2—Typical Sample Probe Installation for a Pump

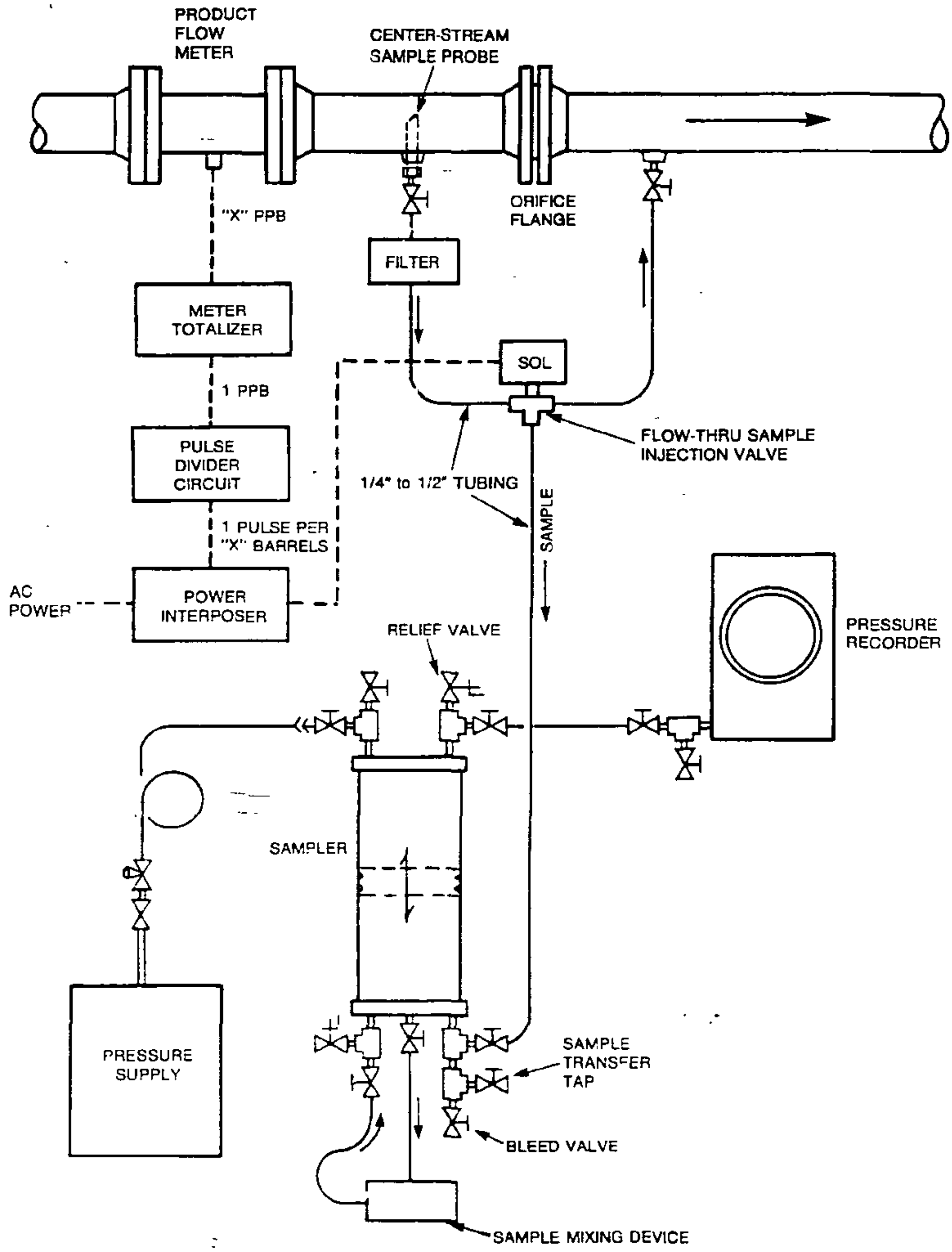

Figure A-3—Typical Proportional Sampler

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Table 3-B-5—Conversion of $Re_D/10^6$ to $Q_v/1000$ (Q_v in Thousands of Cubic Feet per Hour): $Q_v/1000 = Re_D/1000D/28.2435$

	Nominal Pipe Diameter										
	2 Inches			3 Inches				4 Inches			
$Re_D/10^6$	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.020	1.2	1.4	1.5	1.6	1.9	2.1	2.2	2.2	2.4	2.7	2.9
0.030	1.8	2.1	2.2	2.4	2.8	3.1	3.3	3.3	3.7	4.1	4.3
0.040	2.4	2.7	2.9	3.3	3.7	4.1	4.3	4.5	4.9	5.4	5.7
0.050	3.0	3.4	3.7	4.1	4.6	5.1	5.4	5.6	6.1	6.8	7.1
0.060	3.6	4.1	4.4	4.9	5.6	6.2	6.5	6.7	7.3	8.1	8.6
0.070	4.2	4.8	5.1	5.7	6.5	7.2	7.6	7.8	8.5	9.5	10.0
0.080	4.8	5.5	5.9	6.5	7.4	8.2	8.7	8.9	9.7	10.8	11.4
0.090	5.4	6.2	6.6	7.3	8.4	9.2	9.8	10.0	11.0	12.2	12.8
0.100	6.0	6.9	7.3	8.1	9.3	10.3	10.9	11.2	12.2	13.5	14.3
0.150	9.0	10.3	11.0	12.2	13.9	15.4	16.3	16.7	18.3	20.3	21.4
0.200	11.9	13.7	14.6	16.3	18.6	20.5	21.7	22.3	24.3	27.1	28.5
0.250	14.9	17.2	18.3	20.4	23.2	25.7	27.2	27.9	30.4	33.9	35.6
0.300	17.9	20.6	22.0	24.4	27.9	30.8	32.6	33.5	36.5	40.6	42.8
0.350	20.9	24.0	25.6	28.5	32.5	35.9	38.0	39.1	42.6	47.4	49.9
0.400	23.9	27.5	29.3	32.6	37.2	41.1	43.5	44.6	48.7	54.2	57.0
0.450	26.9	30.9	32.9	36.6	41.8	46.2	48.9	50.2	54.8	61.0	64.1
0.500	29.9	34.3	36.6	40.7	46.5	51.3	54.3	55.8	60.9	67.7	71.3
0.600	35.8	41.2	43.9	48.9	55.7	61.6	65.2	67.0	73.0	81.3	85.5
0.700	41.8	48.1	51.2	57.0	65.0	71.9	76.0	78.1	85.2	94.8	99.8
0.800	47.8	54.9	58.5	65.1	74.3	82.1	86.9	89.3	97.4	108	114
0.900	53.8	61.8	65.9	73.3	83.6	92.4	97.8	100	110	122	128
1.000	59.7	68.7	73.2	81.4	92.9	103	109	112	122	135	143
1.500	89.6	103	110	122	139	154	163	167	183	203	214
2.000	119	137	146	163	186	205	217	223	243	271	285
2.500	149	172	183	204	232	257	272	279	304	339	356
3.000	179	206	220	244	279	308	326	335	365	406	428
3.500	209	240	256	285	325	359	380	391	426	474	499
4.000	239	275	293	326	372	411	435	446	487	542	570
4.500	269	309	329	366	418	462	489	502	548	610	641
5.000	299	343	366	407	465	513	543	558	609	677	713
5.500	329	378	403	448	511	565	597	614	670	745	784
6.000	358	412	439	489	557	616	652	670	730	813	855
6.500	388	446	476	529	604	667	706	725	791	881	927
7.000	418	481	512	570	650	719	760	781	852	948	998
7.500	448	515	549	611	697	770	815	837	913	1,016	1,069
8.000	478	549	585	651	743	821	869	893	974	1,084	1,140
8.500	508	584	622	692	790	873	923	949	1,035	1,151	1,212
9.000	538	618	659	733	836	924	978	1,004	1,096	1,219	1,283
9.500	567	652	695	774	883	975	1,032	1,060	1,156	1,287	1,354
10.000	597	687	732	814	929	1,027	1,086	1,116	1,217	1,355	1,425

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6, μ = 0.000069; k = 1.3; P_b = 14.73, and T_b = 519.67°R

Table 3-B-5—Continued

	Nominal Pipe Diameter									
	6 Inches				8 Inches			10 Inches		
$Re_D/10^6$	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.036
0.020	3.5	3.7	4.1	4.3	5.4	5.7	5.7	6.8	7.1	7.1
0.030	5.2	5.5	6.1	6.4	8.1	8.5	8.6	10.2	10.6	10.7
0.040	6.9	7.3	8.2	8.6	10.8	11.3	11.4	13.5	14.2	14.2
0.050	8.7	9.2	10.2	10.7	13.5	14.1	14.3	16.9	17.7	17.8
0.060	10.4	11.0	12.2	12.9	16.2	17.0	17.1	20.3	21.3	21.3
0.070	12.1	12.9	14.3	15.0	18.9	19.8	20.0	23.7	24.8	24.9
0.080	13.9	14.7	16.3	17.2	21.6	22.6	22.9	27.1	28.4	28.4
0.090	15.6	16.5	18.4	19.3	24.3	25.4	25.7	30.5	31.9	32.0
0.100	17.3	18.4	20.4	21.5	27.0	28.3	28.6	33.9	35.5	35.5
0.150	26.0	27.5	30.6	32.2	40.5	42.4	42.9	50.8	53.2	53.3
0.200	34.7	36.7	40.8	42.9	54.0	56.5	57.2	67.7	71.0	71.1
0.250	43.3	45.9	51.0	53.7	67.5	70.6	71.4	84.6	88.7	88.8
0.300	52.0	55.1	61.2	64.4	81.0	84.8	85.7	102	106	107
0.350	60.7	64.3	71.4	75.2	94.5	98.9	100	118	124	124
0.400	69.4	73.5	81.6	85.9	108	113	114	135	142	142
0.450	78.0	82.6	91.8	96.6	121	127	129	152	160	160
0.500	86.7	91.8	102	107	135	141	143	169	177	178
0.600	104	110	122	129	162	170	171	203	213	213
0.700	121	129	143	150	189	198	200	237	248	249
0.800	139	147	163	172	216	226	229	271	284	284
0.900	156	165	184	193	243	254	257	305	319	320
1.000	173	184	204	215	270	283	286	339	355	355
1.500	260	275	306	322	405	424	429	508	532	533
2.000	347	367	408	429	540	565	572	677	710	711
2.500	433	459	510	537	675	706	714	846	887	888
3.000	520	551	612	644	810	848	857	1,016	1,064	1,066
3.500	607	643	714	752	945	989	1,000	1,185	1,242	1,244
4.000	694	735	816	859	1,080	1,130	1,143	1,354	1,419	1,421
4.500	780	826	918	966	1,215	1,272	1,286	1,524	1,596	1,599
5.000	867	918	1,020	1,074	1,350	1,413	1,429	1,693	1,774	1,777
5.500	954	1,010	1,122	1,181	1,485	1,554	1,572	1,862	1,951	1,954
6.000	1,040	1,102	1,224	1,288	1,620	1,695	1,715	2,031	2,129	2,132
6.500	1,127	1,194	1,326	1,396	1,755	1,837	1,857	2,201	2,306	2,310
7.000	1,214	1,286	1,428	1,503	1,890	1,978	2,000	2,370	2,483	2,487
7.500	1,300	1,377	1,530	1,611	2,025	2,119	2,143	2,539	2,661	2,665
8.000	1,387	1,469	1,632	1,718	2,160	2,261	2,286	2,708	2,838	2,843
8.500	1,474	1,561	1,734	1,825	2,295	2,402	2,429	2,878	3,016	3,020
9.000	1,560	1,653	1,836	1,933	2,430	2,543	2,572	3,047	3,193	3,198
9.500	1,647	1,745	1,938	2,040	2,565	2,685	2,715	3,216	3,370	3,376
10.000	1,734	1,837	2,040	2,147	2,700	2,826	2,858	3,386	3,548	3,553

Note. This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73, and T_b = 519.67°R.

Table 3-B-5—Continued

	Nominal Pipe Diameter														
	12 Inches			16 Inches			20 Inches			24 Inches			30 Inches		
$Re_D/10^6$	11.374	11.938	12.090	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
0.150	60.4	63.4	64.2	78.0	79.7	81.0	99.9	101	102	120	122	123	153	154	155
0.200	80.5	84.5	85.6	104	106	108	133	135	136	160	163	165	204	205	207
0.250	101	106	107	130	133	135	167	168	170	200	204	206	254	257	259
0.300	121	127	128	156	159	162	200	202	204	240	244	247	305	308	311
0.350	141	148	150	182	186	189	233	235	239	280	285	288	356	359	362
0.400	161	169	171	208	212	216	266	269	273	320	326	329	407	411	414
0.450	181	190	193	234	239	243	300	303	307	360	366	370	458	462	466
0.500	201	211	214	260	266	270	333	336	341	401	407	412	509	513	518
0.600	242	254	257	312	319	324	400	404	409	481	489	494	611	616	621
0.700	282	296	300	364	372	378	466	471	477	561	570	576	713	719	725
0.800	322	338	342	416	425	432	533	538	545	641	651	659	814	821	829
0.900	362	380	385	468	478	486	599	605	613	721	733	741	916	924	932
1.000	403	423	428	520	531	540	666	673	682	801	814	823	1,018	1,027	1,036
1.500	604	634	642	780	797	810	999	1,009	1,022	1,202	1,222	1,235	1,527	1,540	1,553
2.000	805	845	856	1,040	1,062	1,080	1,332	1,345	1,363	1,602	1,629	1,646	2,036	2,054	2,071
2.500	1,007	1,057	1,070	1,300	1,328	1,350	1,665	1,682	1,704	2,003	2,036	2,058	2,545	2,567	2,589
3.000	1,208	1,268	1,284	1,560	1,593	1,620	1,998	2,018	2,045	2,403	2,443	2,470	3,054	3,080	3,107
3.500	1,409	1,479	1,498	1,820	1,859	1,890	2,331	2,355	2,386	2,804	2,850	2,881	3,563	3,594	3,625
4.000	1,611	1,691	1,712	2,080	2,124	2,160	2,664	2,691	2,726	3,204	3,257	3,293	4,072	4,107	4,143
4.500	1,812	1,902	1,926	2,340	2,390	2,430	2,997	3,027	3,067	3,605	3,665	3,704	4,581	4,621	4,660
5.000	2,014	2,113	2,140	2,600	2,655	2,700	3,330	3,364	3,408	4,005	4,072	4,116	5,090	5,134	5,178
5.500	2,215	2,325	2,354	2,860	2,921	2,970	3,663	3,700	3,749	4,406	4,479	4,528	5,599	5,647	5,696
6.000	2,416	2,536	2,568	3,120	3,187	3,240	3,996	4,036	4,089	4,806	4,886	4,939	6,108	6,161	6,214
6.500	2,618	2,747	2,782	3,380	3,452	3,510	4,329	4,373	4,430	5,207	5,293	5,351	6,617	6,674	6,732
7.000	2,819	2,959	2,996	3,640	3,718	3,780	4,662	4,709	4,771	5,607	5,700	5,762	7,126	7,188	7,249
7.500	3,020	3,170	3,210	3,900	3,983	4,050	4,996	5,045	5,112	6,008	6,108	6,174	7,635	7,701	7,767
8.000	3,222	3,381	3,425	4,160	4,249	4,320	5,329	5,382	5,453	6,408	6,515	6,586	8,143	8,214	8,285
8.500	3,423	3,593	3,639	4,420	4,514	4,590	5,662	5,718	5,793	6,809	6,922	6,997	8,652	8,728	8,803
9.000	3,624	3,804	3,853	4,680	4,780	4,860	5,995	6,055	6,134	7,209	7,329	7,409	9,161	9,241	9,321
9.500	3,826	4,015	4,067	4,940	5,045	5,130	6,328	6,391	6,475	7,610	7,736	7,820	9,670	9,754	9,839
10.000	4,027	4,227	4,281	5,201	5,311	5,399	6,661	6,727	6,816	8,010	8,143	8,232	10,179	10,268	10,356
12.000	4,833	5,072	5,137	6,241	6,373	6,479	7,993	8,073	8,179	9,612	9,772	9,878	12,215	12,321	12,428
15.000	6,041	6,340	6,421	7,801	7,966	8,099	9,991	10,091	10,224	12,016	12,215	12,348	15,269	15,402	15,535
18.000	7,249	7,608	7,705	9,361	9,560	9,719	11,989	12,109	12,268	14,419	14,658	14,818	18,323	18,482	18,642
21.000	8,457	8,876	8,989	10,921	11,153	11,339	13,987	14,127	14,313	16,822	17,101	17,287	21,377	21,563	21,748
24.000	9,665	10,144	10,274	12,481	12,746	12,959	15,986	16,145	16,358	19,225	19,544	19,757	24,430	24,643	24,855
27.000	10,873	11,412	11,558	14,041	14,340	14,579	17,984	18,164	18,403	21,628	21,987	22,226	27,484	27,723	27,962
30.000	12,081	12,680	12,842	15,602	15,933	16,198	19,982	20,182	20,447	24,031	24,430	24,696	30,538	30,804	31,069

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R

Table 3-B-6—Expansion Factors for Flange Taps (Y_1): Static Pressure Taken From Upstream Taps

	$\beta = d/D$												
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60	0.61	0.62
0.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.1	0.9989	0.9989	0.9989	0.9988	0.9988	0.9988	0.9988	0.9988	0.9988	0.9988	0.9987	0.9987	0.9987
0.2	0.9977	0.9977	0.9977	0.9977	0.9976	0.9976	0.9976	0.9976	0.9975	0.9975	0.9975	0.9975	0.9974
0.3	0.9966	0.9966	0.9966	0.9965	0.9965	0.9964	0.9964	0.9963	0.9963	0.9963	0.9962	0.9962	0.9962
0.4	0.9954	0.9954	0.9954	0.9953	0.9953	0.9952	0.9952	0.9951	0.9951	0.9950	0.9949	0.9949	0.9949
0.5	0.9943	0.9943	0.9943	0.9942	0.9941	0.9940	0.9940	0.9939	0.9938	0.9938	0.9937	0.9936	0.9936
0.6	0.9932	0.9932	0.9931	0.9930	0.9929	0.9928	0.9927	0.9927	0.9926	0.9925	0.9924	0.9924	0.9923
0.7	0.9920	0.9920	0.9920	0.9919	0.9918	0.9916	0.9915	0.9915	0.9914	0.9913	0.9912	0.9911	0.9910
0.8	0.9909	0.9909	0.9908	0.9907	0.9906	0.9904	0.9903	0.9902	0.9901	0.9900	0.9899	0.9898	0.9897
0.9	0.9898	0.9897	0.9897	0.9895	0.9894	0.9892	0.9891	0.9890	0.9889	0.9888	0.9886	0.9885	0.9885
1.0	0.9886	0.9886	0.9885	0.9884	0.9882	0.9880	0.9879	0.9878	0.9877	0.9875	0.9874	0.9873	0.9872
1.1	0.9875	0.9875	0.9874	0.9872	0.9870	0.9868	0.9867	0.9866	0.9864	0.9863	0.9861	0.9860	0.9859
1.2	0.9863	0.9863	0.9862	0.9860	0.9859	0.9856	0.9855	0.9853	0.9852	0.9850	0.9848	0.9847	0.9846
1.3	0.9852	0.9852	0.9851	0.9849	0.9847	0.9844	0.9843	0.9841	0.9840	0.9838	0.9836	0.9835	0.9833
1.4	0.9841	0.9840	0.9840	0.9837	0.9835	0.9832	0.9831	0.9829	0.9827	0.9825	0.9823	0.9822	0.9821
1.5	0.9829	0.9829	0.9828	0.9826	0.9823	0.9820	0.9819	0.9817	0.9815	0.9813	0.9810	0.9809	0.9808
1.6	0.9818	0.9818	0.9817	0.9814	0.9811	0.9808	0.9806	0.9805	0.9803	0.9800	0.9798	0.9796	0.9795
1.7	0.9806	0.9806	0.9805	0.9802	0.9800	0.9796	0.9794	0.9792	0.9790	0.9788	0.9785	0.9784	0.9782
1.8	0.9795	0.9795	0.9794	0.9791	0.9788	0.9784	0.9782	0.9780	0.9778	0.9775	0.9772	0.9771	0.9769
1.9	0.9784	0.9783	0.9782	0.9779	0.9776	0.9772	0.9770	0.9768	0.9766	0.9763	0.9760	0.9758	0.9756
2.0	0.9772	0.9772	0.9771	0.9767	0.9764	0.9760	0.9758	0.9756	0.9753	0.9750	0.9747	0.9745	0.9744
2.1	0.9761	0.9761	0.9759	0.9756	0.9753	0.9748	0.9746	0.9744	0.9741	0.9738	0.9734	0.9733	0.9731
2.2	0.9750	0.9749	0.9748	0.9744	0.9741	0.9736	0.9734	0.9731	0.9729	0.9725	0.9722	0.9720	0.9718
2.3	0.9738	0.9738	0.9736	0.9732	0.9729	0.9724	0.9722	0.9719	0.9716	0.9713	0.9709	0.9707	0.9705
2.4	0.9727	0.9726	0.9725	0.9721	0.9717	0.9712	0.9710	0.9707	0.9704	0.9700	0.9697	0.9694	0.9692
2.5	0.9715	0.9715	0.9713	0.9709	0.9705	0.9700	0.9698	0.9695	0.9692	0.9688	0.9684	0.9682	0.9680
2.6	0.9704	0.9704	0.9702	0.9698	0.9694	0.9688	0.9686	0.9683	0.9679	0.9675	0.9671	0.9669	0.9667
2.7	0.9693	0.9692	0.9691	0.9686	0.9682	0.9676	0.9673	0.9670	0.9667	0.9663	0.9659	0.9656	0.9654
2.8	0.9681	0.9681	0.9679	0.9674	0.9670	0.9664	0.9661	0.9658	0.9654	0.9650	0.9646	0.9644	0.9641
2.9	0.9670	0.9669	0.9668	0.9663	0.9658	0.9652	0.9649	0.9646	0.9642	0.9638	0.9633	0.9631	0.9628
3.0	0.9658	0.9658	0.9656	0.9651	0.9647	0.9640	0.9637	0.9634	0.9630	0.9626	0.9621	0.9618	0.9615
3.1	0.9647	0.9647	0.9645	0.9639	0.9635	0.9628	0.9625	0.9622	0.9617	0.9613	0.9608	0.9605	0.9603
3.2	0.9636	0.9635	0.9633	0.9628	0.9623	0.9616	0.9613	0.9609	0.9605	0.9601	0.9595	0.9593	0.9590
3.3	0.9624	0.9624	0.9622	0.9616	0.9611	0.9604	0.9601	0.9597	0.9593	0.9588	0.9583	0.9580	0.9577
3.4	0.9613	0.9612	0.9610	0.9604	0.9599	0.9592	0.9589	0.9585	0.9580	0.9576	0.9570	0.9567	0.9564
3.5	0.9602	0.9601	0.9599	0.9593	0.9588	0.9580	0.9577	0.9573	0.9568	0.9563	0.9558	0.9554	0.9551
3.6	0.9590	0.9590	0.9587	0.9581	0.9576	0.9568	0.9565	0.9560	0.9556	0.9551	0.9545	0.9542	0.9538
3.7	0.9579	0.9578	0.9576	0.9570	0.9564	0.9556	0.9553	0.9548	0.9543	0.9538	0.9532	0.9529	0.9526
3.8	0.9567	0.9567	0.9564	0.9558	0.9552	0.9544	0.9540	0.9536	0.9531	0.9526	0.9520	0.9516	0.9513
3.9	0.9556	0.9555	0.9553	0.9545	0.9540	0.9532	0.9528	0.9524	0.9519	0.9513	0.9507	0.9504	0.9500
4.0	0.9545	0.9544	0.9542	0.9536	0.9529	0.9520	0.9516	0.9512	0.9506	0.9501	0.9494	0.9491	0.9487

Table 3-B-6—Continued

	$\beta = d/D$												
h_w/P_{f1}	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70	0.71	0.72	0.73	0.74	0.75
0.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.1	0.9987	0.9987	0.9987	0.9987	0.9987	0.9987	0.9986	0.9986	0.9986	0.9986	0.9986	0.9986	0.9986
0.2	0.9974	0.9974	0.9974	0.9974	0.9973	0.9973	0.9973	0.9973	0.9972	0.9972	0.9972	0.9971	0.9971
0.3	0.9961	0.9961	0.9961	0.9960	0.9960	0.9960	0.9959	0.9959	0.9958	0.9958	0.9958	0.9957	0.9957
0.4	0.9948	0.9948	0.9948	0.9947	0.9947	0.9946	0.9946	0.9945	0.9945	0.9944	0.9943	0.9943	0.9942
0.5	0.9935	0.9935	0.9934	0.9934	0.9933	0.9933	0.9932	0.9931	0.9931	0.9930	0.9929	0.9929	0.9928
0.6	0.9923	0.9922	0.9921	0.9921	0.9920	0.9919	0.9918	0.9918	0.9917	0.9916	0.9915	0.9914	0.9913
0.7	0.9910	0.9909	0.9908	0.9907	0.9907	0.9906	0.9905	0.9904	0.9903	0.9902	0.9901	0.9900	0.9899
0.8	0.9897	0.9896	0.9895	0.9894	0.9893	0.9892	0.9891	0.9890	0.9889	0.9888	0.9887	0.9886	0.9884
0.9	0.9884	0.9883	0.9882	0.9881	0.9880	0.9879	0.9878	0.9877	0.9875	0.9874	0.9873	0.9871	0.9870
1.0	0.9871	0.9870	0.9869	0.9868	0.9867	0.9865	0.9864	0.9863	0.9861	0.9860	0.9859	0.9857	0.9855
1.1	0.9858	0.9857	0.9856	0.9854	0.9853	0.9852	0.9851	0.9849	0.9848	0.9846	0.9844	0.9843	0.9841
1.2	0.9845	0.9844	0.9843	0.9841	0.9840	0.9838	0.9837	0.9835	0.9834	0.9832	0.9830	0.9828	0.9826
1.3	0.9832	0.9831	0.9829	0.9828	0.9827	0.9825	0.9823	0.9822	0.9820	0.9818	0.9816	0.9814	0.9812
1.4	0.9819	0.9818	0.9816	0.9815	0.9813	0.9812	0.9810	0.9808	0.9806	0.9804	0.9802	0.9800	0.9798
1.5	0.9806	0.9805	0.9803	0.9802	0.9800	0.9798	0.9796	0.9794	0.9792	0.9790	0.9788	0.9786	0.9783
1.6	0.9793	0.9792	0.9790	0.9788	0.9787	0.9785	0.9783	0.9781	0.9778	0.9776	0.9774	0.9771	0.9769
1.7	0.9780	0.9779	0.9777	0.9775	0.9773	0.9771	0.9769	0.9767	0.9764	0.9762	0.9760	0.9757	0.9754
1.8	0.9768	0.9766	0.9764	0.9762	0.9760	0.9758	0.9755	0.9753	0.9751	0.9748	0.9745	0.9743	0.9740
1.9	0.9755	0.9753	0.9751	0.9749	0.9747	0.9744	0.9742	0.9739	0.9737	0.9734	0.9731	0.9728	0.9725
2.0	0.9742	0.9740	0.9738	0.9735	0.9733	0.9731	0.9728	0.9726	0.9723	0.9720	0.9717	0.9714	0.9711
2.1	0.9729	0.9727	0.9725	0.9722	0.9720	0.9717	0.9715	0.9712	0.9709	0.9706	0.9703	0.9700	0.9696
2.2	0.9716	0.9714	0.9711	0.9709	0.9706	0.9704	0.9701	0.9698	0.9695	0.9692	0.9689	0.9685	0.9682
2.3	0.9703	0.9701	0.9698	0.9696	0.9693	0.9690	0.9688	0.9685	0.9681	0.9678	0.9675	0.9671	0.9667
2.4	0.9690	0.9688	0.9685	0.9683	0.9680	0.9677	0.9674	0.9671	0.9668	0.9664	0.9661	0.9657	0.9653
2.5	0.9677	0.9675	0.9672	0.9669	0.9666	0.9663	0.9660	0.9657	0.9654	0.9650	0.9646	0.9643	0.9639
2.6	0.9664	0.9662	0.9659	0.9656	0.9653	0.9650	0.9647	0.9643	0.9640	0.9636	0.9632	0.9628	0.9624
2.7	0.9651	0.9649	0.9646	0.9643	0.9640	0.9637	0.9633	0.9630	0.9626	0.9622	0.9618	0.9614	0.9610
2.8	0.9638	0.9636	0.9633	0.9630	0.9626	0.9623	0.9620	0.9616	0.9612	0.9608	0.9604	0.9600	0.9595
2.9	0.9625	0.9623	0.9620	0.9616	0.9613	0.9610	0.9606	0.9602	0.9598	0.9594	0.9590	0.9585	0.9581
3.0	0.9613	0.9610	0.9606	0.9603	0.9600	0.9596	0.9592	0.9588	0.9584	0.9580	0.9576	0.9571	0.9566
3.1	0.9600	0.9597	0.9593	0.9590	0.9586	0.9583	0.9579	0.9575	0.9571	0.9566	0.9562	0.9557	0.9552
3.2	0.9587	0.9584	0.9580	0.9577	0.9573	0.9569	0.9567	0.9561	0.9557	0.9552	0.9547	0.9542	0.9537
3.3	0.9574	0.9571	0.9567	0.9564	0.9560	0.9556	0.9552	0.9547	0.9543	0.9538	0.9533	0.9528	0.9525
3.4	0.956	0.9558	0.9554	0.9550	0.9546	0.9542	0.9538	0.9534	0.9529	0.9524	0.9519	0.9514	0.9508
3.5	0.9548	0.9545	0.9541	0.9537	0.9533	0.9529	0.9524	0.9520	0.9515	0.9510	0.9505	0.9500	0.9494
3.6	0.9535	0.9532	0.9528	0.9524	0.9520	0.9515	0.9511	0.9506	0.9501	0.9496	0.9491	0.9485	0.9480
3.7	0.9522	0.9518	0.9515	0.9511	0.9506	0.9502	0.9497	0.9492	0.9487	0.9482	0.9477	0.9471	0.9465
3.8	0.9509	0.9505	0.9502	0.9497	0.9493	0.9488	0.9484	0.9479	0.9474	0.9468	0.9463	0.9457	0.9451
3.9	0.9496	0.9492	0.9488	0.9484	0.9480	0.9475	0.9470	0.9465	0.9460	0.9454	0.9448	0.9442	0.9436
4.0	0.9483	0.9479	0.9475	0.9471	0.9465	0.9462	0.9457	0.9451	0.9446	0.9440	0.9434	0.9428	0.9422

Table 3-B-7—F_{pb} Factors Used to Change From a Pressure Base of 14.73 Pounds Force per Square Inch Absolute to Other Pressure Bases

$$F_{pb} = \frac{14.73}{\text{Contract pressure base, psia}}$$

Pressure Base (pounds force per square inch absolute)	F_{pb}
14.4	1.0229
14.525	1.0141
14.65	1.0055
14.696	1.0023
14.70	1.0020
14.725	1.0003
14.73	1.0000
14.735	0.9997
14.775	0.9970
14.90	0.9886
15.025	0.9804
15.15	0.9723
15.225	0.9675
15.275	0.9643
15.325	0.9612
15.40	0.9555
15.525	0.9488
15.65	0.9412
15.775	0.9338
15.90	0.9264
16.025	0.9192
16.15	0.9121
16.275	0.9051
16.40	0.8982
16.70	0.8820

Table 3-B-8—F_{tb} Factors Used to Change From a Temperature Base of 60°F to Other Temperature Bases

$$F_{tb} = \frac{\text{Base °F} + 459.67}{60 + 459.67}$$

Temperature (°F)	F_{tb}	Temperature (°F)	F_{tb}
40	0.9615	65	1.0096
41	0.9634	66	1.0115
42	0.9654	67	1.0135
43	0.9673	68	1.0154
44	0.9692	69	1.0173
45	0.9711	70	1.0192
46	0.9731	71	1.0212
47	0.9750	72	1.0231
48	0.9769	73	1.0250
49	0.9788	74	1.0269
50	0.9808	75	1.0289
51	0.9827	76	1.0308
52	0.9846	77	1.0327
53	0.9865	78	1.0346
54	0.9885	79	1.0366
55	0.9904	80	1.0385
56	0.9923	81	1.0404
57	0.9942	82	1.0423
58	0.9962	83	1.0443
59	0.9981	84	1.0462
60	1.0000	85	1.0481
61	1.0019	86	1.0500
62	1.0038	87	1.0520
63	1.0058	88	1.0539
64	1.0077	89	1.0558
		90	1.0577

Table 3-B-9—F_{tf} Factors Used to Change From a Flowing Temperature of 60°F to Actual Flowing Temperature

$$F_{tf} = \sqrt{\frac{60 + 459.67}{T_f + 459.67}}$$

Temperature (°F)	F_{tf}	Temperature (°F)	F_{tf}	Temperature (°F)	F_{tf}
−20	1.0872	37	1.0229	94	0.9688
−19	1.0859	38	1.0219	95	0.9679
−18	1.0847	39	1.0208	96	0.9671
−17	1.0835	40	1.0198	97	0.9662
−16	1.0823	41	1.0188	98	0.9653
−15	1.0810	42	1.0178	99	0.9645
−14	1.0798	43	1.0168	100	0.9636
−13	1.0786	44	1.0158	101	0.9627
−12	1.0774	45	1.0148	102	0.9619
−11	1.0762	46	1.0137	103	0.9610
−10	1.0750	47	1.0127	104	0.9602
−9	1.0738	48	1.0117	105	0.9593
−8	1.0726	49	1.0108	106	0.9585
−7	1.0715	50	1.0098	107	0.9576
−6	1.0703	51	1.0088	108	0.9568
−5	1.0691	52	1.0078	109	0.9559
−4	1.0679	53	1.0068	110	0.9551
−3	1.0668	54	1.0058	111	0.9543
−2	1.0656	55	1.0048	112	0.9534
−1	1.0644	56	1.0039	113	0.9526
0	1.0633	57	1.0029	114	0.9518
1	1.0621	58	1.0019	115	0.9509
2	1.0610	59	1.0010	116	0.9501
3	1.0598	60	1.0000	117	0.9493
4	1.0587	61	0.9990	118	0.9485
5	1.0575	62	0.9981	119	0.9477
6	1.0564	63	0.9971	120	0.9468
7	1.0553	64	0.9962	121	0.9460
8	1.0541	65	0.9952	122	0.9452
9	1.0530	66	0.9943	123	0.9444
10	1.0519	67	0.9933	124	0.9436
11	1.0508	68	0.9924	125	0.9428
12	1.0497	69	0.9915	126	0.9420
13	1.0485	70	0.9905	127	0.9412
14	1.0474	[illegible]	0.9896	128	0.9404
15	1.0463	72	0.9887	129	0.9396
16	1.0452	73	0.9877	130	0.9388
17	1.0441	74	0.9868	131	0.9380
18	1.0430	75	0.9859	132	0.9372
19	1.0419	76	0.9850	133	0.9364
20	1.0409	77	0.9840	134	0.9356
21	1.0398	78	0.9831	135	0.9348
22	1.0387	79	0.9822	136	0.9340
23	1.0376	80	0.9813	137	0.9332
24	1.0365	81	0.9804	138	0.9325
25	1.0355	82	0.9795	139	0.9317
26	1.0344	83	0.9786	140	0.9309
27	1.0333	84	0.9777	141	0.9301
28	1.0323	85	0.9768	142	0.9294
29	1.0312	86	0.9759	143	0.9286
30	1.0302	87	0.9750	144	0.9278
31	1.0291	88	0.9741	145	0.9271
32	1.0281	89	0.9732	146	0.9263
33	1.0270	90	0.9723	147	0.9255
34	1.0260	91	0.9714	148	0.9248
35	1.0250	92	0.9706	149	0.9240
36	1.0239	93	0.9697	150	0.9232

Table 3-B-10—F_{gr} Factors Used to Adjust for Real Gas Relative Density (G_r): Base Conditions of 60°F and 14.73 Pounds Force per Square Inch Absolute

$$F_r = \sqrt{\frac{1}{G_r}}$$

	F_{gr}									
G_r	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.550	1.3484	1.3472	0.3460	1.3447	1.3435	1.3423	1.3411	1.3399	1.3387	1.3375
0.560	1.3363	1.3351	1.3339	1.3327	1.3316	1.3304	1.3292	1.3280	1.3269	1.3257
0.570	1.3245	1.3234	1.3222	1.3211	1.3199	1.3188	1.3176	1.3165	1.3153	1.3142
0.580	1.3131	1.3119	1.3108	1.3097	1.3086	1.3074	1.3063	1.3052	1.3041	1.3030
0.590	1.3019	1.3008	1.2997	1.2986	1.2975	1.2964	1.2953	1.2942	1.2932	1.2921
0.600	1.2910	1.2899	1.2888	1.2878	1.2867	1.2856	1.2846	1.2835	1.2825	1.2814
0.610	1.2804	1.2793	1.2783	1.2772	1.2762	1.2752	1.2741	1.2731	1.2720	1.2710
0.620	1.2700	1.2690	1.2680	1.2669	1.2659	1.2649	1.2639	1.2629	1.2619	1.2609
0.630	1.2599	1.2589	1.2579	1.2569	1.2559	1.2549	1.2539	1.2529	1.2520	1.2510
0.640	1.2500	1.2490	1.2480	1.2471	1.2461	1.2451	1.2442	1.2432	1.2423	1.2413
0.650	1.2403	1.2394	1.2384	1.2375	1.2365	1.2356	1.2347	1.2337	1.2328	1.2318
0.660	1.2309	1.2300	1.2290	1.2281	1.2272	1.2263	1.2254	1.2244	1.2235	1.2226
0.670	1.2217	1.2208	1.2199	1.2190	1.2181	1.2172	1.2163	1.2154	1.2145	1.2136
0.680	1.2127	1.2118	1.2109	1.2100	1.2091	1.2082	1.2074	1.2065	1.2056	1.2047
0.690	1.2039	1.2030	1.2021	1.2012	1.2004	1.1995	1.1986	1.1978	1.1969	1.1961
0.700	1.1952	1.1944	1.1935	1.1927	1.1918	1.1910	1.1901	1.1893	1.1884	1.1876
0.710	1.1868	1.1859	1.1851	1.1843	1.1834	1.1826	1.1818	1.1810	1.1802	1.1793
0.720	1.1785	1.1777	1.1769	1.1761	1.1752	1.1744	1.1736	1.1728	1.1720	1.1712
0.730	1.1704	1.1696	1.1688	1.1680	1.1672	1.1664	1.1656	1.1648	1.1640	1.1633
0.740	1.1625	1.1617	1.1609	1.1601	1.1593	1.1586	1.1578	1.1570	1.1562	1.1555
0.750	1.1547	1.1539	1.1532	1.1524	1.1516	1.1509	1.1501	1.1493	1.1486	1.1478
0.760	1.1471	1.1463	1.1456	1.1448	1.1441	1.1433	1.1426	1.1418	1.1411	1.1403
0.770	1.1396	1.1389	1.1381	1.1374	1.1366	1.1359	1.1352	1.1345	1.1337	1.1330
0.780	1.1323	1.1316	1.1308	1.1301	1.1294	1.1287	1.1279	1.1272	1.1265	1.1258
0.790	1.1251	1.1244	1.1237	1.1230	1.1222	1.1215	1.1208	1.1201	1.1194	1.1187
0.800	1.1180	1.1173	1.1166	1.1159	1.1152	1.1146	1.1139	1.1132	1.1125	1.1118
0.810	1.1111	1.1104	1.1097	1.1090	1.1084	1.1077	1.1070	1.1063	1.1057	1.1050
0.820	1.1043	1.1036	1.1030	1.1023	1.1016	1.1010	1.1003	1.0996	1.0990	1.0983
0.830	1.0976	1.0970	1.0963	1.0957	1.0950	1.0944	1.0937	1.0930	1.0924	1.0917
0.840	1.0911	1.0904	1.0898	1.0891	1.0885	1.0878	1.0872	1.0866	1.0859	1.0853
0.850	1.0846	1.0840	1.0834	1.0827	1.0821	1.0815	1.0808	1.0802	1.0796	1.0790
0.860	1.0783	1.0777	1.0771	1.0764	1.0758	1.0752	1.0746	1.0740	1.0733	1.0727
0.870	1.0721	1.0715	1.0709	1.0703	1.0696	1.0690	1.0684	1.0678	1.0672	1.0666
0.880	1.0660	1.0654	1.0648	1.0642	1.0636	1.0630	1.0624	1.0618	1.0612	1.0606
0.890	1.0600	1.0594	1.0588	1.0582	1.0576	1.0570	1.0564	1.0558	1.0553	1.0547
0.900	1.0541	1.0535	1.0529	1.0523	1.0518	1.0512	1.0506	1.0500	1.0494	1.0489
0.910	1.0483	1.0477	1.0471	1.0466	1.0460	1.0454	1.0448	1.0443	1.0437	1.0431
0.920	1.0426	1.0420	1.0414	1.0409	1.0403	1.0398	1.0392	1.0386	1.0381	1.0375
0.930	1.0370	1.0364	1.0358	1.0353	1.0347	1.0342	1.0336	1.0331	1.0325	1.0320
0.940	1.0314	1.0309	1.0303	1.0298	1.0292	1.0287	1.0281	1.0276	1.0270	1.0265
0.950	1.0260	1.0254	1.0249	1.0244	1.0238	1.0233	1.0228	1.0222	1.0217	1.0212
0.960	1.0206	1.0201	1.0196	1.0190	1.0185	1.0180	1.0174	1.0169	1.0164	1.0159
0.970	1.0153	1.0148	1.0143	1.0138	1.0132	1.0127	1.0122	1.0117	1.0112	1.0107
0.980	1.0102	1.0096	1.0091	1.0086	1.0081	1.0076	1.0071	1.0066	1.0060	1.0055
0.990	1.0050	1.0045	1.0040	1.0035	1.0030	1.0025	1.0020	1.0015	1.0010	1.0005
1.000	1.0000									

Table 3-B-11—Supercompressibility Factors (F_{pv}) for G_r = 0.6 Without Nitrogen or Carbon Dioxide

Pressure (psia)	Temperature (°F)					
	20	40	60	80	100	120
100	1.00947	1.00807	1.00687	1.00504	1.00496	1.00419
200	1.02058	1.01762	1.01512	1.01294	1.01116	1.00958
300	1.03218	1.02748	1.02355	1.02022	1.01740	1.01497
400	1.04427	1.03764	1.03216	1.02756	1.02367	1.02035
500	1.05688	1.04810	1.04093	1.03497	1.02996	1.02572
600	1.06999	1.05884	1.04983	1.04243	1.03625	1.03104
700	1.08360	1.06983	1.05885	1.04990	1.04251	1.03631
800	1.09766	1.08103	1.06793	1.05737	1.04871	1.04149
900	1.11209	1.09237	1.07703	1.06479	1.05482	1.04656
1000	1.12679	1.10375	1.08608	1.07211	1.06081	1.05150
1100	1.14156	1.11508	1.09501	1.07927	1.06663	1.05628
1200	1.15616	1.12621	1.10372	1.08622	1.07225	1.06087
1300	1.17029	1.13696	1.11211	1.09289	1.07763	1.06524
1400	1.18358	1.14715	1.12007	1.09922	1.08271	1.06935
1500	1.19565	1.15657	1.12749	1.10512	1.08745	1.07318
1600	1.20615	1.16504	1.13425	1.11054	1.09180	1.07669
1700	1.21481	1.17237	1.14025	1.11540	1.09573	1.07986
1800	1.22146	1.17845	1.14541	1.11965	1.09919	1.08267
1900	1.22606	1.18318	1.14965	1.12324	1.10216	1.08509
2000	1.22868	1.18655	1.15294	1.12615	1.10462	1.08710

Note The data in this table were generated using the A.G.A. Gas Measurement Program. Copyright © 1988 American Gas Association All rights reserved Gas input data are as follows: % CO_2 = 0; % N_2 = 0; specific gravity = 0 6. This table was developed for informational purposes only and is specific to the gas quality listed. The data in this table are *not* subject to adjustment for nitrogen or carbon dioxide content and, because of their broad range, should not be interpolated. With the A.G.A Program, the user establishes the gas composition parameters and specifies the table range that is consistent with field or measurement conditions.

APPENDIX 3-C—FLOW CALCULATION EXAMPLES

3-C.1 General

This appendix presents two methods for calculating the volume flow rate of natural gas through an orifice meter equipped with flange taps. The first method uses the equations presented in 3.3 through 3.5. The second method is based on the more traditional calculation format, which involves the computation of various factors. The equations used for the factor approach are presented in Appendix 3-B.

To assist the user in interpreting the calculation methodology, the data set given below, which is for a single orifice meter, is used consistently throughout the flow calculation examples. The volume flow rate is computed under the assumption that the measurements are absolute and without error. It should be noted that depending on the type of instrumentation used and the calibration methods employed, calibration and correction factors may need to be applied. *For simplicity in using hand calculations and for ease of interpretation in the following examples, intermediate values are rounded to six significant digits. Part 4 should be used for any implementation of the equations.*

3-C.2 Given Data

The orifice meter consists of a carbon steel meter tube equipped with flange taps and a Type 304 stainless steel orifice plate. Static pressure measurements are taken from the upstream tap.

d_r = mean orifice bore diameter at T_r of 68°F, in inches
= 4.000.
D_r = mean meter tube internal diameter at T_r of 68°F, in inches
= 8.071.
G_r = real gas relative density (specific gravity)
= 0.570.
h_w = average differential pressure, in inches of water at 60°F
= 50.0.
P_b = contract base pressure, in pounds force per square inch absolute
= 14.65
P_{f1} = average upstream absolute static pressure, in pounds force per square inch absolute
= 370.0.
T_b = contract base temperature of 50°F, in degrees Rankine (50°F + 459.67)
= 509.67
T_f = flowing temperature of 65°F, in degrees Rankine (65°F + 459.67)
= 524.67.
xc = carbon dioxide content, in mole percent
= 0.00
xn = nitrogen content, in mole percent
= 1.10
k = isentropic exponent (c_p/c_v)
= 1.3.
α_1 = linear coefficient of thermal expansion for a stainless steel orifice plate, in inches per inch-°F
= 0.00000925.
α_2 = linear coefficient of thermal expansion for a carbon steel meter tube, in inches per inch-°F
= 0.00000620.
μ = dynamic viscosity, in pounds mass per foot-second
= 0.0000069.

3–C.3 Calculation Examples

3–C.3.1 METHOD 1: VOLUME FLOW RATE CALCULATION BASED ON 3.3 THROUGH 3.5

3–C.3.1.1 General

Using the given data set, the volume flow rate of natural gas, in cubic feet per hour at standard conditions, can be calculated using Equation 3-6b:

$$Q_v = 7709.61 C_d(\mathrm{FT}) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \qquad (3\text{-}6\text{b})$$

Note: Since the given data contain values for the contract base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate at standard conditions will require conversion to the flow rate at base conditions of 14.65 pounds force per square inch absolute and 50°F.

The systematic approach to solving the volume flow rate equation above involves the calculation of the intermediate values described 3-C.3.1.2 through 3-C.3.1.7.

3–C.3.1.2 Flange–Tapped Orifice Meter Coefficient of Discharge [C_d(FT)]

The following equations are used to calculate the coefficient of discharge, C_d(FT):

$$C_d(\mathrm{FT}) = C_i(\mathrm{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4 C \qquad (3\text{-}11)$$

$$C_i(\mathrm{FT}) = C_i(\mathrm{CT}) + Tap\ Term \qquad (3\text{-}12)$$

$$C_i(\mathrm{CT}) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1 - \beta)M_1 \qquad (3\text{-}13)$$

$$Tap\ Term = Upstrm + Dnstrm \qquad (3\text{-}14)$$

$$Upstrm = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \qquad (3\text{-}15)$$

$$Dnstrm = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \qquad (3\text{-}16)$$

Also,

$$B = \frac{\beta^4}{1 - \beta^4} \qquad (3\text{-}17)$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4},\ 0.0\right) \qquad (3\text{-}18)$$

$$M_2 = \frac{2L_2}{1 - \beta} \qquad (3\text{-}19)$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \qquad (3\text{-}20)$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \qquad (3\text{-}21)$$

Where

C_d(FT) = coefficient of discharge at a specified pipe Reynolds number for a flange-tapped orifice meter

C_i(CT) = coefficient of discharge at an infinite pipe Reynolds number for corner-tapped orifice meter

C_i(FT) = coefficient of discharge at an infinite pipe Reynolds number for a flange-tapped orifice meter

d = orifice plate bore diameter calculated at T_f, in inches.
D = meter tube internal diameter calculated at T_f, in inches.
e = Napierian constant
= 2.71828.
$L_1 = L_2$
= dimensionless correction for tap location
= N_4/D for flange taps.
N_4 = 1.0 when D is in inches.
Re_D = pipe Reynolds number.
β = diameter ratio
= d/D

Note: For this example, M_1 is equal to 0.0, since the given meter tube diameter (D) is greater than or equal to 2.8 inches. For meter tube diameters (D) less than 2.8 inches, $M_1 = 2.8 - D$. The solution of the intermediate equations presented above for the flow coefficient calculation follows.

3–C.3.1.3 Meter Tube Diameter, Orifice Plate Bore Diameter, and Diameter Ratio (D, d, and β)

Calculate the values of d, D, and β at a flowing temperature of 65°F from the given diameters d_r and D_r:

$$\begin{aligned} d &= d_r[1 + \alpha_1(T_f - T_r)] \\ &= 4.000[1 + 0.00000925(524.67 - 527.67)] \\ &= 3.99989 \end{aligned} \tag{3-9}$$

And

$$\begin{aligned} D &= D_r[1 - \alpha_2(T_f - T_r)] \\ &= 8.071[1 + 0.00000620(524.67 - 527.67)] \\ &= 8.07085 \end{aligned} \tag{3-10}$$

Substitute the given values of d and D at 65°F into Equation 3-8:

$$\begin{aligned} \beta &= d / D \\ &= 3.99989 / 8.07085 \\ &= 0.495597 \end{aligned} \tag{3-8}$$

3–C.3.1.4 Velocity of Approach Factor (E_v)

The following equation is used to calculate the velocity of approach factor:

$$\begin{aligned} E_v &= \frac{1}{\sqrt{1 - \beta^4}} \\ &= \frac{1}{\sqrt{1 - 0.495597^4}} \\ &= 1.03160 \end{aligned} \tag{3-22}$$

3–C.3.1.5 Expansion Factor (Y)

The following equation is used to calculate the expansion factor:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \tag{3-32}$$

The intermediate value, x_1, is calculated as follows:

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707 P_{f_1}} \qquad (3\text{-}33)$$

Substitute the given values of h_w and P_{f_1} into Equation 3-32:

$$x_1 = \frac{50.0}{(27.707)(370.0)}$$
$$= 0.00487729$$

Substitute the values for k, x_1, and β into Equation 3-32:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \qquad (3\text{-}32)$$
$$= 1 - [0.41 + 0.35(0.495597)^4]\left(\frac{0.00487729}{1.3}\right)$$
$$= 0.998383$$

3–C.3.1.6 Compressibility (Z_b, Z_s, and Z_{f_1})

The derivation of the equation for compressibility is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the calculation procedures necessary for determining the compressibility at base conditions (Z_b), standard conditions (Z_s), or flowing conditions (Z_{f_1}). The following values for gas compressibility at the conditions given in the data set were obtained from the A.G.A. computer program that uses the calculation given in A.G.A. Transmission Measurement Committee Report No. 8. At G_r = 0.57,

Z_b = 0.997839 at 14.65 pounds force per square inch absolute and 509.67°R (50°F)
Z_s = 0.997971 at 14.73 pounds force per square inch absolute and 519.67°R (60°F)
Z_{f_1} = 0.951308 at 370 pounds force per square inch absolute and 524.67°R (65°F)

3–C.3.1.7 Reynolds Number (Re_D)

The following equation is used to calculate the pipe Reynolds number:

$$Re_D = 0.0114541\left(\frac{Q_b P_b G_r}{\mu D T_b Z_{b_{air}}}\right) \qquad (3\text{-}28)$$

Substituting the calculated value for D, standard conditions for P_b and T_b, a value of 0.999590 for $Z_{b_{air}}$, and the data set values for G_r and μ in Equation 3-28 produce the following:

$$Re_D = (0.0114541)\left(\frac{Q_v(14.73)(0.570)}{(0.0000069)(8.07085)(519.67)(0.999590)}\right)$$
$$= 3.32449 Q_v$$

When the flow rate is not known, the Reynolds number can be developed by assuming an initial value for the flange-tapped orifice meter coefficient of discharge, C_d(FT), and iterating for the correct values, as stated in 3.4.5. The following flow rate calculation provides the initial iteration of the Reynolds number. This initial iteration is based on an assumed value for C_d(FT) of 0.60. Based on experience, from three to five iterations should provide results consistent with the requirements of Part 4.

3–C.3.1.8 Volume Flow Rate (Q_v and Q_b)

The volume flow rate can be calculated by substituting the given parameters, the intermediate calculated values, and an assumed value of 0.60 for C_d(FT) in Equation 3-6b and iterating for the final solution:

$$\begin{aligned} Q_v &= 7709.61C_d(\text{FT})E_vY_1d^2\sqrt{\frac{P_{f1}Z_sh_w}{G_rZ_{f1}T_f}} \qquad (3\text{-}6b)\\ &= 7709.61(0.60)(1.03160)(0.998383)(3.99989)^2\\ &\quad\times\sqrt{\frac{(370.0)(0.997971)(50.0)}{(0.951308)(0.570)(524.67)}}\\ &= 614{,}033 \text{ cubic feet per hour at standard conditions}\end{aligned}$$

[This is an estimate of the initial flow rate based on an assumed $C_d(\text{FT})$ of 0.60.]

Substitute the estimate of initial flow rate into the Reynolds number equation and calculate the estimated initial Reynolds number:

$$\begin{aligned} Re_D &= 3.32449Q_v\\ &= 3.32449(614{,}033)\\ &= 2{,}041{,}347 \text{ (initial estimate of Reynolds number)}\end{aligned}$$

Substitute the calculated value of β into Equation 3-17:

$$\begin{aligned} B &= \frac{\beta^4}{1-\beta^4} \qquad (3\text{-}17)\\ &= \frac{0.495597^4}{1-0.495597^4}\\ &= 0.0642005\end{aligned}$$

Substitute the calculated values of β and D into Equation 3-19:

$$\begin{aligned} M_2' &= \frac{2L_2}{1-\beta} \qquad (3\text{-}19)\\ &= \frac{2}{8.07085(1-0.495597)}\\ &= 0.491284\end{aligned}$$

Substitute the calculated values of Re_D and β into Equation 3-20:

$$\begin{aligned} A &= \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \qquad (3\text{-}20)\\ &= \left[\frac{19{,}000(0.495597)}{2{,}041{,}347}\right]^{0.8}\\ &= 0.0135261\end{aligned}$$

Substitute the calculated value of Re_D into Equation 3-21:

$$\begin{aligned} C &= \left(\frac{10^6}{Re_D}\right)^{0.35} \qquad (3\text{-}21)\\ &= \left(\frac{10^6}{2{,}041{,}347}\right)^{0.35}\\ &= 0.778985\end{aligned}$$

Substitute the appropriate calculated values into Equation 3-13 to determine the $C_i(\text{CT})$ term of the coefficient of discharge, $C_d(\text{FT})$:

$$\begin{aligned} C_i(\text{CT}) &= 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1-\beta)M_1 \qquad (3\text{-}13)\\ &= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8\\ &\quad + 0.003(1-0.495597)(0.0)\\ &= 0.602414\end{aligned}$$

Substitute the applicable calculated values into Equation 3-15 to compute the *Upstrm* term of the coefficient of discharge, C_d(FT):

$$\begin{aligned} Upstrm &= [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \qquad (3\text{-}15) \\ &= [0.0433 + 0.0712e^{-8.5/\text{[illegible]}} - 0.1145e^{-6.0/\text{[illegible]}}] \\ &\quad \times [1 - 0.23(0.0135269)](0.0642005) \\ &= 0.000851774 \end{aligned}$$

Substitute the applicable calculated values into Equation 3-16 to compute the *Dnstrm* term of the coefficient of discharge, C_d(FT):

$$\begin{aligned} Dnstrm &= -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \qquad (3\text{-}16) \\ &= -0.0116[0.491284 - 0.52(0.491284)^{1.3}](0.495597)^{1.1} \\ &\quad \times [1 - 0.14(0.0134223)] \\ &= -0.00149777 \end{aligned}$$

Substitute the applicable calculated values into Equation 3-14 to compute the *Tap Term* of the coefficient of discharge, C_d(FT):

$$\begin{aligned} Tap\ Term &= Upstrm + Dnstrm \qquad (3\text{-}14) \\ &= 0.000851774 + (-0.00149777) \\ &= -0.000645999 \end{aligned}$$

Substitute the applicable calculated values into Equation 3-13 to compute the C_i(FT) term of the coefficient of discharge, C_d(FT):

$$\begin{aligned} C_i(\text{FT}) &= C_i(\text{CT}) + Tap\ Term \qquad (3\text{-}12) \\ &= 0.602414 - 0.000645999 \\ &= 0.601768 \end{aligned}$$

Substitute the value for C_i(FT) and the intermediate values into Equation 3-11 to calculate the discharge coefficient, C_d(FT):

$$\begin{aligned} C_d(\text{FT}) &= C_i(\text{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4C \qquad (3\text{-}11) \\ &= 0.601768 + 0.000511\left[\frac{10^6(0.495597)}{2{,}041{,}347}\right]^{0.7} \\ &\quad + [0.0210 + 0.0049(0.0135261)](0.495597)^4(0.778985) \\ &= 0.602947 \text{ (second estimate of the coefficient of discharge)} \end{aligned}$$

By substituting the value of C_d(FT) into the applicable equations, the volume flow rate can be recalculated following the same process outlined in this example. The resulting volume flow rate value is as follows:

$$\begin{aligned} Q_v &= 617{,}049 \text{ cubic feet per hour at standard conditions} \\ &\quad [\text{based on } C_d(\text{FT}) = 0.602947] \end{aligned}$$

And

$$\begin{aligned} Re_D &= 3.32449Q_v = 3.32449(617{,}049) \\ &= 2{,}051{,}373 \text{ (second estimate of Reynolds number)} \end{aligned}$$

Resulting in

$$C_d(\text{FT}) = 0.602944 \text{ (third estimate of coefficient of discharge)}$$

On page 57, Equation 3-20 should read as follows:

$$\begin{aligned} A &= \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \\ &= \left[\frac{19{,}000(0.495597)}{2{,}041{,}328}\right]^{0.8} \qquad (3\text{-}20) \\ &= 0.0135262 \end{aligned}$$

On page 57, Equation 3-21 should read as follows:

$$\begin{aligned} C &= \left(\frac{10^6}{Re_D}\right)^{0.35} \\ &= \left(\frac{10^6}{2{,}041{,}328}\right)^{0.35} \qquad (3\text{-}21) \\ &= 0.778988 \end{aligned}$$

On page 58, Equation 3-15 should read as follows:

$$\begin{aligned} Upstrm &= [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \\ &= [0.0433 + 0.0712e^{\text{[illegible]}} - 0.1145e^{\text{[illegible]}}] \\ &\quad \times [1 - 0.23(0.0135262)](0.0642005) \qquad (3\text{-}15) \\ &= 0.000876388 \end{aligned}$$

On page 58, Equation 3-16 should read as follows:

$$\begin{aligned} Dnstrm &= -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \\ &= -0.0116[0.491284 - 0.52(0.491284)^{1.3}](0.495597)^{1.1} \\ &\quad \times [1 - 0.14(0.0135262)] \qquad (3\text{-}16) \\ &= -0.00152379 \end{aligned}$$

On page 58, Equation 3-14 should read as follows:

$$\begin{aligned} Tap\ Term &= Upstrm + Dnstrm \\ &= 0.000876388 + (-0.00152379) \qquad (3\text{-}14) \\ &= -0.000647402 \end{aligned}$$

On page 58, Equation 3-12 should read as follows;

$$\begin{aligned} C(\text{FT}) &= C_i(\text{CT}) + Tap\ Term \\ &= 0.602414 - 0.000647402 \qquad (3\text{-}12) \\ &= 0.601767 \end{aligned}$$

On page 58, Equation 3-11 should read as follows

$$\begin{aligned} C_d(\text{FT}) &= C_i(\text{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4C \\ &= 0.601767 + 0.000511\left[\frac{10^6(0.495597)}{2{,}041{,}328}\right]^{0.7} \qquad (3\text{-}11) \\ &\quad + [0.0210 + 0.0049(0.0135262)](0.495597)^4(0.778988) \\ &= 0.602947 \text{ (second estimate of the coefficient of discharge)} \end{aligned}$$

Following the same calculation procedure for iteration of flow rate, the resulting volumetric flow rate is as follows:

$$Q_v = 617{,}046 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(FT) = 0.602944]$$

And

$$Re_D = 3.32449Q_v = 3.32449(617{,}046)$$
$$= 2{,}051{,}363 \text{ (third estimate of Reynolds number)}$$

Resulting in

$$C_d(FT) = 0.602944 \text{ (fourth estimate of coefficient of discharge)}$$

The volume flow rate calculation based on the fourth estimate of C_d(FT) follows. As stated above, three estimates of C_d(FT) should normally provide volume flow rate calculation results that are consistent with the requirements of Part 4.

$$Q_v = 617{,}046 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(FT) = 0.602944]$$

Since the given data contain values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate is the standard volume flow rate. To calculate the flow rate at the given base conditions. (P_b = 14.65 pounds force per square inch absolute and T_b = 509.67°R), the standard volume flow rate and the appropriate values for P, T, and Z are substituted into Equation 3-7 as follows:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \quad (3\text{-}7)$$

$$= 617{,}046\left(\frac{509.67}{519.67}\right)\left(\frac{14.73}{14.65}\right)\left(\frac{0.997839}{0.997971}\right)$$

$$= 608{,}396 \text{ cubic feet per hour at base conditions}$$

3–C.3.2 METHOD 2: VOLUME FLOW RATE CALCULATION BASED ON THE FACTOR APPROACH PRESENTED IN APPENDIX 3–B

3–C.3.2.1 General

Using the given data, the volume flow rate of natural gas, in cubic feet per hour at standard conditions, can be calculated using Equation 3-B-2, as stated in Appendix 3-B:

$$Q_v = F_n(F_c + F_{sl})Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv}\sqrt{P_{f1} h_w} \quad (3\text{-}B\text{-}2)$$

Since the given data contain values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate requires conversion to the flow rate at base conditions of 14.65 pounds force per square inch absolute and 60°F.

The systematic approach to solving Equation 3-B-2 involves calculation of the individual factors as shown in 3-C.3.2.2 through 3-C.3.2.10.

3–C.3.2.2 Numeric Conversion Factor (F_n)

Equation 3-B-5b is used to calculate the numeric conversion factor:

$$F_n = 338.196E_v D^2\beta^2 \quad (3\text{-}B\text{-}5b)$$

Where

$$E_v = \frac{1}{\sqrt{1 - \beta^4}} \qquad (3\text{-}22)$$

Calculate the value of d, D, and β at a flowing temperature of 65°F from the given diameters d_r and D_r:

$$\begin{aligned} d &= d_r[1 + \alpha_1(T_f - T_r)] \qquad (3\text{-}9)\\ &= 4.000[1 + 0.00000925(524.67 - 527.67)]\\ &= 3.99989 \end{aligned}$$

And

$$\begin{aligned} D &= D_r[1 + \alpha_2(T_f - T_r)] \qquad (3\text{-}10)\\ &= 8.071[1 + 0.00000620(524.67 - 527.67)]\\ &= 8.07085 \end{aligned}$$

$$\begin{aligned} \beta &= d/D \qquad (3\text{-}8)\\ &= 3.99989/8.07085\\ &= 0.495597 \end{aligned}$$

Substitute the values for β and D into Equation 3-B-5:

$$\begin{aligned} F_n &= 338.196 E_v D^2 \beta^2 \qquad (3\text{-B-}5)\\ &= 338.196 \frac{1}{\sqrt{1 - \beta^4}} D^2 \beta^2\\ &= 338.196 \frac{1}{\sqrt{1 - (0.495597)^4}} (8.07085)^2 (0.495597)^2\\ &= 5581.82 \end{aligned}$$

3–C.3.2.3 Flange–Tapped Orifice Meter Coefficient of Discharge [C_d(FT)]

The following equation is used to calculate the coefficient of discharge:

$$C_d(\text{FT}) = F_c + F_{sl} \qquad (3\text{-B-}6)$$

Where

$$\begin{aligned} F_c = {} & 0.5961 + 0.0291\beta^2 - 0.2290\beta^8\\ & + \left(0.0433 + 0.0712e^{-8.5/D} - 0.1145e^{-6.0/D}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1 - \beta^4}\\ & - 0.0116\left[\frac{2}{D(1 - \beta)} - 0.52\left(\frac{2}{D(1 - \beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right] \qquad (3\text{-B-}7) \end{aligned}$$

$$\begin{aligned} F_{sl} = {} & 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7}\\ & + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.35} \qquad (3\text{-B-}9) \end{aligned}$$

$$Re_D = 0.0114541\left(\frac{Q_b P_b G_r}{\mu D T_b Z_b}\right) \qquad (3\text{-}28)$$

On page 58, the third to the last equation should read as follows:

$$Q_s = 617{,}048 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(FT) = 0.602947]$$

On page 58, the second to the last equation should read as follows:

$$Re_D = 3.32446Q_s = 3.32446(617{,}048)$$
$$= 2{,}051{,}351 \text{ (second estimate of Reynolds number)}$$

On page 59, the second equation should read as follows:

$$Re_D = 3.32446Q_s = 3.32446(617{,}046)$$
$$= 2{,}051{,}345 \text{ (third estimate of Reynolds number)}$$

On page 59, Equation 3-7 should read as follows:

$$Q_b = Q_s\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right)$$
$$= 617{,}046\left(\frac{14.73}{14.65}\right)\left(\frac{509.67}{519.67}\right)\left(\frac{0.997839}{0.997971}\right) \qquad (3\text{-}7)$$
$$= 608{,}396 \text{ cubic feet per hour at base conditions}$$

On page 60, Equation 3-B-9 should read as follows.

$$F_c = 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7}$$
$$+ \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000}{Re_D}\right)^{0.35} \qquad (3\text{-}B\text{-}9)$$

On page 62, the first equation should read as follows:

$$F_c = 0.5961 - 0.0291\beta^2 - 0.2290\beta^8$$
$$+ \left(0.0433 - 0.0712e^{-8.5/D} - 0.1145e^{-6.0/D}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1 - \beta^4}$$
$$- 0.0116\left[\frac{2}{D(1 - \beta)} - 0.52\left(\frac{2}{D(1 - \beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]$$
$$= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8$$
$$+ (0.0433 - 0.0712e^{-8.5/8.071} - 0.1145e^{-6.0/8.071})[1 - 0.23(0.0137493)](0.0642005)$$
$$- 0.0116[0.491284 - 0.52(0.491284^{1.3})](0.495597)^{1.1}[1 - 0.14(0.0137493)]$$
$$= 0.601767$$

$$B = \frac{\beta^4}{1 - \beta^4} \tag{3-17}$$

$$M_2 = \frac{2L_2}{1 - \beta} \tag{3-19}$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \tag{3-20}$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \tag{3-21}$$

Note: In this example, since the given meter tube diameter (D) is greater than 2.8 inches, Equation 3-B-7 is used to calculate the F_c term. For meter tube diameters (D) less than 2.8 inches, Equation 3-B-8 must be used to calculate the F_c term. The solution of the intermediate equations presented above for the flow coefficient calculation follows.

Substituting the calculated values of β and D gives the following:

$$\frac{\beta^4}{1 - \beta^4} = \frac{(0.495597)^4}{1 - (0.495597)^4}$$

$$= 0.0642005$$

$$\frac{2}{D(1 - \beta)} = \frac{2}{8.07085(1 - 0.495597)}$$

$$= 0.491284$$

As discussed in 3.4.5, the Reynolds number (Re_D) for natural gas can be approximated using Equation 3-28. Note that the parameters of this example are within the recommended tolerances for viscosity, temperature, and specific gravity. Furthermore, 3.4.5 states that when the flow rate is not known, a more precise value for the Reynolds number can be determined through iteration of Equation 3-28 and that three to five iterations will provide results that are consistent with the requirements of Part 4. The initial assumption needed for the first iteration can come from assuming a value for C_d(FT) as in the previous example or from assuming an initial Reynolds number for the pipe Reynolds number. Table 3-B-1, Appendix 3-B, provides values for pipe Reynolds numbers versus nominal pipe diameters for the purpose of initiating the iteration process. This example uses Table 3-B-1 for the initial estimate of pipe Reynolds number.

$$Re_D = 2{,}000{,}000 \quad \text{(initial assumption from Table 3-B-1)}$$

Substituting the values of Re_D and β gives the following:

$$\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} = \left[\frac{19{,}000(0.495597)}{2{,}000{,}000}\right]^{0.8}$$

$$= 0.0137493$$

$$\left(\frac{10^6}{Re_D}\right)^{0.35} = \left(\frac{10^6}{2{,}000{,}000}\right)^{0.35}$$

$$= 0.784584$$

Substitute the appropriate calculated values into Equation 3-B-7 to determine the orifice calculation factor, F_c

$$
\begin{aligned}
F_c &= 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 \\
&\quad + \left(0.0433 + 0.0712e^{-8.5/D} - 0.1145e^{-6.0/D}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4} \\
&\quad - 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right] \\
&= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8 \\
&\quad + \left(0.0433 + 0.0712e^{-8.5/8.0701} - 0.1145e^{-6.0/8.0701}\right)[1 - 0.23(0.0137493)](0.0642005) \\
&\quad - 0.0116[0.491284 - 0.52(0.491284)]^{1.3}(0.495597)^{1.1}[1 - 0.14(0.0137493)] \\
&= 0.601767
\end{aligned}
$$

Substitute the applicable calculated values into Equation 3-B-9 to compute the orifice slope factor, F_{sl}:

$$
\begin{aligned}
F_{sl} &= 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} \\
&\quad + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.35} \qquad \text{(3-B-9)} \\
&= 0.000511\left(\frac{1{,}000{,}000(0.4955972)}{2{,}000{,}000}\right)^{0.7} \\
&\quad + [0.0210 + 0.0049(0.0137493)](0.495597)^4(0.784584) \\
&= 0.00118960
\end{aligned}
$$

Substitute the values for F_c and F in Equation 3-B-6 to calculate the discharge coefficient, C_d(FT):

$$
\begin{aligned}
C_d(\mathrm{FT}) &= F_c + F_{sl} \\
&= 0.601767 + 0.00118960 \\
&= 0.602957
\end{aligned}
$$

3–C.3.2.4 Expansion Factor (Y_1)

The following equation is used to calculate the expansion factor:

$$
Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \qquad \text{(3-32)}
$$

The intermediate value, x_1, is calculated as follows:

$$
x = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\,P_{f_1}} \qquad \text{(3-33)}
$$

Substitute the given values of h_w and P_{f_1} into Equation 3-33:

$$
\begin{aligned}
x_1 &= \frac{50.0}{27.707(370.0)} \\
&= 0.00487729
\end{aligned}
$$

Substitute the values for k, x_1, and β into Equation 3-32:

On page 62, Equation 3-B-9 should read as follows:

$$
\begin{aligned}
F_{sl} &= 0.000511\left(\frac{1,000,000\beta}{Re_D}\right)^{0.7} \\
&\quad + \left[0.0210 + 0.0049\left(\frac{19,000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1,000,000}{Re_D}\right)^{0.35} \qquad (3\text{-}B\text{-}9) \\
&= 0.000511\left(\frac{1,000,000(0.495597)}{2,000,000}\right)^{0.7} \\
&\quad + [0.0210 + 0.0049(0.0137493)](0.495597)^4(0.784584) \\
&= 0.00118960
\end{aligned}
$$

On page 65, the first equation should read as follows:

$$
\begin{aligned}
Re_D &= 0.0114588\left(\frac{Q_v P G_r}{\mu D T_v}\right) \\
&= 3.32446 Q_v \\
&= 3.32446(617,057) \\
&= 2,051,400 \text{ (second iteration)}
\end{aligned}
$$

On page 80, Equation 3-D-9 should read as follows (that is, Kpipe, *should be inserted in the equation and the second line of the equation should be deleted):*

$$Re_d = 220.858 d F_m \sqrt{\rho h_w}\ x\ (Kpipe) \qquad (3\text{-}D\text{-}9)$$

On page 80, the nomenclature should read as follows (that is, Kpipe, *should be inserted in the list):*

Where:

G = specific gravity.
Kpipe = values from Table 3-D-4
Re_d = orifice bore Reynolds number
T_f = absolute flowing temperature, in degrees Rankine
ρ = specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F

On page 97, Equations 3-F-4 and 3-F-5 should read as follows:

$$H_i^{id} = \phi_1 (H^{id})_1 + \phi_2 (H^{id})_2 + \ldots + \phi_n (H_i^{id})_n \qquad (3\text{-}F\text{-}4)$$

$$H_i^{id} = \sum_{i=1}^{n} \phi_i (H_i^{id})_i \qquad (3\text{-}F\text{-}5)$$

On page 102, the second line of Equation 3-4a should read as follows:

$$Q_v = 359.072 C_d (FT) E_v Y d^2 \sqrt{\frac{P_f G_i (28.9625)(144) h_w}{Z_f R T_f}}\ \frac{Z_b R T_b}{P_b G_i (28.9625)(144)}$$

$$
\begin{aligned}
Y_1 &= 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) && \text{(3-32)}\\
&= 1 - [0.41 + 0.35(0.495597)^4]\left(\frac{0.00487729}{1.3}\right)\\
&= 0.998383
\end{aligned}
$$

3–C.3.2.5 Compressibility (Z_b, Z_s, and Z_{f_1})

The derivation of the compressibility equation is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the procedures necessary for calculating the compressibility at base conditions (Z_b), standard conditions (Z_s), or flowing conditions (Z_{f_1}). The following values for gas compressibility at the given conditions were obtained from the A.G.A. computer program, using the A.G.A. Transmission Measurement Committee Report No. 8 calculation.

At $G_r = 0.57$,

$Z_b = 0.997839$ at 14.65 pounds force per square inch absolute and 509.67°R (50°F)
$Z_s = 0.997971$ at 14.73 pounds force per square inch absolute and 519.67°R (60°F)
$Z_{f_1} = 0.951308$ at 370 pounds force per square inch absolute and 524.67°R (65°F)

3–C.3.2.6 Base Pressure Factor (F_{pb})

The base pressure factor is calculated using Equation 3-B-10 as follows:

$$
\begin{aligned}
F_{pb} &= \frac{14.73}{P_b} && \text{(3-B-10)}\\
&= \frac{14.73}{14.73}\\
&= 1.00000
\end{aligned}
$$

In this example, F_{pb} has been calculated for a base pressure of 14.73 pounds force per square inch absolute, instead of 14.65 pounds force per square inch absolute as in the given data, and a base volume at the given base conditions has been calculated after the standard volume was determined. This procedure was necessary because of the use of the base compressibility of air ($Z_{b_{air}}$) of 0.999590 at 14.73 pounds force per square inch absolute and 60°F in the development of the numerical constant 338.196 in the F_n factor (see Appendix 3-G).

3–C.3.2.7 Base Temperature Factor (F_{tb})

Equation 3-B-11 is used to calculate the base temperature factor:

$$
\begin{aligned}
F_{tb} &= \frac{T_b}{519.67} && \text{(3-B-11)}\\
&= \frac{519.67}{519.67}\\
&= 1.00000
\end{aligned}
$$

In this example, F_{tb} has been calculated for a base temperature of 519.67°R (60°F) instead of 509.67°R(50°F) as in the given data, and a base volume at the given base conditions has been calculated after the standard volume was determined. This procedure was necessary because of the use of the base compressibility of air ($Z_{b_{air}}$) of 0.999590 at 14.73 pounds force per square inch absolute and 60°F in the development of the numerical constant 338.196 in the F_n factor (see Appendix 3-G).

3–C.3.2.8 Flowing Temperature Factor (F_{tf})

The flowing temperature factor is calculated using Equation 3-B-12 as follows:

$$F_{tf} = \sqrt{\frac{519.67}{T_f}} \tag{3-B-12}$$

Substitute the given flowing temperature, T_f, into Equation 3-B-12:

$$\begin{aligned} F_{tf} &= \sqrt{\frac{519.67}{T_f}} \\ &= \sqrt{\frac{519.67}{524.67}} \\ &= 0.995224 \end{aligned}$$

3–C.3.2.9 Real Gas Relative Density Factor (F_{gr})

Equation 3-B-13 is used to calculate the real gas relative density factor.

$$F_{gr} = \sqrt{\frac{1}{G_r}} \tag{3-B-13}$$

Substitute the given specific gravity, G_r, into Equation 3-B-13:

$$\begin{aligned} F_{gr} &= \sqrt{\frac{1}{G_r}} \\ &= \sqrt{\frac{1}{0.570}} \\ &= 1.32453 \end{aligned}$$

3–C.3.2.10 Supercompressibility Factor (F_{pv})

As stated in the calculations in 3-C.3.1, the derivation of the equation for compressibility is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the procedures necessary for calculating the compressibility at standard conditions (Z_s) or at flowing conditions (Z_{f_1})

$$\begin{aligned} Z_s &= 0.997971 \\ Z_{f_1} &= 0.951308 \end{aligned}$$

Equation 3-B-14 is used to calculate the supercompressibility factor:

$$\begin{aligned} F_{pv} &= \sqrt{\frac{Z_s}{Z_f}} \\ &= \sqrt{\frac{0.997971}{0.951308}} \\ &= 1.02423 \end{aligned}$$

3–C.3.2.11 Volume Flow Rate (Q_v)

The volume flow rate is calculated by substituting the given parameters and the intermediate calculated factors into Equation 3-B-2.

$$\begin{aligned} Q_v &= F_n (F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \sqrt{P_f h_w} \qquad \text{(3-B-2)} \\ &= 617.057 \end{aligned}$$

The calculated flow rate above is based on an initial assumed value for the Reynolds number (Re_D) of 2,000,000. For the second estimate, the value of Re_D is calculated as follows:

$$\begin{aligned} Re_D &= 0.0114588\left(\frac{Q_v P_s G_r}{\mu D T_s}\right) \\ &= 3.32449 Q_v \\ &= 3.32449(617{,}057) \\ &= 2{,}051{,}400 \text{ (second iteration)} \end{aligned}$$

By substituting the second estimate of Re_D into the applicable equations, the volume flow rate can be recalculated by following the process outlined in 3-C.3.1. The resulting volume flow rate is as follows:

$$Q_v = 617{,}013 \quad \text{(based on the second estimate of } Re_D\text{)}$$

The same calculation procedures are used to obtain the third estimate of Re_D:

$$\begin{aligned} Re_D &= 3.32449 Q_v \\ &= 3.32449(617{,}013) \\ &= 2{,}051{,}254 \text{ (third iteration)} \end{aligned}$$

The volume flow rate calculation based on the third estimate of Re_D follows. As stated above, three to five estimates of Re_D will provide calculation results that are consistent with the requirements of Part 4.

$$\begin{aligned} Q_v &= F_n (F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \sqrt{P_{f_1} h_w} \\ &= (5581.82)(0.601767 + 0.00117736)(0.998383)(1.00000)(1.00000) \\ &\quad \times (0.995224)(1.32453)(1.02423)\sqrt{(370.0)(50.0)} \\ &= 617{,}044 \text{ cubic feet per hour} \end{aligned}$$

Note: The calculated volume flow rate is based on the third estimate of Re_D. The small discrepancy between the calculated volume flow rate, Q_v, in Methods 1 and 2 results from the rounding techniques used in the series of equations in the examples.

Since the given data included values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differed from the values established in Part 3 for standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate is the standard volume flow rate. To calculate the flow rate at base conditions (P_b = 14.65 pounds force per square inch absolute and T_b = 509.67°R), the standard volume flow rate and the appropriate values for P, T, and Z are substituted into Equation 3-7 as follows:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \tag{3-7}$$

$$\begin{aligned} &= 617{,}044\left(\frac{509.67}{519.67}\right)\left(\frac{14.73}{14.65}\right)\left(\frac{0.997839}{0.997971}\right) \\ &= 608.394 \text{ cubic feet per hour at base conditions} \end{aligned}$$

APPENDIX 3-D—PIPE TAP ORIFICE METERING

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3–D.1 Symbols, Units, and Terminology

3–D.1.1 GENERAL

Some of the symbols listed in 3-D.1.2 are specific to this appendix. Unless otherwise noted, all of these symbols are dimensionless. Symbols that are used in this appendix but not listed in 3-D.1.2 are defined in 3.2.2.

3–D.1.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
C'	Orifice flow constant	—
F_b	Basic orifice factor	—
K_e	Coefficient of discharge when Reynolds number = (1,000,000d)/15	—
K_o	Coefficient of discharge for infinite Reynolds number	—
ρ	Specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F	lbm/ft^3

3–D.2 Scope

3–D.2.1 INTRODUCTION

Recent research work on orifice measurement has been restricted to flange, corner, and radius tap meters. It is recognized that a number of "pipe tap" meters continue in operation in natural gas measurement in the United States. The provisions of the second (1985) edition of Chapter 14, Section 3, that are applicable to pipe tap configurations are included in this appendix. The dimensional information, tolerances, and computation methods in this appendix are only applicable to pipe tap meters.

This appendix provides recommendations and specifications relating to the measurement of natural gas and other related hydrocarbon fluids by means of orifice meters equipped with pipe taps. It includes definitions, construction and installation specifications, and instructions for computing flow rate and volume. Also included are equations and tables that provide factors necessary to apply adjustments to the basic pipe tap orifice flow.

This appendix covers the measurement of natural gas by pipe tap orifice meters, including the primary element and the methods of calculation. It does not cover the equipment used to determine the pressure, temperature, specific gravity, and other variances that must be known for the accurate measurement of natural gas.

3–D.2.2 GENERAL

Unless specifically noted in this appendix, all information and data presented in the body of this standard—including recommendations, specifications, and symbols—are applicable to pipe tap orifice metering

3–D.2.3 TYPE OF METER

This appendix is limited to orifice meters that have circular orifices located concentrically in the meter tube, having upstream and downstream pressure taps as specified for pipe taps.

3–D.2.4 DEFINITION OF *PIPE TAP PRESSURE MEASUREMENT*

The definition of *pipe tap pressure measurement* is based on the position of the pair of tap holes: The upstream tap center is located 2.5 times the inside pipe diameter upstream from the nearest plate face, and the downstream tap center is located 8 times the inside pipe diameter downstream from the nearest plate face (see 3-D.3.4.1).

3–D.3 Construction and Installation Specifications

3–D.3.1 BETA RATIO LIMITATIONS OF ORIFICE PLATES

The orifice-to-meter-tube (pipe) diameter ratio ($\beta = d/D$) should fall within the range from 0.20 to 0.67 inclusive. These limits, with an uncertainty as high as ±0.75 percent, may be exceeded when additional flow uncertainty is acceptable. Beta ratios that exceed the range from 0.20 to 0.67, with an uncertainty as high as ±1.5 percent, may be used; however, the flow constants for these extreme values of β are subject to higher tolerances, and the use of these extremes should be avoided.

3–D.3.2 METER TUBE SPECIFICATIONS

3–D.3.2.1 Definition

The term *meter tube* refers to the straight upstream pipe of length A or A' on the installation sketches in Part 2 (including the straightening vanes, if used), the orifice flanges or fittings, and the downstream pipe (length B on the installation sketches in Part 2) beyond the orifice. The length of upstream and downstream pipe is specified in Part 2. The tolerances for the diameter and the restrictions on the inside surface of the meter tube are specified in 3-D.3.2.4. There shall be no pipe connections within these distances other than straightening vanes, the thermometer wells specified in Part 2, and the pressure taps specified in 3-D.2.4 and Part 2.

3–D.3.2.2 Inside Surface

The sections of pipe to which the orifice flanges or fittings are attached and the adjacent pipe sections that constitute the meter tube, as defined in 3-D.3.2.1, shall comply with the following:

a. The roughness of the inside pipe walls shall not exceed 300 microinches. Carefully selected smooth commercial pipe may be used. Seamless pipe or cold drawn seamless pressure tubing may be used, provided its inside wall is smooth. Drawn-over-mandrel (DOM), electric-resistance-welded (ERW), straight-seam tubing manufactured to the requirements of ASTM A 513, T-5, may also be used. To improve smoothness inside the meter tube, the inside pipe walls may be machined, ground, or coated.
b. Grooves, scoring, pits, and ridges resulting from seams; distortion caused by welding; offsets; and other irregularities (regardless of their size) that affect the inside diameter at the points identified in Figure 3-D-1 by more than the tolerances shown are not permitted. When these tolerances are exceeded, the irregularities must be corrected.
c. The interior of the meter tube shall be kept clean and free from accumulations of contaminants, such as dirt and liquids, at all times.

3–D.3.2.3 Meter Tube Diameter

The mean inside diameter of the meter tube shall be determined as follows:

a. Measurements shall be made on at least four diameters equally spaced in a plane 1 inch upstream from the upstream face of the orifice plate. The mean (arithmetic average) of these measurements is defined as the mean meter tube diameter to be used in calculating the flow coefficient when minimum uncertainty of this variable is desired.
b. Check measurements of the upstream inside diameter of the meter tube shall be made at two or more additional cross-sections. The actual locations of the check measurements of the diameter, circumferentially and axially along the tube, are not specified. These checks should be taken at points that will indicate the maximum and minimum diameters that exist and should cover at least two pipe diameters from the face of the orifice plate or extend past the flange or fitting weld, whichever distance is greater. Check measurements are used to verify the uniformity of the upstream meter tube but do not become a part of the mean meter tube diameter.

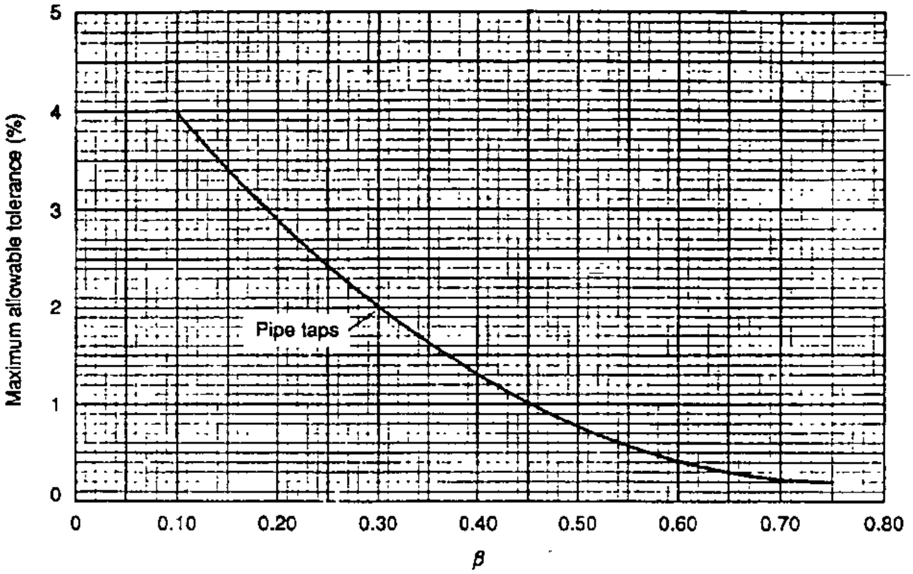


Figure 3-D-1—Maximum Percentage Allowable Meter Tube Tolerance Versus Beta Ratio

c. The inside diameter of the downstream section of the meter tube shall be measured in a plane 1 inch downstream from the downstream face of the orifice plate. Check measurements of the diameter of the downstream section of the meter tube, similar to those described in Item b above, shall be made at two additional cross-sections.

3–D.3.2.4 Tolerances and Restrictions

The tolerances for the diameter and the restrictions on the inside surface of the meter tube are as follows:

a. The difference between the maximum measured diameter and the minimum measured diameter on the inlet section shall not exceed the tolerance shown in Figure 3-D-1 as a percentage of the mean diameter defined in 3-D.3.2.3. The relationship below may be used to calculate the variance of the diameter of the upstream section of the meter tube:

$$\frac{\text{Maximum diameter} - \text{Minimum diameter}}{D} \times 100 \leq \text{Percent tolerance in Figure 3-D-1}$$

b. Abrupt changes in diameter (shoulders, offsets, ridges, and so forth) shall not exist in the meter tube (see 3-D.3.2.3, Item b).

c. When Table 3-D-1 is used for flow measurement estimation, the meter tube diameter, as defined in 3-D.3.2.3, shall agree with the inside diameters listed in the tables within the tolerance shown in Figure 3-D-1.

d. Any diameter measurement in the downstream section shall not vary from the mean diameter of the meter tube, as defined in 3-D.3.2.3, by more than the tolerance shown in Figure 3-D-1. The following relationship may be used to calculate the variance of the diameter of the downstream section of the meter tube:

$$\left|\frac{\text{Any diameter} - D}{D}\right| \times 100 \leq \text{Percent tolerance in Figure 3-D-1}$$

Application of this equation doubles the tolerance for the downstream section of the meter tube.

e. The temperature at which the meter tube measurements are made should be recorded for correction to the operating conditions.

For new installations, in which the beta ratio is likely to be changed, the tolerance permitted for variations in pipe size, as shown in Figure 3-D-1, should be the same as that given for a maximum orifice plate diameter ratio (β) of 0.75.

3–D.3.2.5 Use of Table 3–D–1

If Table 3-D-1 is used for flow estimation, the mean inside diameter of the upstream section of the meter tube should be as nearly the same as the published inside diameter given in Table 3-D-1 as is possible. The inside diameters given in the table were used to calculate the constants in the table. If the mean meter tube diameter differs from the table inside diameter by an amount greater than the tolerance set forth in Figure 3-D-1 or if minimum uncertainty is desired, the mean meter tube diameter should be used to compute the orifice-to-meter-tube diameter ratio, β, as well as the flow coefficient. Other factors should be calculated for this exact value of β.

3–D.3.3 LENGTH OF PIPE PRECEDING AND FOLLOWING THE ORIFICE

The installation sketches and accompanying graphs are not duplicated in this appendix but are available in Part 2, Figures 2-5 through 2-9. The graphs show the minimum lengths of straight pipe required (expressed in nominal pipe diameters) versus beta ratio. It must be noted that when pipe taps are used, lengths *A*, *A'*, and *C* shall be increased by two nominal pipe diameters and length *B* shall be increased by eight nominal pipe diameters. The lengths of straight pipe should be those required for the maximum beta ratio that may be used.

3–D.3.4 PRESSURE TAP HOLES

3–D.3.4.1 Location

Meter tubes that use pipe taps shall have the center of the upstream tap hole located 2.5 times the published or actual inside diameter from the upstream face of the orifice plate.

Table 3-D-1—Basic Orifice Factors (F_b) for Pipe Taps (All Dimensions in Inches)

	Published Inside Diameters at Nominal Pipe Size of 2 Inches			Published Inside Diameters at Nominal Pipe Size of 3 Inches				Published Inside Diameters at Nominal Pipe Size of 4 Inches			
Orifice Diameter	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.250	12.850	12.813	12.800	12.782	22.765	12.754	12.748	12.745	12.737	12.727	12.723
0.375	29.362	29.098	29.006	28.883	28.772	28.711	28.682	28.670	28.635	26.599	28.585
0.500	53.713	52.817	52.482	52.020	51.594	51.354	51.244	51.197	51.065	50.937	50.887
0.625	87.237	84.920	84.085	82.924	81.802	81.143	80.837	80.704	80.334	79.976	79.837
0.750	132.29	126.87	124.99	122.45	120.08	118.67	118.00	117.70	116.87	116.05	115.73
0.875	192.87	181.02	177.09	171.93	167.26	164.58	163.31	162.76	161.17	159.58	158.94
1.000	275.73	251.1[illegible]	243.25	233.30	224.61	219.77	217.53	216.55	213.79	211.03	209.92
1.125	392.50	342.99	327.99	309.44	293.87	285.49	281.67	280.03	275.43	270.91	269.10
1.250		466.00	438.00	404.53	377.[illegible]	363.41	357.13	354.45	347.04	339.88	337.06
1.375			583.98	524.69	478.89	455.83	445.75	441.49	429.84	418.80	414.51
1.500				679.1[illegible]	602.80	565.80	549.95	543.32	525.41	508.77	502.39
1.625					755.89	697.45	672.96	662.83	635.77	611.12	601.81
1.750					9[illegible]7.87	856.39	819.07	803.79	763.53	727.55	714.17
1.875						1,050.4	994.01	971.22	912.00	860.19	841.21
2.000						1,290.7	1,205.6	1,171.9	1,085.5	1,011.7	985.07
2.125							1,465.1	1,415.0	1,289.7	1,185.4	1,148.4
2.250									1,532.0	1,385.4	1,334.5
2.375									1,822.9	1,617.2	1,547.4
2.500										1,887.7	1,792.3
2.625										2,206.1	2,076.0
2.750											2,407.0

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 6 Inches				Published Inside Diameters at Nominal Pipe Size of 8 Inches			Published Inside Diameters at Nominal Pipe Size of 10 Inches			Published Inside Diameters at Nominal Pipe Size of 12 Inches		
	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.136	11.374	11.938	12.090
0.500	50.740	50.707	50.653	50.629									
0.625	79.438	79.351	79.219	79.164									
0.750	114.81	114.62	114.32	114.20									
0.875	157.11	156.72	156.13	155.89	155.11	154.99	154.97						
1.000	206.63	205.92	204.85	204.41	203.01	202.80	202.76	202.16					
1.125	263.71	262.52	260.72	259.99	257.62	257.28	257.20	256.23	256.01	255.96			
1.250	328.73	326.87	324.03	322.87	319.10	318.57	318.44	316.90	316.57	316.49	315.82	315.57	315.51
1.375	402.07	399.32	395.09	393.34	387.63	386.81	386.63	384.30	383.80	383.68	382.67	382.31	382.22
1.500	484.21	480.26	474.21	471.70	463.40	462.20	461.93	458.53	457.80	457.64	456.17	455.65	455.53
1.625	575.75	570.19	561.74	558.25	546.62	544.93	544.54	539.73	538.70	538.47	536.40	535.67	535.49
1.750	677.39	669.69	658.09	653.34	637.52	635.20	634.67	628.05	626.63	626.30	623.46	622.46	622.22
1.875	790.00	779.49	763.79	757.41	736.36	733.25	732.53	723.63	721.72	721.28	717.45	716.12	715.79
2.000	914.59	900.39	879.40	870.95	843.36	839.31	838.37	826.66	824.14	823.56	818.51	816.75	816.32
2.125	1,052.3	1,033.4	1,005.6	994.54	958.80	953.61	952.40	937.31	934.04	933.29	926.74	924.46	923.90
2.250	1,204.7	1,179.6	1,143.2	1,128.9	1,083.0	1,076.4	1,074.9	1,055.8	1,051.6	1,050.7	1,042.3	1,039.4	1,038.7
2.375	1,373.4	1,340.5	1,293.2	1,274.6	1,216.3	1,208.0	1,206.1	1,182.3	1,177.0	1,175.8	1,165.3	1,161.7	1,160.8
2.500	1,560.5	1,517.5	1,456.5	1,432.8	1,359.2	1,348.9	1,346.5	1,316.9	1,310.5	1,309.0	1,296.0	1,291.4	1,290.3
2.625	1,768.3	1,712.6	1,634.4	1,604.3	1,512.1	1,499.3	1,496.4	1,460.1	1,452.2	1,450.4	1,434.4	1,428.8	1,427.4
2.750	1,999.9	1,928.1	1,828.3	1,790.4	1,675.4	1,659.7	1,656.1	1,611.8	1,602.3	1,600.1	1,580.7	1,573.9	1,572.2
2.875	2,258.6	2,166.5	2,040.0	1,992.3	1,849.9	1,830.7	1,826.3	1,771.6	1,761.1	1,758.4	1,735.2	1,727.0	1,725.0
3.000	2,548.6	2,431.0	2,271.2	2,211.6	2,036.1	2,012.7	2,007.4	1,942.6	1,928.8	1,925.6	1,897.9	1,888.2	1,885.8
3.125	2,875.3	2,725.3	2,524.3	2,450.2	2,234.7	2,206.4	2,200.0	2,122.2	2,105.8	2,102.0	2,069.1	2,057.6	2,054.7
3.250	3,244.9	3,054.0	2,801.9	2,710.0	2,446.6	2,412.5	2,404.8	2,311.8	2,292.3	2,287.8	2,249.0	2,235.4	2,232.1
3.375	3,665.7	3,422.4	3,106.9	2,993.4	2,672.6	2,631.7	2,622.4	2,511.7	2,488.7	2,483.4	2,437.8	2,421.9	2,418.0
3.500		3,837.6	3,443.1	3,303.1	2,913.7	2,864.8	2,853.7	2,722.5	2,695.4	2,689.2	2,635.8	2,617.2	2,612.7
3.625		4,308.1	3,814.5	3,642.4	3,171.2	3,112.8	3,099.6	2,944.5	2,912.8	2,905.5	2,843.2	2,821.6	2,816.4
3.750			4,226.4	4,014.9	3,446.1	3,376.7	3,361.1	3,178.4	3,141.3	3,132.8	3,060.3	3,035.4	3,029.3
3.875			4,685.0	4,425.2	3,739.9	3,657.7	3,639.3	3,424.6	3,381.4	3,371.5	3,287.5	3,258.8	3,251.8
4.000			5,197.9	4,878.5	4,054.3	3,957.1	3,935.3	3,683.9	3,633.6	3,622.2	3,525.2	3,492.1	3,484.0
4.250					4,751.6	4,616.7	4,586.7	4,244.2	4,176.9	4,161.7	4,033.1	3,989.6	3,979.1
4.500					5,554.8	5,369.1	5,328.1	4,865.6	4,776.3	4,756.2	4,587.4	4,530.9	4,517.3
4.750					6,485.5	6,231.3	6,175.4	5,555.6	5,438.0	5,411.6	5,191.9	5,119.1	5,101.6
5.000					7,571.6	7,224.5	7,148.8	6,323.1	6,169.4	6,135.0	5,851.1	5,757.9	5,735.6
5.250					8,850.5	8,376.6	8,274.2	7,178.8	6,979.1	6,934.6	6,570.1	6,451.7	6,423.4
5.500						9,724.0	9,585.4	8,135.5	7,877.4	7,820.2	7,354.9	7,205.3	7,169.7
5.750								9,208.8	8,876.6	8,803.3	8,212.4	8,024.4	7,979.8
6.000								10,418	9,991.5	9,898.0	9,150.7	8,915.6	8,860.0
6.250								11,786	11,240	11,121	10,179	9,886.4	9,817.5
6.500								13,344	12,644	12,493	11,309	10,946	10,860
6.750									14,231	14,038	12,552	12,103	11,998
7.000									16,035	15,790	13,925	13,371	13,242
7.250											15,446	14,763	14,605
7.500											17,135	16,295	16,102
7.750											19,021	17,986	17,750
8.000												19,861	19,572
8.250												21,948	21,594

The center of the downstream tap hole shall be located eight times the published or actual inside diameter from the downstream face of the orifice plate. Figure 3-D-2 shows the allowable tolerances. A maximum beta ratio of 0.75 should be used in the design of new installations.

3–D.3.4.2 Fabrication

Meter tubes that use pipe taps shall have a hole of the proper size drilled through the pipe wall. Proper hole sizes are listed in Table 3-D-2. The hole shall not be threaded. A fitting

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
1.500	453.93	453.79										
1.625	533.28	533.09	532.94									
1.750	619.20	618.94	618.74									
1.875	711.75	711.41	711.14									
2.000	811.01	810.55	810.21	806.73	806.59	806.42						
2.125	917.03	916.45	916.01	911.54	911.37	911.15						
2.250	1,029.9	1,029.2	1,028.6	1,022.9	1,022.7	1,022.5						
2.375	1,149.7	1,148.8	1,148.1	1,141.0	1,140.7	1,140.4	1,136.8	1,136.5	1,136.3			
2.500	1,276.6	1,275.4	1,274.5	1,265.7	1,265.4	1,265.0	1,260.6	1,260.2	1,260.0			
2.625	1,410.5	1,409.1	1,408.0	1,397.2	1,396.8	1,396.3	1,390.9	1,390.5	1,390.2			
2.750	1,551.7	1,550.0	1,548.6	1,535.5	1,535.0	1,534.4	1,527.9	1,527.4	1,527.0			
2.875	1,700.2	1,698.1	1,696.5	1,680.7	1,680.1	1,679.4	1,671.6	1,670.9	1,670.5	1,663.7		
3.000	1,856.1	1,853.6	1,851.7	1,832.8	1,832.1	1,831.2	1,821.9	1,821.1	1,820.6	1,821.6	1,812.3	1,812.1
3.125	2,019.6	2,016.6	2,014.4	1,991.9	1,991.1	1,990.0	1,979.0	1,978.1	1,977.5	1,968.0	1,967.7	1,967.4
3.250	2,190.7	2,187.2	2,184.6	2,158.1	2,157.1	2,155.8	2,142.9	2,141.8	2,141.1	2,130.0	2,129.7	2,129.3
3.375	2,369.7	2,365.6	2,362.5	2,331.4	2,330.3	2,328.8	2,313.6	2,312.3	2,311.5	2,298.6	2,298.2	2,297.8
3.500	2,556.5	2,551.7	2,548.1	2,512.0	2,510.6	2,508.9	2,491.2	2,489.8	2,488.8	2,473.9	2,473.4	2,472.9
3.625	2,751.5	2,745.9	2,741.7	2,699.8	2,698.3	2,696.3	2,675.8	2,674.1	2,673.0	2,655.8	2,655.2	2,654.7
3.750	2,954.6	2,948.2	2,943.4	2,895.1	2,893.3	2,891.0	2,867.4	2,865.5	2,864.2	2,844.4	2,843.7	2,843.1
3.875	3,166.0	3,158.7	3,153.2	3,097.8	3,095.7	3,093.1	3,066.1	3,063.8	3,062.4	3,039.7	3,039.0	3,038.3
4.000	3,385.8	3,377.5	3,371.3	3,308.1	3,305.7	3,302.7	3,271.9	3,269.3	3,267.7	3,241.8	3,241.0	3,240.2
4.250	3,851.7	3,841.0	3,832.9	3,751.8	3,748.8	3,744.9	3,705.1	3,701.8	3,699.7	3,666.5	3,665.4	3,664.4
4.500	4,353.5	4,339.9	4,329.7	4,226.9	4,223.1	4,218.2	4,167.7	4,163.5	4,160.8	4,118.7	4,117.4	4,116.1
4.750	4,893.0	4,875.9	4,863.0	4,734.3	4,729.5	4,723.4	4,660.2	4,654.9	4,651.5	4,598.9	4,597.2	4,595.5
5.000	5,472.1	5,450.6	5,434.5	5,274.7	5,266.8	5,261.3	5,183.1	5,176.6	5,172.4	5,107.3	5,105.2	5,103.1
5.250	6,092.7	6,066.0	6,046.0	5,849.2	5,842.0	5,832.8	5,737.2	5,729.2	5,724.1	5,644.3	5,641.8	5,639.3
5.500	6,757.2	6,724.3	6,699.6	6,458.8	6,450.1	6,438.8	6,323.1	6,313.4	6,307.2	6,210.4	6,207.3	6,204.3
5.750	7,468.2	7,427.8	7,397.6	7,104.7	7,094.2	7,080.6	6,941.5	6,929.8	6,922.4	6,806.0	6,802.3	6,798.7
6.000	8,228.7	8,179.4	8,142.5	7,778.2	7,775.5	7,759.3	7,593.1	7,579.2	7,570.3	7,431.5	7,427.1	7,422.8
6.250	9,041.9	8,981.9	8,937.2	8,510.8	8,495.6	8,476.2	8,278.6	8,262.2	8,251.7	8,087.5	8,082.2	8,077.1
6.500	9,911.4	9,838.9	9,784.9	9,273.6	9,255.8	9,232.7	8,999.1	8,979.7	8,967.3	8,774.3	8,768.1	8,762.1
6.750	10,842	10,754	10,689	10,079	10,058	10,031	9,755.4	9,732.6	9,718.1	9,492.6	9,485.4	9,478.4
7.000	11,837	11,732	11,654	10,929	10,903	10,871	10,548	10,522	10,505	10,243	10,234	10,226
7.250	12,902	12,777	12,684	11,824	11,795	11,757	11,380	11,349	11,329	11,026	11,016	11,007
7.500	14,044	13,894	13,784	12,768	12,733	12,689	12,250	12,214	12,191	11,841	11,830	11,819
7.750	15,269	15,091	14,959	13,763	13,722	13,671	13,161	13,119	13,093	12,691	12,678	12,666
8.000	16,583	16,372	16,216	14,811	14,764	14,704	14,113	14,065	14,036	13,575	13,560	13,546

should be fastened to the pipe at this point, and great care must be exercised to ensure that the inside of the pipe is not distorted in any way.

The diameter of the tap hole shall not be reduced within a length equal to 2.5 times the tap hole diameter as measured from the inside surface of the meter tube. If the fitting is welded to the pipe used to fabricate the meter tube, the tap hole shall not be drilled until after the welding is done

In Table 3-D-2, the finished tap hole shall be ± $\frac{1}{64}$ inch from the selected nominal tap hole diameter along the drilled length of the hole.

3–D.4 Computing the Flow of Natural Gas and Other Related Hydrocarbon Fluids Through Orifice Meters Equipped With Pipe Taps

3–D.4.1 GENERAL

The recommendations in 3-D.4.2 through 3-D.4.8 concerning calculations and computations are confined strictly to pipe tap orifice meters installed and operated according to the provisions of this appendix. The equations use inch-pound units and absolute values

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
8.250	17,996	17,746	17,562	15,915	15,861	15,791	15,109	15,055	15,020	14,494	14,477	14,461
8.500	19,517	19,221	19,004	17,079	17,016	16,935	16,150	16,088	16,048	15,448	15,429	15,411
8.750	21,157	20,807	20,551	18,306	18,233	18,140	17,238	17,166	17,121	16,439	16,418	16,398
9.000	22,927	22,515	22,214	19,600	19,515	19,408	18,374	18,293	18,241	17,468	17,444	17,421
9.250	24,842	24,357	24,004	20,964	20,867	20,744	19,561	19,468	19,410	18,535	18,508	18,482
9.500	26,917	26,347	25,932	22,404	22,293	22,151	20,801	20,695	20,629	19,642	19,612	19,582
9.750	29,173	28,502	28,015	23,925	12,797	23,635	22,096	21,976	21,901	20,789	20,755	20,722
10.000	31,630	30,840	30,269	25,531	25,384	25,199	23,448	23,313	23,228	21,977	21,939	21,902
10.250	34,316	33,384	32,714	27,229	27,062	26,850	24,861	24,708	24,612	23,208	23,165	23,124
10.500		36,161	35,373	29,026	28,834	28,593	26,337	26,165	26,057	24,482	24,435	24,389
10.750				30,928	30,710	30,435	27,879	27,686	27,564	25,802	25,749	25,698
11.000				32,944	32,695	32,382	29,492	29,274	29,137	27,168	27,109	27,053
11.250				35,082	34,799	34,444	31,177	30,933	30,780	28,582	28,517	28,454
11.500				37,353	37,031	36,627	32,941	32,667	32,495	30,045	29,973	29,904
11.750				39,766	39,401	38,942	34,786	34,479	34,286	31,559	31,480	31,403
12.000				42,336	41,921	41,400	36,717	36,374	36,158	33,126	33,038	32,953
12.500				47,998	47,462	46,791	40,859	40,430	40,162	36,426	36,319	36,216
13.000				54,472	53,779	52,915	45,410	44,878	44,545	39,960	39,830	39,705
13.500							50,425	49,765	49,353	43,746	43,590	43,438
14.000							55,965	55,148	54,640	47,805	47,617	47,435
14.500							62,106	61,096	60,469	52,159	51,933	51,715
15.000							68,938	67,689	66,917	56,833	56,563	56,303
15.500							76,572	75,027	74,075	61,857	61,535	61,225
16.000								83,233	82,057	67,263	66,879	66,511
16.500										73,087	72,632	72,195
17.000										79,372	78,833	78,315
17.500										86,165	85,227	84,915
18.000										93,522	92,767	92,044
18.500										101,506	100,614	99,761
19.000										110,192	109,137	108,130
19.500										119,667	118,420	117,231
20.000										130,036	128,559	127,153

throughout. Constants and variables that have a subscript of 1 indicate upstream measurements; those that have a subscript of 2 indicate downstream measurements.

3-D.4.2 EQUATION

In the measurement of most gases, especially natural gas, the general practice is to express the flow rate in cubic feet per hour at some specified reference or base conditions of pressure and temperature (that is, in standard cubic feet per hour). To calculate the quantity of gas, the following equation shall be used:

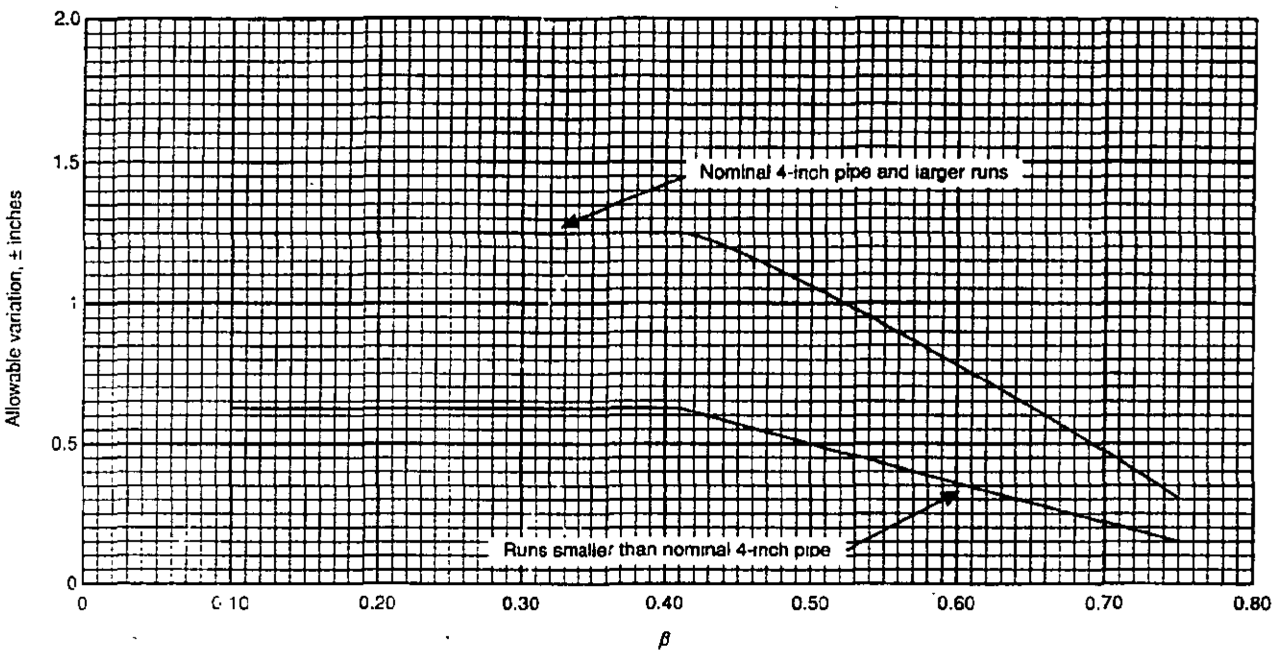
$$Q_v = C'\sqrt{h_w P_f} \qquad \text{(3-D-1)}$$

Where:

C' = orifice flow constant.
h_w = differential pressure at 60°F, in inches of water
P_f = static pressure, in pounds force per square inch absolute.
Q_v = volume flow rate at base conditions, in standard cubic feet per hour.

3-D.4.3 ORIFICE FLOW CONSTANT (C')

The orifice flow constant, C', is defined as the rate of airflow as a real gas, in standard cubic feet per hour, when the extension, $(h_w P_f)^{0.5}$, equals unity. The orifice flow constant



Note: A maximum β ratio of 0.75 should be used in the design of new installations.

Figure 3-D-2—Allowable Variations in Pressure Tap Hole Location

should not be confused with the flow coefficient or coefficient of discharge (K). The following equation is used to calculate the orifice flow constant:

$$C' = F_b F_r Y F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \tag{3-D-2}$$

Where.

F_b = basic orifice factor.
F_{gr} = real specific gravity (relative density) factor.
F_{pb} = base pressure factor.
F_{pv} = supercompressibility factor (from A.G.A. Transmission Measurement Committee Report No. 8).
F_r = Reynolds number factor.
F_{tb} = base temperature factor.
F_{tf} = flowing temperature factor.
Y = expansion factor

Table 3-D-2—Meter Tube Pressure Tap Holes (Dimensions in Inches)

Meter Tube Nominal Inside Diameter	Nominal Tap Hole Diameter		
	Recommended	Maximum	Minimum
<2	¼	¼	¼
2 or 3	¼	⅜	¼
≥4	⅜	½	¼

Note: The finished tap hole shall be ±1/64 inch from the selected nominal tap hole diameter along the drilled length of the hole.

The sequence of multiplication in Equation 2 is not binding; however, to duplicate the results obtained using Equation 2, the sequence of multiplication and the manner of rounding or truncation should be agreed upon and practiced. Trim factors to compensate for the type of instrumentation used, the calibration methods, and the elements of meter location are treated separately (see Appendix 3-A). These trim factors may be applied as a multiplier to C'.

The values of all the C' factors are detailed in subsequent sections of this appendix. Both equations and tabular data based on the equations are provided. The tables are to be used as an alternative to calculations by equations or to check computed results.

3–D.4.4 COEFFICIENTS OF DISCHARGE (K)

To calculate the coefficients of discharge, K, the following empirical equations are used:

$$K_o = \frac{K_e}{1 + \dfrac{15E}{1{,}000{,}000d}} \qquad \text{(3-D-3)}$$

Where

$$K_e = 0.5925 + \frac{0.0182}{D} + \left(0.44 - \frac{0.06}{D}\right)\beta^2 + \left(0.935 + \frac{0.225}{D}\right)\beta^5 + 1.35\beta^{14} + \frac{1.43}{\sqrt{D}}(0.25 - \beta)^{3/2} \qquad \text{(3-D-4)}$$

$$E = d(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + B) \qquad \text{(3-D-5)}$$

$$B = \frac{875}{D} + 75 \qquad \text{(3-D-6)}$$

Note: In Equation 3-D-4, the signs of some of the terms with fractional exponents become negative for some values of β. In such cases, these terms are to be neglected or their value treated as zero, and where these terms are a factor to another term, the whole product is to be treated as zero.

Where:

d = measured orifice diameter, in inches.
D = measured inside meter tube diameter, in inches
K_e = coefficient of discharge when Reynolds number is equal to $(1{,}000{,}000d)/15$.
K_o = coefficient of discharge when Reynolds number equals infinity, which will be the minimum value for any particular orifice and meter tube size.
β = beta ratio
= d/D

These values will be used in subsequent intermediate calculations of the orifice flow constant factors.

3–D.4.5 BASIC ORIFICE FACTOR (F_b)

To calculate the basic orifice factor, F_b, use the following equation and note the standard conditions:

$$F_b = 338.178d^2K_o \qquad \text{(3-D-7)}$$

When

P_b (base pressure) = 14.73 pounds force per square inch absolute
Specific gravity = 1.000
T_b (base temperature) = 60°F (519.67°R)

Table 3-D-1 was developed using Equation 3-D-7 and various combinations of d and D; to use it, however, the measured inside diameter (D) of the meter tube must be within the limits specified in 3-D.3.2 and Figure 3-D-1. Table 3-D-2 may not be interpolated.

3-D.4.6 REYNOLDS NUMBER FACTOR (F_r)

To calculate the Reynolds number factor, F_r, use the following equations:

$$F_r = 1 + \frac{E}{Re_d} \qquad \text{(3-D-8)}$$

$$Re_d = 220{,}858\, dF_{pv}\sqrt{\rho h_w} \times (0.613408 - 0.152756\beta + 0.803833\beta^2 - 1.701111\beta^3 + 1.569336\beta^4) \qquad \text{(3-D-9)}$$

$$\rho = \left(\frac{P_f}{14.7}\right)\left(\frac{491.67}{T_f}\right)G \qquad \text{(3-D-10)}$$

Where:

G = specific gravity.
Re_d = orifice bore Reynolds number.
T_f = absolute flowing temperature, in degrees Rankine.
ρ = specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F.

Table 3-D-3, which may not be interpolated, may be used to determine the value of b; this value may then be applied to Equation 3-D-11:

Table 3-D-3—b Values for Determining Reynolds Number Factor F_r for Pipe Taps (All Dimensions in Inches)

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 2 Inches			Published Inside Diameters at Nominal Pipe Size of 3 Inches				Published Inside Diameters at Nominal Pipe Size of 4 Inches			
	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.250	0.1106	0.1091	0.1087	0.1081	0.1078	0.1078	0.1079	0.1079	0.1081	0.1084	0.1085
0.375	0.0890	0.0878	0.0877	0.0879	0.0888	0.0898	0.0905	0.0908	0.0918	0.0932	0.0939
0.500	0.0758	0.0734	0.0729	0.0728	0.0737	0.0750	0.0758	0.0763	0.0778	0.0800	0.0810
0.625	0.0694	0.0647	0.0635	0.0624	0.0624	0.0634	0.0642	0.0646	0.0662	0.0685	0.0697
0.750	0.0676	0.0608	0.0586	0.0559	0.0546	0.0548	0.0552	0.0555	0.0568	0.0590	0.0602
0.875	0.0684	0.0602	0.0570	0.0528	0.0497	0.0488	0.0488	0.0489	0.0496	0.0513	0.0524
1.000	0.0702	0.0614	0.0576	0.0522	0.0473	0.0452	0.0445	0.0443	0.0443	0.0453	0.0461
1.125	0.0709	0.0635	0.0595	0.0532	0.0469	0.0435	0.0422	0.0417	0.0407	0.0408	0.0412
1.250		0.0650	0.0617	0.0552	0.0478	0.0434	0.0414	0.0406	0.0387	0.0376	0.0377
1.375			0.0629	0.0575	0.0496	0.0443	0.0418	0.0408	0.0379	0.0358	0.0353
1.500				0.0590	0.0518	0.0461	0.0431	0.0418	0.0382	0.0350	0.0341
1.625					0.0539	0.0482	0.0450	0.0435	0.0392	0.0351	0.0336
1.750					0.0554	0.0504	0.0471	0.0456	0.0408	0.0359	0.0340
1.875						0.0521	0.0492	0.0477	0.0427	0.0372	0.0349
2.000						0.0532	0.0508	0.0495	0.0448	0.0388	0.0363
2.125							0.0519	0.0509	0.0467	0.0407	0.0380
2.250									0.0483	0.0427	0.0398
2.375									0.0494	0.0445	0.0417
2.500										0.0461	0.0435
2.625										0.0472	0.0450
2.750											0.0462

Note: The b values are calculated from the following equation:

$$b = \frac{E}{12{,}835dK}$$

Where:

d = mean orifice diameter, in inches.
E = value from Equation 3-D-5
K = value approximated from Table 3-D-4.

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}} \qquad (3\text{-D-}11)$$

$$b = \frac{E}{12{,}835dK} \qquad (3\text{-D-}12)$$

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

	Published Inside Diameters at Nominal Pipe Size of 6 Inches				Published Inside Diameters at Nominal Pipe Size of 8 Inches			Published Inside Diameters at Nominal Pipe Size of 10 Inches			Published Inside Diameters at Nominal Pipe Size of 12 Inches		
Orifice Diameter	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.136	11.374	11.938	12.090
0.500	0.0850	0.0862	0.0883	0.0893									
0.625	0.0747	0.0762	0.0789	0.0802									
0.750	0.0655	0.0672	0.0703	0.0719									
0.875	0.0575	0.0592	0.0625	0.0642	0.0716	0.0730	0.0734						
1.000	0.0506	0.0523	0.0556	0.0573	0.0652	0.0668	0.0672	0.0728					
1.125	0.0448	0.0464	0.0495	0.0512	0.0593	0.0609	0.0613	0.0674	0.0691	0.0695			
1.250	0.0401	0.0414	0.0442	0.0458	0.0538	0.0555	0.0560	0.0624	0.0641	0.0646	0.0687	0.0704	0.0708
1.375	0.0363	0.0373	0.0397	0.0412	0.0489	0.0506	0.0511	0.0576	0.0594	0.0599	0.0643	0.0661	0.0666
1.500	0.0334	0.0341	0.0360	0.0372	0.0445	0.0462	0.0466	0.0532	0.0550	0.0555	0.0601	0.0620	0.0625
1.625	0.0313	0.0315	0.0329	0.0339	0.0405	0.0421	0.0425	0.0490	0.0509	0.0514	0.0561	0.0580	0.0585
1.750	0.0300	0.0298	0.0304	0.0311	0.0369	0.0384	0.0388	0.0452	0.0471	0.0476	0.0523	0.0543	0.0548
1.875	0.0293	0.0287	0.0285	0.0290	0.0338	0.0352	0.0355	0.0417	0.0436	0.0440	0.0488	0.0508	0.0513
2.000	0.0292	0.0281	0.0273	0.0273	0.0311	0.0323	0.0327	0.0385	0.0403	0.0407	0.0454	0.0475	0.0480
2.125	0.0297	0.0281	0.0265	0.0262	0.0288	0.0299	0.0301	0.0355	0.0373	0.0377	0.0423	0.0443	0.0449
2.250	0.0305	0.0285	0.0261	0.0256	0.0268	0.0277	0.0280	0.0329	0.0345	0.0349	0.0394	0.0414	0.0419
2.375	0.0316	0.0293	0.0262	0.0253	0.0252	0.0259	0.0261	0.0305	0.0320	0.0324	0.0367	0.0387	0.0392
2.500	0.0330	0.0304	0.0267	0.0254	0.0239	0.0244	0.0246	0.0283	0.0298	0.0301	0.0342	0.0361	0.0366
2.625	0.0345	0.0317	0.0274	0.0258	0.0230	0.0232	0.0233	0.0265	0.0277	0.0281	0.0319	0.0337	0.0342
2.750	0.0362	0.0332	0.0284	0.0265	0.0224	0.0224	0.0224	0.0248	0.0260	0.0263	0.0298	0.0316	0.0320
2.875	0.0379	0.0348	0.0295	0.0274	0.0220	0.0218	0.0218	0.0234	0.0244	0.0246	0.0279	0.0295	0.0300
3.000	0.0395	0.0364	0.0308	0.0285	0.0219	0.0214	0.0213	0.0222	0.0230	0.0233	0.0262	0.0277	0.0281
3.125	0.0410	0.0380	0.0323	0.0297	0.0220	0.0213	0.0211	0.0212	0.0218	0.0220	0.0246	0.0260	0.0264
3.250	0.0422	0.0394	0.0338	0.0311	0.0223	0.0214	0.0212	0.0205	0.0209	0.0210	0.0232	0.0245	0.0249
3.375	0.0433	0.0408	0.0353	0.0325	0.0228	0.0217	0.0214	0.0199	0.0201	0.0202	0.0220	0.0232	0.0235
3.500		0.0419	0.0367	0.0339	0.0235	0.0221	0.0218	0.0195	0.0195	0.0196	0.0210	0.0220	0.0223
3.625		0.0428	0.0381	0.0354	0.0243	0.0227	0.0224	0.0193	0.0191	0.0191	0.0200	0.0209	0.0212
3.750			0.0393	0.0367	0.0252	0.0234	0.0230	0.0192	0.0188	0.0188	0.0193	0.0200	0.0202
3.875			0.0404	0.0380	0.0262	0.0243	0.0238	0.0193	0.0187	0.0186	0.0187	0.0192	0.0194
4.000			0.0413	0.0391	0.0273	0.0252	0.0248	0.0195	0.0187	0.0186	0.0182	0.0185	0.0187
4.250					0.0297	0.0273	0.0268	0.0203	0.0192	0.0189	0.0176	0.0176	0.0177
4.500					0.0321	0.0296	0.0290	0.0215	0.0200	0.0197	0.0175	0.0172	0.0171
4.750					0.0344	0.0320	0.0314	0.0230	0.0212	0.0208	0.0178	0.0171	0.0170
5.000					0.0364	0.0342	0.0336	0.0248	0.0228	0.0223	0.0185	0.0175	0.0172
5.250					0.0381	0.0361	0.0356	0.0267	0.0245	0.0239	0.0195	0.0181	0.0178
5.500						0.0377	0.0373	0.0287	0.0263	0.0257	0.0207	0.0190	0.0186
5.750								0.0307	0.0282	0.0276	0.0221	0.0202	0.0197
6.000								0.0326	0.0302	0.0295	0.0236	0.0215	0.0210
6.250								0.0343	0.0320	0.0314	0.0253	0.0230	0.0224
6.500								0.0358	0.0336	0.0331	0.0270	0.0246	0.0240
6.750									0.0351	0.0346	0.0288	0.0262	0.0256
7.000									0.0363	0.0359	0.0304	0.0279	0.0272
7.250											0.0320	0.0295	0.0288
7.500											0.0334	0.0310	0.0304
7.750											0.0347	0.0325	0.0318
8.000												0.0338	0.0332
8.250												0.0349	0.0344

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
1.500	0.0697	0.0705										
1.625	0.0662	0.0670	0.0676									
1.750	0.0628	0.0636	0.0642									
1.875	0.0595	0.0603	0.0610									
2.000	0.0563	0.0571	0.0578	0.0663	0.0667	0.0672						
2.125	0.0532	0.0541	0.0548	0.0635	0.0639	0.0645						
2.250	0.0503	0.0512	0.0519	0.0609	0.0613	0.0618						
2.375	0.0475	0.0485	0.0492	0.0583	0.0588	0.0593	0.0658	0.0665	0.0669			
2.500	0.0449	0.0458	0.0466	0.0558	0.0562	0.0568	0.0635	0.0642	0.0646			
2.625	0.0424	0.0433	0.0441	0.0534	0.0538	0.0544	0.0613	0.0620	0.0624			
2.750	0.0400	0.0409	0.0417	0.0510	0.0515	0.0520	0.0591	0.0598	0.0603			
2.875	0.0378	0.0387	0.0394	0.0488	0.0492	0.0498	0.0570	0.0577	0.0582	0.0669		
3.000	0.0356	0.0365	0.0372	0.0466	0.0470	0.0476	0.0549	0.0556	0.0561	0.0650	0.0654	0.0657
3.125	0.0336	0.0345	0.0352	0.0445	0.0449	0.0455	0.0529	0.0536	0.0541	0.0632	0.0636	0.0639
3.250	0.0317	0.0326	0.0333	0.0425	0.0429	0.0435	0.0509	0.0517	0.0521	0.0615	0.0618	0.0622
3.375	0.0300	0.0308	0.0314	0.0405	0.0410	0.0416	0.0490	0.0497	0.0502	0.0597	0.0601	0.0604
3.500	0.0283	0.0291	0.0297	0.0387	0.0391	0.0397	0.0471	0.0479	0.0484	0.0580	0.0584	0.0587
3.625	0.0268	0.0275	0.0281	0.0369	0.0373	0.0379	0.0453	0.0461	0.0466	0.0563	0.0567	0.0571
3.750	0.0254	0.0261	0.0267	0.0352	0.0356	0.0362	0.0436	0.0444	0.0449	0.0547	0.0551	0.0554
3.875	0.0240	0.0247	0.0253	0.0336	0.0340	0.0346	0.0419	0.0427	0.0432	0.0530	0.0534	0.0538
4.000	0.0228	0.0235	0.0240	0.0320	0.0324	0.0330	0.0403	0.0411	0.0416	0.0515	0.0519	0.0523
4.250	0.0207	0.0213	0.0217	0.0291	0.0295	0.0301	0.0372	0.0380	0.0385	0.0484	0.0488	0.0492
4.500	0.0190	0.0194	0.0198	0.0265	0.0269	0.0274	0.0343	0.0351	0.0356	0.0455	0.0459	0.0463
4.750	0.0176	0.0180	0.0183	0.0242	0.0246	0.0250	0.0316	0.0324	0.0329	0.0427	0.0431	0.0435
5.000	0.0166	0.0168	0.0171	0.0221	0.0225	0.0229	0.0292	0.0299	0.0303	0.0401	0.0405	0.0409
5.250	0.0160	0.0161	0.0162	0.0203	0.0206	0.0210	0.0269	0.0276	0.0280	0.0376	0.0380	0.0384
5.500	0.0156	0.0156	0.0156	0.0188	0.0190	0.0194	0.0248	0.0255	0.0259	0.0352	0.0356	0.0360
5.750	0.0155	0.0154	0.0153	0.0175	0.0177	0.0180	0.0230	0.0236	0.0240	0.0330	0.0334	0.0338
6.000	0.0157	0.0154	0.0153	0.0164	0.0165	0.0168	0.0213	0.0218	0.0222	0.0309	0.0313	0.0317
6.250	0.0161	0.0157	0.0154	0.0155	0.0156	0.0158	0.0197	0.0203	0.0206	0.0289	0.0293	0.0297
6.500	0.0167	0.0162	0.0159	0.0148	0.0149	0.0151	0.0184	0.0189	0.0192	0.0271	0.0274	0.0278
6.750	0.0175	0.0169	0.0164	0.0144	0.0144	0.0145	0.0172	0.0176	0.0179	0.0253	0.0257	0.0261
7.000	0.0184	0.0177	0.0172	0.0141	0.0141	0.0141	0.0162	0.0166	0.0168	0.0237	0.0241	0.0244
7.250	0.0195	0.0187	0.0181	0.0140	0.0140	0.0139	0.0153	0.0156	0.0159	0.0223	0.0226	0.0229
7.500	0.0206	0.0198	0.019	0.0140	0.0140	0.0139	0.0146	0.0149	0.0150	0.0209	0.0212	0.0215
7.750	0.0219	0.0209	0.0202	0.0143	0.0141	0.0140	0.0140	0.0142	0.0144	0.0196	0.0199	0.0202
8.000	0.0232	0.0222	0.0214	0.0146	0.0144	0.0142	0.0136	0.0138	0.0139	0.0185	0.0187	0.0190

Table 3-D-4 must be used to determine the value of K in Equation 3-D-12. First-order linear interpolation of Table 3-D-4 is permissible. In calculating the extension for determinations of F_r, average or estimated values may be used.

3–D.4.7 EXPANSION FACTOR (Y)

3–D.4.7.1 Expansion Factor Based on Upstream Static Pressure (Y_1)

If the static pressure is measured at the upstream pressure tap, the calculations for the expansion factor, Y_1, use the following equations.

$$Y_1 = 1 - [0.333 + 1.145(\beta^2 + 0.7\beta^5 + 12\beta^{13})]\frac{x_1}{k} \qquad (3\text{-D-}13)$$

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
8.250	0.0246	0.0235	0.0227	0.0151	0.0149	0.0146	0.0133	0.0134	0.0135	0.0174	0.0177	0.0179
8.500	0.0260	0.0249	0.0240	0.0157	0.0154	0.0151	0.0132	0.0132	0.0132	0.0165	0.0167	0.0170
8.750	0.0273	0.0262	0.0253	0.0163	0.0160	0.0157	0.0131	0.0130	0.0130	0.0156	0.0158	0.0161
9.000	0.0286	0.0276	0.0267	0.0171	0.0168	0.0163	0.0131	0.0130	0.0130	0.0149	0.0151	0.0153
9.250	0.0299	0.0288	0.0280	0.0180	0.0176	0.0171	0.0133	0.0131	0.0130	0.0142	0.0144	0.0146
9.500	0.0311	0.0301	0.0292	0.0189	0.0185	0.0180	0.0136	0.0133	0.0132	0.0137	0.0138	0.0140
9.750	0.0322	0.0312	0.0304	0.0198	0.0194	0.0189	0.0139	0.0136	0.0134	0.0132	0.0133	0.0135
10.000	0.0332	0.0323	0.0315	0.0209	0.0204	0.0198	0.0143	0.0140	0.0138	0.0129	0.0129	0.0130
10.250	0.0341	0.0333	0.0326	0.0219	0.0214	0.0208	0.0149	0.0144	0.0142	0.0126	0.0126	0.0127
10.500		0.0341	0.0335	0.0230	0.0225	0.0219	0.0154	0.0150	0.0147	0.0123	0.0124	0.0124
10.750				0.0241	0.0236	0.0229	0.0161	0.0155	0.0152	0.0122	0.0122	0.0122
11.000				0.0252	0.0247	0.0240	0.0168	0.0162	0.0158	0.0121	0.0121	0.0121
11.250				0.0263	0.0258	0.0251	0.0175	0.0169	0.0165	0.0121	0.0121	0.0121
11.500				0.0273	0.0268	0.0261	0.0183	0.0176	0.0172	0.0122	0.0122	0.0121
11.750				0.0284	0.0278	0.0272	0.0191	0.0184	0.0180	0.0124	0.0123	0.0122
12.000				0.0293	0.0288	0.0282	0.0200	0.0192	0.0188	0.0126	0.0124	0.0123
12.500				0.0312	0.0307	0.0301	0.0218	0.0210	0.0205	0.0131	0.0130	0.0128
13.000				0.0327	0.0323	0.0318	0.0236	0.0228	0.0222	0.0139	0.0137	0.0135
13.500							0.0255	0.0246	0.0240	0.0148	0.0146	0.0143
14.000							0.0272	0.0264	0.0258	0.0159	0.0156	0.0153
14.500							0.0289	0.0280	0.0275	0.0172	0.0168	0.0165
15.000							0.0304	0.0296	0.0291	0.0185	0.0181	0.0177
15.500							0.0318	0.0311	0.0306	0.0199	0.0194	0.0191
16.000								0.0323	0.0319	0.0213	0.0209	0.0205
16.500										0.0228	0.0223	0.0219
17.000										0.0242	0.0238	0.0233
17.500										0.0257	0.0252	0.0248
18.000										0.0270	0.0266	0.0261
18.500										0.0283	0.0279	0.0275
19.000										0.0296	0.0292	0.0288
19.500										0.0307	0.0303	0.0299
20.000										0.0317	0.0313	0.0310

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\,P_{f_1}} \qquad \text{(3-D-14)}$$

Where:

k = ratio of specific heats, c_p/c_v (that is, the ratio of the specific heat of a gas at constant pressure to the specific heat of the gas at constant volume at standard conditions).

x_1/k = acoustic ratio.

Table 3-D-5 was developed using Equations 3-D-13 and 3-D-14 with a value of $k = 1.3$. First- or second-order linear interpolation of Table 3-D-5 is permissible.

The values of Y_1 are subject to an uncertainty varying from 0 when $x_1 = 0$ to ±0.5 percent when $x_1 = 0.2$. For larger values of x_1, a somewhat larger uncertainity can be expected. Equation 3-D-13 may be used over a range of $0.1 \leq \beta \leq 0.7$.

Table 3-D-4—Values of K to Be Used in Determining R_d for Calculation of F_r Factor

β	K (pipe)
0.100	0.607
0.125	0.608
0.150	0.611
0.175	0.614
0.200	0.618
0.225	0.623
0.250	0.628
0.275	0.634
0.300	0.641
0.325	0.650
0.350	0.658
0.375	0.668
0.400	0.680
0.425	0.692
0.450	0.707
0.475	0.724
0.500	0.742
0.525	0.763
0.550	0.785
0.575	0.810
0.600	0.837
0.625	0.869
0.650	0.904
0.675	0.943
0.700	0.988

3–D.4.7.2 Expansion Factor Based on Downstream Static Pressure (Y_2)

If the static pressure is measured at the downstream pressure tap, the calculations for the expansion factor, Y_2, use the following equations:

$$Y_2 = \sqrt{1 + x_2} - [0.333 + 1.145(\beta^2 + 0.7\beta^5 + 12\beta^{13})]\frac{x_2}{k\sqrt{1 + x_2}} \quad (3\text{-D-}15)$$

$$x_2 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\,P_{f_2}} \quad (3\text{-D-}16)$$

Table 3-D-6 was developed using Equations 3-D-15 and 3-D-16 with a value of $k = 1.3$. First- or second-order linear interpolation of Table 3-D-6 is permissible.

3–D.4.8 OTHER C' FACTORS

The remaining orifice flow constant C' factors (namely, F_{pb}, F_{tb}, F_{tf}, F_{gr}, and F_{pv}) are calculated exactly as described in the body of this standard. Computations using equations or tables are permissible with these factors when calculating the flow of natural gas through orifice meters equipped with pipe taps.

3–D.4.9 EXAMPLES

3–D.4.9.1 Example 1

Given the following physical parameters and flowing conditions, calculate the flow rate for a pipe tap orifice meter through one meter tube:

Tube diameter	2.067 in
Orifice diameter	1 in
Static pressure	500 psig (measured upstream)
Differential pressure	50 inches of water at 60°F

Base pressure	14.73 psia
Atmospheric pressure	14.7 psia (barometric)
Flowing temperature	100°F
Base temperature	60°F
Relative density (specific gravity)	0.600
Carbon dioxide	0.5 mole percent
Nitrogen	0.5 mole percent
Differential pressure device	Bellows (recorder, dry)

The solution is calculated as follows:

Diameter ratio (β) = 0.483793

Extension = 160.421

Basic orifice factor (F_b) = 243.279
(from Equations 3-D-3, 3-D-4, 3-D-5, 3-D-6, and 3-D-7; or Table 3-D-2)

Table 3-D-5—Expansion Factors for Pipe Taps (Y_1): Static Pressure Taken From Upstream Taps

	$\beta = d/D$										
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9990	0.9989	0.9988	0.9985	0.9984	0.9982	0.9981	0.9980	0.9979	0.9978	0.9977
0.2	0.9981	0.9979	0.9976	0.9971	0.9968	0.9964	0.9962	0.9961	0.9959	0.9957	0.9954
0.3	0.9971	0.9968	0.9964	0.9956	0.9952	0.9946	0.9944	0.9941	0.9938	0.9935	0.9931
0.4	0.9962	0.9958	0.9951	0.9942	0.9936	0.9928	0.9925	0.9921	0.9917	0.9913	0.9908
0.5	0.9952	0.9947	0.9939	0.9927	0.9919	0.9910	0.9906	0.9902	0.9897	0.9891	0.9885
0.6	0.9943	0.9937	0.9927	0.9913	0.9903	0.9892	0.9887	0.9882	0.9876	0.9870	0.9862
0.7	0.9933	0.9926	0.9915	0.9898	0.9887	0.9874	0.9869	0.9862	0.9856	0.9848	0.9840
0.8	0.9923	0.9916	0.9903	0.9883	0.9871	0.9857	0.9850	0.9843	0.9835	0.9826	0.9817
0.9	0.9914	0.9905	0.9891	0.9869	0.9855	0.9839	0.9831	0.9823	0.9814	0.9805	0.9794
1.0	0.9904	0.9895	0.9878	0.9854	0.9839	0.9821	0.9812	0.9803	0.9794	0.9783	0.9771
1.1	0.9895	0.9884	0.9866	0.9840	0.9823	0.9803	0.9794	0.9784	0.9773	0.9761	0.9748
1.2	0.9885	0.9874	0.9854	0.9825	0.9807	0.9785	0.9775	0.9764	0.9752	0.9739	0.9725
1.3	0.9876	0.9863	0.9842	0.9811	0.9791	0.9767	0.9756	0.9744	0.9732	0.9718	0.9702
1.4	0.9866	0.9853	0.9830	0.9796	0.9775	0.9749	0.9737	0.9725	0.9711	0.9696	0.9679
1.5	0.9857	0.9842	0.9818	0.9782	0.9758	0.9731	0.9719	0.9705	0.9690	0.9674	0.9656
1.6	0.9847	0.9832	0.9805	0.9767	0.9742	0.9713	0.9700	0.9685	0.9670	0.9652	0.9633
1.7	0.9837	0.9821	0.9793	0.9752	0.9726	0.9695	0.9681	0.9666	0.9649	0.9631	0.9610
1.8	0.9828	0.9811	0.9781	0.9738	0.9710	0.9677	0.9662	0.9646	0.9628	0.9609	0.9587
1.9	0.9818	0.9800	0.9769	0.9723	0.9694	0.9659	0.9643	0.9626	0.9608	0.9587	0.9565
2.0	0.9809	0.9790	0.9757	0.9709	0.9678	0.9641	0.9625	0.9607	0.9587	0.9566	0.9542
2.1	0.9799	0.9779	0.9745	0.9694	0.9662	0.9623	0.9606	0.9587	0.9566	0.9544	0.9519
2.2	0.9790	0.9768	0.9732	0.9680	0.9646	0.9605	0.9587	0.9567	0.9546	0.9522	0.9496
2.3	0.9780	0.9758	0.9720	0.9665	0.9630	0.9587	0.9568	0.9548	0.9525	0.9500	0.9473
2.4	0.9770	0.9747	0.9708	0.9650	0.9613	0.9570	0.9550	0.9528	0.9505	0.9479	0.9450
2.5	0.9761	0.9737	0.9696	0.9636	0.9597	0.9552	0.9531	0.9508	0.9484	0.9457	0.9427
2.6	0.9751	0.9726	0.9681	0.9621	0.9581	0.9534	0.9512	0.9489	0.9463	0.9435	0.9404
2.7	0.9742	0.9716	0.9672	0.9607	0.9565	0.9516	0.9493	0.9469	0.9443	0.9414	0.9381
2.8	0.9732	0.9705	0.9659	0.9592	0.9549	0.9198	0.9475	0.9449	0.9422	0.9392	0.9358
2.9	0.9723	0.9695	0.9647	0.9578	0.9533	0.9480	0.9456	0.9430	0.9401	0.9370	0.9335
3.0	0.9713	0.9684	0.9635	0.9563	0.9517	0.9462	0.9437	0.9410	0.9381	0.9348	0.9312
3.1	0.9704	0.9674	0.9623	0.9549	0.9501	0.9444	0.9418	0.9390	0.9360	0.9327	0.9290
3.2	0.9694	0.9663	0.9611	0.9534	0.9485	0.9426	0.9400	0.9371	0.9339	0.9305	0.9267
3.3	0.9684	0.9653	0.9599	0.9519	0.9469	0.9408	0.9381	0.9351	0.9319	0.9283	0.9244
3.4	0.9675	0.9642	0.9587	0.9505	0.9452	0.9390	0.9362	0.9331	0.9298	0.9261	0.9221
3.5	0.9665	0.9632	0.9574	0.9490	0.9436	0.9372	0.9343	0.9312	0.9277	0.9240	0.9198
3.6	0.9656	0.9621	0.9562	0.9476	0.9420	0.9354	0.9324	0.9292	0.9257	0.9218	0.9175
3.7	0.9646	0.9611	0.9550	0.9461	0.9404	0.9336	0.9306	0.9272	0.9236	0.9196	0.9152
3.8	0.9637	0.9600	0.9538	0.9447	0.9388	0.9318	0.9287	0.9253	0.9216	0.9175	0.9129
3.9	0.9627	0.9590	0.9526	0.9432	0.9372	0.9301	0.9263	0.9233	0.9195	0.9153	0.9106
4.0	0.9617	0.9579	0.9514	0.9417	0.9356	0.9283	0.9249	0.9213	0.9174	0.9131	0.9083

Table 3-D-5—Continued

	$\beta = d/D$									
h_w/P_{f_1}	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9976	0.9976	0.9975	0.9974	0.9973	0.9972	0.9971	0.9970	0.9969	0.9968
0.2	0.9953	0.9951	0.9950	0.9948	0.9947	0.9945	0.9943	0.9941	0.9938	0.9935
0.3	0.9929	0.9927	0.9925	0.9923	0.9920	0.9917	0.9914	0.9911	0.9907	0.9903
0.4	0.9906	0.9903	0.9900	0.9897	0.9893	0.9890	0.9986	0.9881	0.9876	0.9871
0.5	0.9882	0.9879	0.9875	0.9871	0.9867	0.9862	0.9857	0.9851	0.9845	0.9389
0.6	0.9859	0.9854	0.9850	0.9845	0.9840	0.9834	0.9828	0.9822	0.9814	0.9806
0.7	0.9835	0.9830	0.9825	0.9819	0.9813	0.9807	0.9800	0.9792	0.9784	0.9774
0.8	0.9811	0.9806	0.9800	0.9794	0.9787	0.9779	0.9771	0.9762	0.9753	0.9742
0.9	0.9788	0.9782	0.9775	0.9768	0.9760	0.9752	0.9742	0.9733	0.9722	0.9710
1.0	0.9764	0.9757	0.9750	0.9742	0.9733	0.9724	0.9714	0.9703	0.9691	0.9677
1.1	0.9741	0.9733	0.9725	0.9716	0.9707	0.9696	0.9685	0.9673	0.9660	0.9645
1.2	0.9717	0.9709	0.9700	0.9690	0.9680	0.9669	0.9657	0.9643	0.9629	0.9613
1.3	0.9694	0.9685	0.9675	0.9664	0.9653	0.9641	0.9628	0.9614	0.9598	0.9581
1.4	0.9670	0.9660	0.9650	0.9639	0.9627	0.9614	0.9599	0.9584	0.9567	0.9548
1.5	0.9646	0.9636	0.9625	0.9613	0.9600	0.9586	0.9571	0.9554	0.9536	0.9516
1.6	0.9623	0.9612	0.9600	0.9587	0.9573	0.9558	0.9542	0.9525	0.9505	0.9484
1.7	0.9599	0.9587	0.9575	0.9561	0.9547	0.9531	0.9514	0.9495	0.9474	0.9452
1.8	0.9576	0.9563	0.9550	0.9535	0.9520	0.9503	0.9485	0.9465	0.9443	0.9419
1.9	0.9552	0.9539	0.9525	0.9510	0.9493	0.9476	0.9456	0.9435	0.9412	0.9387
2.0	0.9529	0.9515	0.9500	0.9484	0.9467	0.9448	0.9428	0.9406	0.9381	0.9355
2.1	0.9505	0.9490	0.9475	0.9458	0.9440	0.9420	0.9399	0.9376	0.9351	0.9323
2.2	0.9481	0.9466	0.9450	0.9432	0.9413	0.9393	0.9371	0.9346	0.9320	0.9290
2.3	0.9458	0.9442	0.9425	0.9406	0.9387	0.9365	0.9342	0.9317	0.9289	0.9258
2.4	0.9434	0.9418	0.9400	0.9381	0.9360	0.9338	0.9313	0.9287	0.9258	0.9226
2.5	0.9411	0.9393	0.9375	0.9355	0.9333	0.9310	0.9285	0.9257	0.9227	0.9194
2.6	0.9387	0.9369	0.9350	0.9329	0.9307	0.9282	0.9256	0.9227	0.9196	0.9161
2.7	0.9364	0.9345	0.9325	0.9303	0.9280	0.9255	0.9227	0.9198	0.9165	0.9129
2.8	0.9340	0.9321	0.9300	0.9277	0.9253	0.9227	0.9199	0.9168	0.9134	0.9097
2.9	0.9316	0.9296	0.9275	0.9252	0.9227	0.9200	0.9170	0.9138	0.9103	0.9064
3.0	0.9293	0.9272	0.9250	0.9226	0.9200	0.9172	0.9142	0.9108	0.9072	0.9032
3.1	0.9269	0.9248	0.9225	0.9200	0.9173	0.9144	0.9113	0.9079	0.9041	0.9000
3.2	0.9246	0.9223	0.9200	0.9174	0.9147	0.9117	0.9084	0.9049	0.9010	0.8968
3.3	0.9222	0.9199	0.9175	0.9148	0.9120	0.9089	0.9056	0.9019	0.8979	0.8935
3.4	0.9199	0.9175	0.9150	0.9122	0.9093	0.9062	0.9027	0.8990	0.8948	0.8903
3.5	0.9175	0.9151	0.9125	0.9097	0.9067	0.9034	0.8999	0.8960	0.8918	0.8817
3.6	0.9151	0.9126	0.9100	0.9071	0.9040	0.9006	0.8970	0.8930	0.8887	0.8839
3.7	0.9128	0.9102	0.9075	0.9045	0.9013	0.8979	0.8941	0.8900	0.8856	0.8806
3.8	0.9104	0.9078	0.9050	0.9019	0.8987	0.8951	0.8913	0.8871	0.8825	0.8774
3.9	0.9081	0.9054	0.9025	0.8993	0.8960	0.8924	0.8884	0.8841	0.8794	0.8742
4.0	0.9057	0.9029	0.9000	0.8965	0.8933	0.8896	0.8856	0.8811	0.8763	0.8710

Reynolds number factor (F_r) = 1.0004
(from Equations 3-D-5, 3-D-8, 3-D-9, and 3-D-10; or Table 3-D-1 and Equation 3-D-11; or Table 3-D-3 and Equations 3-D-5, 3-D-11, and 3-D-12)
Expansion factor (Y_1) = 0.9983
(from Equations 3-D-13 and 3-D-14 or Table 3-D-4)
Base pressure factor (F_{pb}) = 1.0000
Base temperature factor (F_{tb}) = 1.0000
Flowing temperature factor (F_{tf}) = 0.9636
Relative density factor (F_{gr}) = 1.2910
Supercompressibility factor (F_{pv}) = 1.0299
Orifice flow constant (C') = 311.284
(from Equation 3-D-2)

Flow rate (Q_v) = 49.9367 MSCFH
= 1.19848 MMSCFD
(from Equation 3-D-1)

3-D.4.9.2 Example 2

Given the following physical parameters and flowing conditions, calculate the flow rate from a pipe tap orifice meter through one meter tube:

Tube diameter	10.020 in
Orifice diameter	4.5 in
Static pressure	350 psig (measured upstream)
Differential pressure	40 inches of water at 60°F
Base pressure	14.73 psia
Atmospheric pressure	14.7 psia (barometric)

Table 3-D-6—Expansion Factors for Pipe Taps (Y_2): Static Pressure Taken From Downstream Taps

	$\beta = d/D$										
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	1.0008	1.0008	1.0006	1.0003	1.0002	1.0000	0.9999	0.9998	0.9997	0.9996	0.9995
0.2	1.0017	1.0015	1.0012	1.0007	1.0004	1.0000	0.9999	0.9997	0.9995	0.9993	0.9990
0.3	1.0025	1.0023	1.0018	1.0010	1.0006	1.0000	0.9998	0.9995	0.9992	0.9989	0.9986
0.4	1.0034	1.0030	1.0024	1.0014	1.0008	1.0001	0.9997	0.9994	0.9990	0.9986	0.9981
0.5	1.0042	1.0038	1.0030	1.0018	1.0010	1.0001	0.9997	0.9992	0.9988	0.9982	0.9976
0.6	1.0051	1.0045	1.0036	1.0021	1.0012	1.0001	0.9996	0.9991	0.9985	0.9979	0.9972
0.7	1.0059	1.0053	1.0041	1.0025	1.0014	1.0002	0.9996	0.9990	0.9983	0.9975	0.9967
0.8	1.0068	1.0060	1.0047	1.0028	1.0016	1.0002	0.9995	0.9988	0.9980	0.9972	0.9962
0.9	1.0076	1.0068	1.0053	1.0032	1.0018	1.0002	0.9995	0.9987	0.9978	0.9969	0.9958
1.0	1.0085	1.0075	1.0059	1.0036	1.0021	1.0003	0.9994	0.9986	0.9976	0.9965	0.9954
1.1	1.0093	1.0083	1.0065	1.0039	1.0023	1.0003	0.9994	0.9984	0.9974	0.9962	0.9949
1.2	1.0102	1.0091	1.0071	1.0043	1.0025	1.0004	0.9994	0.9983	0.9972	0.9959	0.9945
1.3	1.0110	1.0098	1.0077	1.0047	1.0027	1.0004	0.9994	0.9982	0.9970	0.9956	0.9941
1.4	1.0119	1.0106	1.0083	1.0051	1.0030	1.0004	0.9993	0.9981	0.9968	0.9953	0.9936
1.5	1.0127	1.0113	1.0089	1.0054	1.0032	1.0005	0.9993	0.9980	0.9966	0.9950	0.9932
1.6	1.0136	1.0121	1.0096	1.0058	1.0034	1.0006	0.9993	0.9979	0.9964	0.9947	0.9928
1.7	1.0144	1.0128	1.0102	1.0062	1.0036	1.0006	0.9992	0.9978	0.9962	0.9944	0.9924
1.8	1.0153	1.0136	1.0108	1.0066	1.0039	1.0007	0.9992	0.9977	0.9960	0.9941	0.9920
1.9	1.0161	1.0144	1.0114	1.0070	1.0041	1.0008	0.9992	0.9976	0.9958	0.9938	0.9916
2.0	1.0170	1.0151	1.0120	1.0073	1.0044	1.0008	0.9992	0.9975	0.9956	0.9935	0.9912
2.1	1.0178	1.0159	1.0126	1.0077	1.0046	1.0009	0.9992	0.9974	0.9954	0.9932	0.9908
2.2	1.0187	1.0167	1.0132	1.0081	1.0048	1.0010	0.9992	0.9973	0.9952	0.9929	0.9904
2.3	1.0195	1.0174	1.0138	1.0085	1.0051	1.0010	0.9992	0.9972	0.9950	0.9927	0.9900
2.4	1.0204	1.0182	1.0144	1.0089	1.0053	1.0011	0.9992	0.9971	0.9949	0.9924	0.9896
2.5	1.0212	1.0189	1.0150	1.0093	1.0056	1.0012	0.9992	0.9971	0.9947	0.9921	0.9893
2.6	1.0221	1.0197	1.0156	1.0097	1.0058	1.0013	0.9992	0.9970	0.9945	0.9919	0.9889
2.7	1.0229	1.0205	1.0162	1.0101	1.0061	1.0014	0.9992	0.9969	0.9944	0.9916	0.9885
2.8	1.0238	1.0212	1.0169	1.0104	1.0063	1.0014	0.9992	0.9968	0.9942	0.9914	0.9882
2.9	1.0246	1.0220	1.0175	1.0108	1.0066	1.0015	0.9992	0.9968	0.9941	0.9911	0.9878
3.0	1.0255	1.0228	1.0181	1.0112	1.0068	1.0016	0.9993	0.9967	0.9939	0.9908	0.9874
3.1	1.0264	1.0235	1.0187	1.0116	1.0071	1.0017	0.9993	0.9966	0.9938	0.9906	0.9871
3.2	1.0272	1.0243	1.0193	1.0120	1.0074	1.0018	0.9993	0.9966	0.9936	0.9904	0.9867
3.3	1.0280	1.0250	1.0199	1.0124	1.0076	1.0019	0.9993	0.9965	0.9935	0.9901	0.9864
3.4	1.0289	1.0258	1.0206	1.0128	1.0079	1.0020	0.9994	0.9965	0.9933	0.9899	0.9860
3.5	1.0298	1.0266	1.0212	1.0133	1.0082	1.0021	0.9994	0.9964	0.9932	0.9896	0.9857
3.6	1.0306	1.0273	1.0218	1.0137	1.0084	1.0022	0.9994	0.9964	0.9931	0.9894	0.9854
3.7	1.0314	1.0281	1.0224	1.0141	1.0087	1.0024	0.9994	0.9963	0.9929	0.9892	0.9850
3.8	1.0323	1.0289	1.0230	1.0145	1.0090	1.0025	0.9995	0.9963	0.9928	0.9890	0.9847
3.9	1.0332	1.0296	1.0237	1.0149	1.0093	1.0026	0.9995	0.9963	0.9927	0.9888	0.9844
4.0	1.0340	1.0304	1.0243	1.0153	1.0095	1.0027	0.9996	0.9962	0.9926	0.9885	0.9840

Table 3-D-6—Continued

	$\beta = d/D$									
h_w/P_{f_1}	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9994	0.9994	0.9993	0.9992	0.9991	0.9990	0.9989	0.9988	0.9987	0.9986
0.2	0.9989	0.9988	0.9986	0.9985	0.9983	0.9981	0.9979	0.9977	0.9974	0.9972
0.3	0.9984	0.9982	0.9979	0.9977	0.9974	0.9972	0.9969	0.9965	0.9962	0.9958
0.4	0.9978	0.9976	0.9972	0.9969	0.9966	0.9962	0.9958	0.9954	0.9949	0.9944
0.5	0.9973	0.9970	0.9966	0.9962	0.9958	0.9953	0.9948	0.9942	0.9936	0.9930
0.6	0.9968	0.9964	0.9959	0.9954	0.9949	0.9944	0.9938	0.9931	0.9924	0.9916
0.7	0.9962	0.9958	0.9953	0.9947	0.9941	0.9935	0.9928	0.9920	0.9912	0.9902
0.8	0.9957	0.9952	0.9946	0.9940	0.9933	0.9926	0.9918	0.9909	0.9899	0.9889
0.9	0.9952	0.9946	0.9940	0.9932	0.9925	0.9917	0.9908	0.9898	0.9887	0.9875
1.0	0.9947	0.9940	0.9933	0.9925	0.9917	0.9908	0.9898	0.9887	0.9875	0.9862
1.1	0.9942	0.9935	0.9927	0.9918	0.9909	0.9899	0.9888	0.9876	0.9863	0.9848
1.2	0.9937	0.9929	0.9920	0.9911	0.9901	0.9890	0.9878	0.9865	0.9851	0.9835
1.3	0.9932	0.9924	0.9914	0.9904	0.9893	0.9881	0.9868	0.9854	0.9839	0.9822
1.4	0.9928	0.9918	0.9908	0.9897	0.9885	0.9872	0.9859	0.9844	0.9827	0.9809
1.5	0.9923	0.9912	0.9902	0.9890	0.9877	0.9864	0.9849	0.9833	0.9815	0.9796
1.6	0.9918	0.9907	0.9896	0.9883	0.9870	0.9855	0.9840	0.9822	0.9804	0.9783
1.7	0.9913	0.9902	0.9889	0.9876	0.9862	0.9847	0.9830	0.9812	0.9792	0.9770
1.8	0.9908	0.9896	0.9883	0.9870	0.9854	0.9838	0.9821	0.9801	0.9780	0.9757
1.9	0.9904	0.9891	0.9877	0.9863	0.9847	0.9830	0.9811	0.9791	0.9769	0.9744
2.0	0.9899	0.9886	0.9872	0.9856	0.9840	0.9822	0.9802	0.9781	0.9757	0.9732
2.1	0.9895	0.9881	0.9866	0.9849	0.9832	0.9813	0.9793	0.9770	0.9746	0.9719
2.2	0.9890	0.9876	0.9860	0.9843	0.9825	0.9805	0.9784	0.9760	0.9734	0.9706
2.3	0.9886	0.9870	0.9854	0.9836	0.9817	0.9797	0.9774	0.9750	0.9723	0.9694
2.4	0.9881	0.9865	0.9948	0.9830	0.9810	0.9789	0.9765	0.9740	0.9712	0.9681
2.5	0.9877	0.9860	0.9842	0.9823	0.9803	0.9780	0.9756	0.9730	0.9701	0.9669
2.6	0.9873	0.9855	0.9837	0.9817	0.9796	0.9772	0.9747	0.9720	0.9690	0.9657
2.7	0.9868	0.9850	0.9831	0.9811	0.9788	0.9764	0.9738	0.9710	0.9679	0.9644
2.8	0.9864	0.9846	0.9826	0.9804	0.9781	0.9757	0.9730	0.9700	0.9668	0.9632
2.9	0.9860	0.9841	0.9820	0.9798	0.9774	0.9749	0.9721	0.9690	0.9657	0.9620
3.0	0.9856	0.9836	0.9815	0.9792	0.9767	0.9741	0.9712	0.9681	0.9646	0.9608
3.1	0.9852	0.9831	0.9809	0.9786	0.9760	0.9733	0.9703	0.9671	0.9635	0.9596
3.2	0.9848	0.9826	0.9804	0.9780	0.9754	0.9725	0.9695	0.9661	0.9625	0.9584
3.3	0.9843	0.9822	0.9798	0.9774	0.9747	0.9718	0.9686	0.9652	0.9614	0.9572
3.4	0.9839	0.9817	0.9793	0.9768	0.9740	0.9710	0.9678	0.9642	0.9603	0.9561
3.5	0.9835	0.9812	0.9788	0.9762	0.9733	0.9702	0.9669	0.9633	0.9593	0.9549
3.6	0.9832	0.9808	0.9783	0.9756	0.9727	0.9695	0.9661	0.9623	0.9582	0.9537
3.7	0.9828	0.9803	0.9778	0.9750	0.9720	0.9688	0.9652	0.9614	0.9572	0.9526
3.8	0.9824	0.9799	0.9772	0.9744	0.9713	0.9680	0.9644	0.9605	0.9562	0.9514
3.9	0.9820	0.9794	0.9767	0.9738	0.9707	0.9673	0.9636	0.9596	0.9551	0.9503
4.0	0.9816	0.9790	0.9762	0.9732	0.9700	0.9665	0.9628	0.9586	0.9541	0.9491

Flowing temperature	60°F
Base temperature	60°F
Relative density (specific gravity)	0.620
Carbon dioxide	2 mole percent
Nitrogen	3 mole percent
Differential pressure device	Bellows (recorder, dry)

The solution is calculated as follows:

Diameter ratio (β) = 0.449102
Extension = 120.781
Basic orifice factor (F_b) = 4776.30
Reynolds number factor (F_r) = 1.0002
Expansion factor (Y_1) = 0.9982
Base pressure factor (F_{pb}) = 1.0000

Base temperature factor (F_{tb}) = 1.0000
Flowing temperature factor (F_{tf}) = 1.0000
Relative density factor (F_{gr}) = 1.2700
Supercompressibility factor (F_{pv}) = 1.0273
Orifice flow constant (C') = 6221.53
Flow rate (Q_v) = 751.441 MSCFH
= 18.0346 MMSCFD

3–D.4.10 ADJUSTMENTS FOR INSTRUMENTATION CALIBRATION AND USE

Other multiplying factors may be applied to the orifice flow constant, C', as a function of the type of instrumentation applied, the method of calibration, the meter environment, or any combination of these. These factors are discussed in the body of the standard and in other appendixes to the standard. These factors are calculated and applied independently of tap type. With these factors, the orifice flow rate is calculated using the following equation:

$$Q_v = C' F_{hg} F_a F_{am} F_{wl} F_{wt} F_{pwl} F_{hgm} F_{hgt} \sqrt{h_w P_f} \quad (3\text{-D-}17)$$

Where:

F_{hg} = mercury manometer factor (formerly F_m).
F_a = orifice thermal expansion factor.
F_{am} = correction for air over water in a water manometer during differential instrument calibration.
F_{wl} = local gravitational correction for water column calibration.
F_{wt} = water density correction (temperature or composition) for water column calibration.
F_{pwl} = local gravitational correction for deadweight tester static pressure calibration.
F_{hgm} = correction for gas column in a mercury manometer.
F_{hgt} = mercury manometer span correction for instrument temperature change after calibration.

APPENDIX 3-E—SI CONVERSIONS

This appendix contains tables of SI conversions that are pertinent to the information in this part of Chapter 14, Section 3. For additional information on SI units, refer to Chapter 15.

Table 3-E-1—Volume Reference Conditions for Custody Transfer Operations: Natural Gas Volume

Common Reference Conditions (ft³) Pressure (psia)	Temperature (°F)	To Convert From ft³ to m³, Multiply by	m³ to ft³, Multiply by
14.4	60	0.02769321	36.10994
14.65	60	0.02817399	35.49373
14.696	60	0.02826245	35.38263
14.7	60	0.02827015	35.37300
14.73	60	0.02832784	35.30096
14.7347	60	0.02833688	35.28970
14.735	60	0.02833746	35.28898
14.9	60	0.02865478	34.89819
15.025	60	0.02889517	34.60786

Note: The following standard conditions were used for inch-pound units—a temperature of 60°F and a pressure of 14.73 pounds per square inch absolute. The following standard conditions were used for SI units—a temperature of 15°C and an absolute pressure of 101.325 kPa. The following values were assumed: 1 ft = 0.3048 m; 1 psi = 6.894757 kPa. The following methodology was used to obtain the conversion factors:

$$\left(\frac{\text{ft}^3}{\text{m}^3}\right)\left(\frac{T_{rep}}{T_{st}}\right)\left(\frac{P_{st}}{P_{rep}}\right) = \text{factor}$$

Table 3-E-2—Energy Reference Conditions

Unit	Used in	Definition	To Convert Btu to J, Multiply by
Btu_{IT}	International steam tables	1 Btu/lbm = 2326 J/kg	1055.056

Table 3-E-3—Heating Value Reference Conditions

Reference Conditions (ft³) Pressure (psia)	Temperature (°F)	To Convert From Btu_{IT}/ft³ to MJ/m³, Multiply by
14.4	60	0.03809801
14.65	60	0.03744787
14.696	60	0.03733066
14.7	60	0.03732050
14.73	60	0.03724449
14.7347	60	0.03723261
14.735	60	0.03723185
14.9	60	0.03681955
15.025	60	0.03651323

Note: The following standard conditions were used for inch-pound units—a temperature of 60°F and a pressure of 14.73 pounds per square inch absolute. The following standard conditions were used for SI units—a temperature of 15°C and an absolute pressure of 101.325 kPa. The following values were assumed: 1 ft = 0.3048 m; 1 psi = 6.894757 kPa; 1 Btu_{IT} = 1055.056 J. The following methodology was used to obtain the conversion factors:

$$\left(\frac{\text{J}}{\text{Btu}}\right)\left(\frac{\text{MJ}}{1 \times 10^6\ \text{J}}\right)\left(\frac{\text{ft}^3}{\text{m}^3}\right)\left(\frac{T_{rep}}{T_{st}}\right)\left(\frac{P_{st}}{P_{rep}}\right) = \text{factor}$$

APPENDIX F—HEATING VALUE CALCULATION

3–F.1 General

Heating value is a gas property evaluated on a per-unit mass basis (H_m). This property is technically termed an "ideal property" (H_m^{id}). From a practical standpoint, in mass measurement there is no difference between the "ideal" and the "real." The value is converted to a heating value per cubic foot (*HV*) using the following relationships. The more common convention has been applied in this appendix.

$$HV = H_m \frac{\rho_b^{id}}{Z_b} = H_m \rho_b \qquad (3\text{-F-1})$$

The value of *HV* is used as a factor in calculating the energy flow rate, or the total energy passing through the flow meter. *HV* is also used for product specifications.

It is also convenient to define the following:

$$HV = \frac{H_v^{id}}{Z_b} \qquad (3\text{-F-2})$$

3–F.2 Heating Value Symbols

Symbol	Description	Units
H_m	Heating value per pound mass	Btu/lbm
H_m^{id}	Ideal heating value per pound mass	Btu/lbm
H_v^{id}	Ideal heating value per cubic foot	Btu/ft³
HV	Gross heating value	Btu/ft³
Mr_i	Molar mass of component	lbm/lb-mol
P_b	Base pressure	lbf/in² (abs)
P_f	Flowing pressure (upstream tap)	lbf/in² (abs)
P_v	Vapor pressure of water	lbf/in² (abs)
°R	Absolute temperature	—
T_b	Base temperature	°R
Z_b	Gas compressibility at base conditions (P_b, T_b)	—
ρ_b	Density at base conditions (P_b, T_b)	lbm/ft³
ρ_b^{id}	Ideal density at base conditions	lbm/ft³
ϕ	Mole fraction	%/100
ϕ	Mole fraction water	%/100

3–F.3 Heating Value

The gross heating value is an ideal gas property based on the ideal reaction:

$$\text{Fuel}^{id} + O_2^{id} \rightarrow CO_2^{id} + H_2O_l + SO_2^{id} \qquad (3\text{-F-3})$$

Where,

Superscript id = ideal gas.
Subscript l = liquid.

(Each fuel requires different stoichiometric coefficients.) This gross ideal heating value includes the energy obtained from the condensation of the water vapor (formed by the ideal reaction expressed in the equation) to the liquid phase.

It should be noted that the gross heating value is expressed per unit (pound mass or cubic foot) of dry gas. Although water is a product of combustion, it is not indicated on the left-hand side of Equation 3-F-3 as either the fuel or the oxygen; water is a result, not a part, of the reaction.

Heating value may be determined directly by a calorimeter, either on line or from a sample cylinder. Heating value may also be calculated from gas analysis.

3–F.4 Physical Properties

Table 3-F-1 lists physical properties of many of the compounds present in natural gas in various hydrocarbon mixtures. The data in Table 3-F-1 have been adjusted to base or standard conditions, as defined in 3.2.3.4.

Table 3-F-1 provides the best currently available data on physical properties and is taken from GPA 2145-91. These data are subject to modification yearly as additional research is accomplished. Future revisions to GPA 2145 may include updated values. The values of the most recent edition of GPA 2145 should be used. The user of the GPA tables is cautioned that the information presented in them is calculated from different base conditions and that conversion is required when the information is used with Part 3 (see 3.5.2).

3–F.5 Heating Value Determined on a Volume Basis

A calculation of a mixture's gross ideal heating value, using H_v values from Table 3-F-1 and using mole fractions of the gas composition, involves determining the heating value per unit volume of real gas. *HV* can be determined by using Equation 3-F-2 and the following relationship:

Table 3-F-1—Physical Properties of Gases at Exactly 14.73 Pounds Force per Square Inch Absolute and 60°F (See Note 1)

Compound	Formula	*Mr* (Note 2)	P_c (psia) (Note 3)	T_c (°R) (Note 3)	G_i (Note 4)	Ideal Density (lbm/ft³) (Note 5)	Viscosity (cp) (Note 6)	Thermal Energy H_m^{id} (Btu/lbm) (Note 7)	 H_v^{id} (Btu/ft³) (Note 7)
Hydrogen	H_2	2.0159	187.5	59.36	0.06960	0.00532	0.00871	61,025	324.9
Helium	He	4.0026	32.9	9.34	0.13820	0.01057	0.01927	0	0
Water	H_2O	18.0153	3,200.1	1,164.85	0.62202	0.04758		1,059.8	50.4
Carbon monoxide	CO	28.010	507.5	239.26	0.96711	0.07398	0.01725	4,342.4	321.3
Nitrogen	N_2	28.0134	493.1	227.16	0.96723	0.07399	0.01735	0	0
Oxygen	O_2	31.9988	731.4	278.24	1.10484	0.08452	0.02006	0	0
Hydrogen sulfide	H_2S	34.08	1306	672.12	1.17669	0.09001	0.01240	7,094.2	638.6
Argon	Ar	39.948	710.4	271.55	1.37930	0.10551	0.02201	0	0
Carbon dioxide	CO_2	44.010	1,071.0	547.42	1.51955	0.11624	0.01439	0	0
Air (Note 8)		28.9625	546.9	238.36	1.00000	0.07650	0.01790	0	0
Methane	CH_4	16.043	667.0	343.00	0.55392	0.04237	0.01078	23,891	1,012.3
Ethane	C_2H_6	30.070	707.8	549.76	1.03824	0.07942	0.00901	22,333	1,773.7
Propane	C_3H_8	44.097	615.0	665.64	1.52256	0.11647	0.00788	21,653	2,521.9
iso-Butane	C_4H_{10}	58.123	527.9	734.13	2.00684	0.15351	0.00732	21,232	3,259.4
n-Butane	C_4H_{10}	58.123	548.8	765.25	2.00684	0.15351	0.00724	21,300	3,269.8
iso-Pentane	C_5H_{12}	72.150	490.4	828.70	2.49115	0.19057		21,043	4,010.2
n-Pentane	C_5H_{12}	72.150	488.1	845.44	2.49115	0.19057		21,085	4,018.2
n-Hexane	C_6H_{14}	86.177	439.5	911.47	2.97547	0.22762		20,943	4,766.9
n-Heptane	C_7H_{16}	100.204	397.4	970.57	3.45978	0.26466		20,839	5,515.2
n-Octane	C_8H_{18}	114.231	361.1	1,017.67	3.94410	0.30172		20,759	6,263.4
n-Nonane	C_9H_{20}	128.258	330.7	1,070.57	4.42842	0.33876		20,701	7,012.7
n-Decane	$C_{10}H_{22}$	142.285	304.6	1,111.87	4.91273	0.37581		20,651	7,760.8

Notes

1. The source for the data in this table is Gas Processors Association 2145-91. The accuracy of the experimental numbers is estimated to be 1 in 1000; the additional figures are for calculation consistency
2. The following molecular weights were used. C = 12.011; H = 1.00794, O = 15.9994; N = 14.0067; and S = 32.06 (1979).
3. The data in these columns come from the Thermodynamics Research Center, Texas A&M University, IUPAC and National Bureau of Standards selections.
4. The ideal relative density is the ratio of the molecular weight of the gas to that of air (Mr/Mr_a).
5. Ideal density = 0.0026413*Mr* at 60°F and 14.73 pounds force per square inch absolute
6. The data in this column are from N. B. Vargaftik, *Tables on Thermodynamic Properties of Liquids and Gases* (2nd ed.), New York, Wiley, 1975.
7. See Equation 3-F-3. Depending on the fuel, the reaction has various stoichiometric coefficients. The H_m^{id} column comes from data, whereas the H_v^{id} comes from multiplying H_m^{id} by the ideal gas density. The ideal energy released as heat is H_m^{id} multiplied by the real gas flow rate (in cubic feet per hour) divided by Z. Water has gross values for H_m^{id} and H_v^{id} (the ideal enthalpy of condensation)
8. The data in this row are from F. E. Jones, *National Bureau of Standards Journal of Research*, 1978, Volume 83, p. 491.

$$H_v^{id} = \phi_1(H_{mi}^{id})_1 + \phi_2(H_{mi}^{id})_2 + \ldots + \phi_n(H_{mi}^{id})_n \tag{3-F-4}$$

Or

$$H_v^{id} = \sum_{i=1}^{n} \phi_i(H_{mi}^{id})_i \tag{3-F-5}$$

When

$$HV = \frac{H_v^{id}}{Z_b} \tag{3-F-2}$$

Where:

ϕ = mole fraction (percent/100).

3–F.6 Heating Value Determined on a Mass Basis

The question of compressibility factor disappears when the ideal heating value per pound mass is used with the mass flow rate. The following equation is applicable for using H_{mi} and Mr values from Table 3-F-1 to calculate the heating value:

$$H_m^{id} = \frac{\phi_1 Mr_1(H_{mi}^{id})_1 + \phi_2 Mr_2(H_{mi}^{id})_2 + \ldots + \phi_n Mr_n(H_{mi}^{id})_n}{\phi_1 Mr_1 + \phi_2 Mr_2 + \ldots + \phi_n Mr_n} \tag{3-F-6}$$

Or

$$H_m^{id} = \frac{\sum_{i=1}^{n} \phi_i Mr_i(H_{mi}^{id})_i}{\sum_{i=1}^{n} \phi_i Mr_i} \tag{3-F-7}$$

The result from Equation 3-F-7 can be converted to the gross heating value per cubic foot of real gas at base conditions by using Equation 3-F-1:

$$HV = H_{mi}^{id}\frac{\rho_b^{id}}{Z_b} = H_{mi}^{id}\rho_b$$

3–F.7 Heating Value of a Natural Gas Mixture Containing Water

To define heating value on a dry basis for gas containing water, the relationships in Equations 3-F-1 and 3-F-2 are valid if the mole fractions of the components are corrected for water content by using Equation 3-F-8 and the compressibility (Z) reflects the water content:

$$\phi_{i,wet} = \phi_i(1 - \phi_w) \tag{3-F-8}$$

Where the gas is water saturated under flowing conditions, Raoult's law may be used to estimate the mole fraction of water:

$$\phi_w = \frac{P_v}{P_f} \tag{3-F-9}$$

Where:

P_v = absolute vapor pressure of water at flowing conditions or T_f.

Therefore,

$$\phi_{i,wet} = \phi_i\left(1 - \frac{P_v}{P_f}\right) \tag{3-F-10}$$

APPENDIX G—DEVELOPMENT OF CONSTANTS FOR FLOW EQUATIONS

3–G.1 General

The practical orifice flow equation used in Part 3 is given in Part 1 of this standard as Equation 1-2:

$$q_m = N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P} \qquad (1\text{-}2)$$

Where:

$C_d(FT)$ = coefficient of discharge at a specific pipe Reynolds number for a flange-tapped orifice meter.
d = orifice plate bore diameter calculated at flowing temperature.
ΔP = orifice differential pressure.
E_v = velocity of approach factor.
q_m = mass flow rate.
$\rho_{t,p}$ = density of fluid at flowing conditions (P_f, T_f).

And

N_1 = factor that incorporates the "constants" from Equation 1-1 and the required numeric conversions, including the following:

$\dfrac{3.14159}{4}$ = constant in Equation 1-1.
$\sqrt{2(32.1740)}$ = constant in Equation 1-1.
$\sqrt{\dfrac{62.3663}{12}}$ = converts differential pressure (ΔP) from pounds force per square foot to inches of water at 60°F.
$\dfrac{1}{12^2}$ = converts the diameter of the orifice bore (d) from feet to inches

Therefore,

$$N_1 = \left(\frac{3.14159}{4}\right)\sqrt{2(32.1740)}\sqrt{\frac{62.3663}{12}}\left(\frac{1}{12^2}\right)$$
$$= 0.0997424$$

(This is shown as the factor for U.S. units in Part 1, Table 1-2.)

Note: Some numeric constants do not have absolute values (for example, π and e.). To express six significant digits accurately, the values were computed using double precision (16 significant digits). The results were then rounded to the values shown. In this appendix, for ease of understanding, the computations are shown to only six significant digits.

Mass flow can be modified to provide volume units by dividing the mass by the density at base conditions:

$$q_v = \frac{q_m}{\rho_b}$$

Where

q_m = mass flow rate, in pounds mass per second.
q_v = volume flow rate at base conditions, in cubic feet per second.
ρ_b = density at base conditions, in pounds mass per cubic foot.

3–G.2 Symbols and Units

3–G.2.1 GENERAL

Some of the symbols and units listed below are specific to Appendix 3-B and were developed based on the customary inch-pound system of units. Regular conversion factors can

be used where applicable; however, if SI units are used, the more generic equations in Part 1 should be used for consistent results.

3–G.2.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
$C_d(FT)$	Coefficient of discharge at a specified pipe Reynolds number for flanged-tapped orifice meter	—
d	Orifice plate bore diameter calculated at flowing temperature, T_f	in
D	Meter tube internal diameter calculated at flowing temperature, T_f	in
E_v	Velocity of approach factor	—
°F	Temperature, in degrees Fahrenheit	—
°R	Temperature, in degrees Rankine	459.67 + °F
F_n	Numeric conversion factor (see Appendix 3-B)	—
g_c	Gravitational constant	32.1740 (lbm-ft)/(lbf-sec^2)
G_i	Ideal gas relative density (specific gravity)	—
G_r	Real gas relative density (specific gravity)	—
h_w	Orifice differential pressure	inches of water column at 60°F
N_1	Numeric conversion factor (see Part 1)	—
P	Pressure	lbf/in^2 (abs)
P_b	Base pressure	lbf/in^2 (abs)
P_{f_1}	Flowing pressure (upstream tap)	lbf/in^2 (abs)
P_s	Standard pressure	14.73 lbf/in^2 (abs)
Q_m	Mass flow rate per hour	lbm/hr
Q_v	Volume flow rate per hour at standard (base) conditions	ft^3/hr
R	Universal gas constant	1545.35 (lbf-ft)/(lb-mol-°R)
T	Temperature	°R
T_b	Base temperature	°R
T_f	Flowing temperature	°R
T_s	Standard temperature	519.67°R
Y_1	Expansion factor (upstream tap)	—
Z_b	Compressibility at base conditions	—
$Z_{b_{air}}$	Compressibility of air at 14.73 psia and 60°F	0.999590
Z_{f_1}	Compressibility at upstream flowing conditions	—
Z_s	Compressibility at standard conditions (P_s, T_s)	—
β	Ratio of orifice plate bore diameter to meter tube internal diameter (d/D) calculated at flowing temperature, T_f	—
π	Universal constant	3.14159
ρ_b	Gas density at base conditions (P_b, T_b, and Z_b)	lbm/ft^3
$\rho_{b_{air}}$	Density of air at base conditions (P_b, T_b, and Z_b)	lbm/ft^3
$\rho_{t,p}$	Density at flowing conditions (P_f, T_f, and Z_f)	lbm/ft^3
ρ_{t,p_1}	Density at flowing conditions (P_{f_1}, T_f, and Z_{f_1})	lbm/ft^3

3–G.3 General Numeric Constant for Mass Flow

Equation 3-1 expresses flow in pounds mass per hour (Q_m) rather than pounds mass per second (q_m) and requires an additional factor, 3600, to convert from seconds to hours.

Therefore, in Equation 3-1,

$$\begin{aligned} N_1 &= 0.0997424(3600) \\ &= 359.072 \end{aligned}$$

And

$$Q_m = 359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w} \qquad (3\text{-}1)$$

Equation 3-4a is Equation 3-1 divided by ρ_b, as described above. The numeric constant is the same.

$$Q_b = \frac{359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_b} \qquad (3\text{-}4a)$$

3–G.4 Numeric Constant for Mass Flow Developed From Ideal Gas Relative Density

Equation 3-2 substitutes Equation 3-55 for ρ_{t,p_1} in Equation 3-1.

$$Q_m = 359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} G_i (28.9625)(144) h_w}{Z_{f_1} R T_f}}$$

Where:

28.9625 = molecular weight of dry air.
1545.35 = universal gas constant (R).
144 = factor to convert pressure from pounds force per square foot to pounds force per square inch.

In Equation 3-2, therefore,

$$\begin{aligned} N_1 &= 359.072 \sqrt{28.9625\left(\frac{144}{1545.35}\right)} \\ &= 589.885 \end{aligned}$$

And

$$Q_m = 589.885 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{G_i P_{f_1} h_w}{Z_{f_1} T_f}} \qquad (3\text{-}2)$$

3–G.5 Numeric Constant for Mass Flow Developed From Real Gas Relative Density

Equation 3-3 substitutes G_r for G_i in Equation 3-2 through the use of Equation 3-48:

$$Q_m = 589.885 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{Z_b G_r P_{f_1} h_w}{Z_{b_{air}} Z_{f_1} T_f}}$$

And for standard conditions,

$$Z_b = Z_{b_{air}} = 0.999590 \text{ at } 14.73 \text{ psia and } 519.67°\text{R } (60°\text{F})$$

In Equation 3-3, therefore,

$$\begin{aligned} N_1 &= \frac{589.885}{\sqrt{0.999590}} \\ &= 590.006 \end{aligned}$$

And

$$Q_m = 590.006 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{Z_s G_r P_{f_1} h_w}{Z_{f_1} T_f}} \qquad (3\text{-}3)$$

3–G.6 Numeric Constant for Base Volume Developed From Ideal Gas Relative Density

The constant 359.072 in Equation 3-4a was developed in 3-G.3. Equation 3-5a substitutes Equation 3-55 for ρ_{t,p_1} and Equation 3-56 for ρ_b in Equation 3-4a.

$$Q_b = \frac{359.072C_d(FT)E_vY_1d^2\sqrt{\rho_{t,p_1}h_w}}{\rho_b} \tag{3-4a}$$

$$Q_b = 359.072C_d(FT)E_vY_1d^2\sqrt{\frac{P_{f_1}G_i(28.9625)(144)h_w}{Z_{f_1}RT_f}}\sqrt{\frac{Z_bRT_b}{P_bG_i(28.9625)(144)}}$$

Where:

1545.35 = universal gas constant (R).

28.9625 = molecular weight of dry air.

144 = factor to convert flowing pressure (P_{f_1}) from pounds force per square foot to pounds force per square inch.

144 = factor to convert base pressure (P_b) from pounds force per square foot to pounds force per square inch.

In Equation 3-5a, therefore,

$$\begin{aligned} N &= \frac{359.072\sqrt{1545.35\left(\frac{144}{28.9625}\right)}}{144} \\ &= 218.573 \end{aligned}$$

And

$$Q_b = 218.573C_d(FT)E_vY_1d^2\frac{T_bZ_b}{P_b}\sqrt{\frac{P_{f_1}h_w}{G_iZ_{f_1}T_f}} \tag{3-5a}$$

For the following standard conditions:

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ lbf/in}^2 \text{ (abs)} \\ T_b &= T_s \\ &= 519.67°\text{R } (60°\text{F}) \\ Z_b &= Z_s \\ &= \text{compressibility of the gas at } P_s \text{ and } T_s \end{aligned}$$

In Equation 3-5b,

$$\begin{aligned} N_1 &= 218.573\left(\frac{519.67}{14.73}\right) \\ &= 7711.19 \end{aligned}$$

Therefore,

$$Q_s = 7711.19C_d(FT)E_vY_1d^2Z_s\sqrt{\frac{P_{f_1}h_w}{G_iZ_{f_1}T_f}} \tag{3-5b}$$

3–G.7 Numeric Constant for Base Volume Developed From Real Gas Relative Density

Equation 3-6a substitutes G_r for G_i in Equation 3-5a through the use of Equation 3-48. The inclusion of ρ_b moves this correction to the numerator:

$$Q_b = 218.573 C_d(\text{FT}) E_v Y_1 d^2 \frac{T_b}{P_b} \sqrt{\frac{Z_b Z_{b_{air}} P_{f_1} h_w}{G_r Z_{f_1} T_f}}$$

In Equation 3-6a, therefore,

$$N_1 = 218.573$$

For the following standard conditions:

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ lbf/in}^2 \text{ (abs)} \\ T_b &= T_s \\ &= 519.67°\text{R } (60°\text{F}) \\ Z_{b_{air}} &= Z_{s_{air}} \\ &= 0.999590 \end{aligned}$$

In Equation 3-6b,

$$\begin{aligned} N_1 &= 218.573\left(\frac{519.67}{14.73}\right)\sqrt{0.999590} \\ &= 7709.61 \end{aligned}$$

$$Q_v = 7709.61 C_d(\text{FT}) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \quad (3\text{-}6b)$$

3–G.8 Numeric Constant for Standard Volume Developed From Real Gas Relative Density

In Appendix 3-B, F_n, as expressed in Equation 3-B-5, includes additional numeric ratios, as stated in Equation 3-B-1, including the following:

519.67 = base temperature at 60°F, expressed in degrees Rankine.

$\frac{1}{14.73}$ = base pressure of 14.73 pounds force per square inch absolute.

$\sqrt{\frac{1}{519.67}}$ = flowing temperature at 60°F, expressed in degrees Rankine.

$\sqrt{0.999590}$ = compressibility of air at the base pressure of 14.73 pounds force per square inch absolute and the base temperature of 519.57°R.

In Equation 3-B-5, therefore,

$$\begin{aligned} N_1 &= 218.573\left(\frac{519.67}{14.73}\right)\sqrt{\frac{1}{519.67}} \\ &= 338.196 \end{aligned}$$

And

$$F_n = 338.196 E_v d^2 \quad (3\text{-}B\text{-}5a)$$

Or

$$F_n = 338.196 E_v D^2 \beta^2 \quad (3\text{-}B\text{-}5b)$$

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Section 8—Liquefied Petroleum Gas Measurement

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SECTION 8—LIQUEFIED PETROLEUM GAS MEASUREMENT

14.8.0 Scope and Purpose

This publication describes dynamic and static metering systems used to measure liquefied petroleum gas in the density range of 0.30 to 0.70 grams per cubic centimetre. The physical properties of the components to be measured and the mixture composition of liquefied petroleum gas should be reviewed to determine the measurement system to be used. Various systems and methods can be used in metering the product, and mutual agreement on the system and method between the contracting parties is required.

This publication does not endorse or advocate the preferential use of any specific type of meter or metering system. Further, this publication is not intended to restrict the future development of meters or measuring devices nor to in any way affect metering equipment already installed and in operation.

This publication serves as a guide in the selection, installation, operation, and maintenance of measuring systems applicable to liquefied petroleum gases and includes functional descriptions for individual systems.

14.8.1 Application

This publication does not set tolerances or accuracy limits. The application of the information here should be adequate to achieve acceptable measurement performance using good measurement practices, while in addition considering user requirements and applicable codes and regulations.

Systems for measuring liquefied petroleum gases use either volumetric or mass determination methods, and both methods apply to either static or dynamic conditions.

Volumetric methods of measurement are generally used where physical property changes in temperature and pressure are known and correction factors can be applied to correct the measurement to standard conditions.[1] Volumetric measurement is applicable to most pure components and many commercial product grades.

Mass determination methods of measurement are most commonly used where conditions in addition to temperature and pressure will affect the measurement. Such conditions include compositional changes, intermolecular adhesion, and volumetric changes caused by solution mixing. Mass measurement is applicable to liquefied petroleum gas mixtures where accurate physical correction factors have not been determined and in some manufacturing processes for a mass balance.

Many of the measurement procedures pertaining to the measurement of other products are applicable to the measurement of liquefied petroleum gases. However, certain characteristics of liquefied petroleum gas require extra precautions to improve measurement accuracy.

Liquefied petroleum gas will remain in the liquid state only if a pressure sufficiently greater than the equilibrium vapor pressure is maintained (see Chapters 5.3 and 6.6). In liquid meter systems, adequate pressure must be maintained to prevent vaporization caused by pressure drops attributed to piping, valves, and meter tubes. When liquefied

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[1] Standard temperature is 60°F in the English (or customary) system and 15°C in the International System of Units (SI). Standard pressure is the vapor pressure at 60°F (15°C) or 14.696 pounds per square inch absolute (101.325 kilopascals), whichever is higher. This is not the same pressure base standard as that used for gas

petroleum gas is stored in tanks or containers, a portion of the liquid will vaporize and fill the space above the liquid. The amount vaporized will be related to the temperature and the equilibrium constant for the mixture of components.

Liquefied petroleum gas is more compressible and has a greater coefficient of thermal expansion than the heavier hydrocarbons. The application of appropriate compressibility and temperature correction factors is required to correct measurements to standard conditions, except when measurement for mass determination is from density and volume at metering temperatures and pressures.

Meters should be proven on each product at or near the normal operating temperature and pressure. Should the product or operating conditions change so that a significant change in the meter factor occurs, the meter should be proven again according to Chapters 4 and 5.

14.8.2 Referenced Publications

To the extent specified in the text, the latest edition or revision of the following standards and publications form a part of this publication.

API

Manual of Petroleum Measurement Standards

Chapter 2, "Tank Calibration" (in preparation)
Chapter 4, "Proving Systems"
Chapter 5.2, "Measurement of Liquid Hydrocarbons by Positive Displacement Meter"
Chapter 5.3, "Turbine Meters"
Chapter 5.4, "Instrumentation or Accessory Equipment for Liquid Hydrocarbon Metering Systems"
Chapter 6.6, "Pipeline Metering Systems"
Chapter 9.1, "Hydrometer Test Method for Density, Relative Density, or API Gravity of Crude Petroleum and Liquid Petroleum Products"
Chapter 11.1, "Volume Correction Factors"
Chapter 12.2, "Calculation of Liquid Petroleum Quantities Measured by Turbine or Displacement Meters"
Chapter 14.1, "Measuring, Sampling, Testing, and Base Conditions for Natural Gas Fluids"
Chapter 14.3, "Orifice Metering of Natural Gas"
Chapter 14.4, (in preparation)
Chapter 14.6, "Installing and Proving Density Meters"
Chapter 14.7, (in preparation)

ASTM[2]

DS 4A *Physical Constants of Hydrocarbons C_1 to C_{10}*

GPA[3]

2140 *Liquefied Petroleum Gas Specifications and Test Methods* (ASTM D 1265; ANSI Z11.91)
2145 *Physical Constants for the Paraffin Hydrocarbons and Other Components of Natural Gas*
2165 *Method for Analysis of Natural Gas Liquid Mixtures by Gas Chromatography*
2174 *Method for Obtaining Hydrocarbon Fluid Samples Using a Floating Piston Cylinder*

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[2] American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103.
[3] Gas Processors Association, 1812 First Place, Tulsa, Oklahoma 74103.

2177	*Tentative Method for the Analysis of Demethanized Hydrocarbon Liquid Mixtures Containing Nitrogen and Carbon Dioxide by Gas Chromatography*
2261	*Method of Analysis for Natural Gas and Similar Gaseous Mixtures by Gas Chromatography*
8173	*A Standard for Converting Natural Gas Liquids and Vapors to Equivalent Liquid Volumes*

GPSA[4]
Engineering Data Book

14.8.3 Requirements for All Measurement Methods

The following general requirements apply to dynamic measurement systems using either volumetric or mass determination methods of measuring liquefied petroleum gases.

14.8.3.1 PROVISIONS TO ENSURE THAT FLUIDS ARE IN THE LIQUID PHASE

Provisions shall be made to ensure that liquefied petroleum gas measurement conditions of temperature and pressure will be adequate to keep the fluid totally in the liquid phase. Measurement in the liquid phase must occur at a pressure at least 1.25 times the equilibrium vapor pressure at measurement temperature, plus twice the pressure drop across the meter at maximum operating flow rate, or at a pressure 125 pounds per square inch higher than the vapor pressure at a maximum operating temperature, whichever is lower (see Chapters 5.3 and 6.6).

14.8.3.2 ELIMINATION OF SWIRL

To prevent swirl through the measuring device when using turbine or orifice meters, straightening vanes or adequate unrestricted straight lengths of piping should be used in the upstream and downstream metering tube.

14.8.3.3 TEMPERATURE MEASUREMENT

Temperature measurements, where required, should be made at a point that indicates conditions in the measuring device. The accuracy of instruments and the type of measurement used are specified in Chapters 5.2, 5.3, 5.4, and 14.6.

14.8.3.4 PRESSURE MEASUREMENT

Pressure measurements, where required, should be made at a point that will be responsive to varying pressure conditions in the measuring device. The accuracy of instruments and the type of measurement used should be as described in Chapters 5.2 and 14.6.

14.8.3.5 DENSITY OR RELATIVE DENSITY MEASUREMENT

The point for measurement of density or relative density (specific gravity) of the liquid should be sensitive to varying conditions in the measuring device. Densities to be used for mass measurement determination must be obtained at the same flowing conditions that exist at the meter. The accuracy of instruments and the type of measurement used should be as described in Chapters 9 and 14.6.

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[4] Gas Processors Suppliers Association; Order from Gas Processors Association, 1812 First Place, Tulsa, Oklahoma 74103

14.8.3.6 LOCATION OF MEASURING AND SAMPLING EQUIPMENT

Measuring and sampling equipment must be located to minimize or eliminate the influence of pulsation or mechanical vibration caused by pump or control valve generated noise. Special precautions should be taken to minimize or eliminate the effects of electrical interference that may be induced in the flow meter pick-up coil circuit.

14.8.4 Volumetric Determination in Dynamic Systems

Measurement of liquefied petroleum gas (liquid phase) in a dynamic condition can be performed using several measurement devices. The use of a specific type of measuring device is dependent upon mutual agreement between the contracting parties.

14.8.4.1 MEASUREMENT BY ORIFICE METER

Measurement of liquefied petroleum gases by orifice meter shall conform to Chapter 14.3, using orifice and line internal diameter ratios and appropriate coefficients for flow as agreed upon between the parties. Location factors, F_l, and orifice thermal expansion factor, F_a, should be used where applicable according to the procedure in Chapter 14.3, Appendix B.14 and B.15 respectively. Manometer factors, F_m, must be calculated according to the procedure in this section for recorders utilizing mercury manometers. (F_m = 1.000 for bellows type differential pressure instruments.)

Measurement of liquefied petroleum gas having a high vapor pressure is simplified where deliveries are obtained in mass units, by multiplying the volume at flowing conditions times the density or relative density (measured within prescribed limits at the same flowing temperature and pressure that exists at the meter) times an appropriate constant. Calculation of the volume at standard conditions can then be made using 14.8.6 or GPA Standard 8173.

The following equations can be used to determine flow rate:

1. Flow rate in cubic feet per hour at flowing conditions

$$Q_f = 0.134452\, F_b F_r Y\, F_m F_a F_l \sqrt{\frac{h_w}{G_f}}$$

$$Q_f = 1.0618\, F_b F_r Y\, F_m F_a F_l \sqrt{\frac{h_w}{\rho_f}}$$

2. Flow rate in pounds mass per hour.

$$Q_m = 8.3853\; F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, G_f}$$

$$Q_m = 1.0618\; F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, \rho_f}$$

3. Flow rate in cubic feet per hour at base conditions.

$$Q_b = \frac{0.134452}{G_b} F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, G_f}$$

$$Q_b = \frac{1.0618}{\rho_b} F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, \rho_f}$$

Where

F_b = basic orifice factor from Chapter 14.3 ($F_b = 338.17\, d^2 K_o$).

F_m = manometer factor for mercury manometers only.
Y = expansion factor, calculated using a specific heat ratio for flowing conditions as determined from data or an equation of state.
F_r = Reynolds number factor.

The Reynolds number factor may be calculated using b values from Table 5 or Table 9 of Chapter 14.3. CAUTION: Do not use the equations for F_r in Tables 5 or 9, but use the b values only in the following equations to obtain the Reynolds number factor

$$F_r = 1 + \frac{b\ 8{,}423\mu_{pfs}}{\sqrt{h_w\ \rho_f}} = 1 + \frac{b\ 1{,}067\mu_{pfs}}{\sqrt{h_w\ G_f}}$$

$$F_r = 1 + \frac{b\ 271{,}000\mu_c}{\sqrt{h_w\ \rho_f}} = 1 + \frac{b\ 34{,}316\mu_c}{\sqrt{h_w\ G_f}}$$

$$F_r = 1 + \frac{b\ 5.66\mu_{cp}}{\sqrt{h_w\ \rho_f}} = 1 + \frac{b\ 0.7167\mu_{cp}}{\sqrt{h_w\ G_f}}$$

$$b = \frac{E}{12{,}835dK}$$

The Reynolds number factor also may be calculated from the following:

$$F_r = 1 + E/R_d$$

Where:

$$R_d = \frac{V_f d\rho}{12\mu_{pfs}}$$

d = diameter of orifice, in inches.
ρ = density, in pounds per cubic foot.
V_f = velocity of jet in orifice, in feet per second.
μ_{pfs} = absolute viscosity, in pounds per foot per second.

$$R_d = \frac{2{,}267.8\ dK\sqrt{h_w\rho_f}}{\mu_{cp}} = \frac{17{,}909\ dK\sqrt{h_w\ G_f}}{\mu_{cp}}$$

$$R_d = \frac{0.04736\ dK\sqrt{h_w\rho_f}}{\mu_c} = \frac{0.37405\ dK\sqrt{h_w\ G_f}}{\mu_c}$$

$$R_d = \frac{1.5238\ dK\sqrt{h_w\rho_f}}{\mu_{pfs}} = \frac{12.034\ dK\sqrt{h_w\ G_f}}{\mu_{pfs}}$$

R_d can also be determined by trial and error as follows: Set F_r = 1.000 in the flow equation to get an approximate Q_m or Q_b, and use this result to calculate F_r. With this calculated value of F_r, obtain a new value of F_r and of Q_m or Q_b. Repeat this process until the value of Q_m or Q_b is within the limits desired.

$$R_d = R_D/\beta$$

$$R_D = \frac{6.30\ Q_m}{D\mu_{cp}} = \frac{294.30\ Q_b G_b}{D\mu_{cp}}$$

$$R_D = \frac{0.0001319\ Q_m}{D\mu_c} = \frac{0.004244\ Q_m}{D\mu_{pfs}}$$

$$F_r = 1 + \frac{0.1582\beta\, E\, D\mu_{cp}}{Q_m} = 1 + \frac{0.002539\beta\, E\, D\mu_{cp}}{Q_b G_b}$$

$$F_r = 1 + \frac{7581.5\beta\, E\, D\mu_{e}}{Q_m} = 1 + \frac{235.63\beta\, E\, D\mu_{pfs}}{Q_m}$$

Where:

μ_{pfs} = absolute viscosity, in pounds per foot per second. = $g\mu_e$
μ_e = absolute viscosity, in pounds per square foot per second.
μ_{cp} = absolute viscosity, in centipoises.
μ_e = $0.03108\mu_{pfs} = 0.00002089\mu_{cp}$.
ρ_b = density of liquid, in pounds per cubic foot at base conditions.
ρ_f = density of liquid, in pounds per cubic foot at flowing temperature and pressure.
D = diameter (inside) of meter tube, in inches.
d = diameter of orifice bore, in inches.
β = d/D (commonly called the beta ratio).
G_f = relative density at flowing conditions. Ratio of the density of the liquid at flowing conditions to the density of water at 60°F. (The U.S. National Bureau of Standards has established 0.999012 gram per cubic centimetre as the density of air-free pure water in a vacuum at a temperature of 60°F and a pressure of 14.696 pounds per square inch and standard gravitational acceleration of 980.665 centimetres per second per second.)
G_b = relative density of liquid at base conditions.
K = coefficient of discharge for a sharp edge orifice.
K = $K_o\,(1 + E/R_d)$

$$K_o = \frac{K_e}{1 + \dfrac{15E}{1{,}000{,}000d}}$$

Where:

K_o = coefficient of discharge for infinite Reynolds number.
K_e = coefficient of discharge when the Reynolds number is equal to

$$\frac{1{,}000{,}000d}{15}.$$

$$E = d\left(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + \frac{520}{\sqrt{D}}\right), \quad \text{for flange taps}$$

$$E = d\left(905 - 5000\beta + 9000\beta^2 - 4200\beta^3 + \frac{875}{D}\right), \quad \text{for pipe taps.}$$

For flange taps

$$K_e = 0.5993 + \left[0.364 - \frac{0.076}{\sqrt{D}}\right]\beta^4 + 0.4\left[1.6 - \frac{1}{D}\right]^5 \left[\left(0.07 - \frac{0.5}{D}\right) - \beta\right]^{2.5}$$

$$- \left[0.009 + \frac{0.034}{D}\right]\left[0.5 - \beta\right]^{1.5} + \left[\frac{65}{D^2} + 3\right]\left[\beta - 0.7\right]^{2.5} + \frac{0.007}{D}$$

For pipe taps

$$K_e = 0.5925 + \frac{0.0182}{D} + \left[0.440 - \frac{0.06}{D}\right]\beta^2 + \left[0.935 + \frac{0.225}{D}\right]\beta^5$$

$$+ 1.35\ \beta^{14} + \frac{1.43}{\sqrt{D}}\ (0.25 - \beta)^{2.5}$$

NOTE: When any of the terms in K_e is negative, that term is set equal to zero.

F_l = location factor.

The location factor is used to correct for the change in specific weight of (a) the mercury in mercury manometer type differential gages, (b) the calibrating liquid in the test manometer, and (c) the weights for a deadweight gage used in calibrating the instruments. See Chapter 14.3, Appendix B, B. 34 for equations.

F_m = manometer factor

The manometer factor is required only in mercury manometer type gages to correct for the error in differential pressure indication caused by the weight of the liquid column above the mercury and the change in the density of the mercury at temperatures other than the base temperature of 60°F.

$$F_m = 0.034374\ \sqrt{\rho_m - \rho_l}$$

Where:

ρ_m = density of mercury at ambient temperature, in pounds per cubic foot.

ρ_m = $846.324\ [1 - 0.000101(T_a - 60)]$

T_a = ambient temperature, in degrees Fahrenheit.

ρ_l = density of liquid on mercury at ambient temperature, in pounds per cubic foot. See Chapter 11.1, Tables 6, for density correction.

F_a = orifice thermal expansion factor.

This factor is used to correct for the error resulting from the expansion or contraction of the orifice bore at operating temperatures different from the temperature of the plate when bored, usually assumed to be 68°F.

F_a = 1 + 0.0000185 (°F − 68) for Type 304 and 316 stainless steels.

F_a = 1 + 0.0000159 (°F − 68) for Monel.

14.8.4.2 MEASUREMENT BY POSITIVE DISPLACEMENT METER

The manufacturer's recommendations should be carefully considered in sizing turbine and positive displacement meters (see Chapters 5.2 and 5.3).

Air eliminators should be used with caution, particularly where the line in which they are installed could be shut-in occasionally, and where complete vaporization could occur

Vapor formation, resulting from the effects of ambient temperature or heat tracing on the line ahead of the meter, could cause inaccuracies and damage, which are most likely to be encountered during startup Caution must be exercised.

14.8.4.2.1 Volume at Standard or Base Conditions

Liquid measurement by positive displacement meters should conform to the procedures in Chapter 5.2. Appropriate correction factors should be used to adjust the measured volume to standard conditions by correcting for temperature, pressure, and meter factor. Factors to be applied will be found in Chapters 11 and 12.

The positive displacement measurement equation is:

$$V_b = V_f \times \text{M.F.} \times C_{tl} \times C_{pl}$$

Where:

V_b = volume at base or standard conditions.
V_f = volume at flowing conditions, indicated by a measuring device.
M.F. = meter factor, obtained by proving the meter according to Chapters 4 and 12.2.
C_{tl} = correction factor for temperature to correct the volume at flowing temperature to standard temperature. See Chapter 11.1, Tables 24, or other agreed-upon tables.
C_{pl} = correction factor for pressure to correct the volume at flowing pressure to standard conditions. See Chapter 11.1, Tables 24, or other agreed-upon tables.

14.8.4.2.2 Volume at Flowing Conditions for Mass Determination

The volume measured at flowing conditions (V_m) times the meter factor equals the volume at flowing conditions. Displacement meters used for volumetric measurement in deriving total mass shall conform to the standards described in Chapter 5.2 for the service intended. Temperature or pressure compensation devices are not to be used on these meters and the accessories used shall conform to Chapter 5.4.

14.8.4.3 MEASUREMENT BY TURBINE METER

See 14.8.4.2 for cautions about air eliminators and vapor formation in lines. Also carefully consider the manufacturer's recommendations about sizing of meters.

Liquid measurement by turbine meter should conform to the procedures described in Chapter 5.3. Appropriate correction factors should be used that will adjust the measured volume to standard conditions by correcting for temperature, pressure, and meter factor. Factors to be applied will be found in Chapters 4, 11, and 12.

The following equation is used when measuring by turbine meter.

$$V_b = V_f \times \text{M.F} \times C_{tl} \times C_{pl}$$

Where:

V_b = volume at base or standard conditions.
V_f = volume at flowing conditions, indicated by a measuring device.
M.F. = meter factor, obtained by proving the meter according to Chapters 4 and 12.2.
C_{tl} = correction factor for temperature to correct the volume at flowing temperature to standard temperature. See Chapter 11.1, Tables 24, or other agreed-upon tables
C_{pl} = correction factor for pressure to correct the volume at flowing pressure to standard conditions. See Chapter 11.1, Tables 24, or other agreed-upon tables

Turbine meters used for volumetric measurement in deriving total mass shall conform to Chapter 5.3 for the service intended. Temperature or pressure compensating devices shall not be used on these meters and accessories shall conform to Chapter 5.4 The mass delivered and the volume of each component at standard conditions may be determined according to Chapter 14.7.

14.8.4.4 MEASUREMENT BY OTHER DEVICES

Dynamic measurement of liquefied petroleum gas can be accomplished using other types of equipment by mutual agreement of the contracting parties.

14.8.4.5 METER PROVING

The primary measuring device must be compared to a known standard. Comparison to a standard is accomplished by proving displacement and turbine meters using a pipe prover calibrated in accordance with Chapter 4. Tank-type provers are not recommended because liquefied petroleum gas may vaporize in the tank, making accountability for these vapors difficult. When a meter is used to measure more than one product, the meter shall be proved at the operating rates of flow, pressure, and temperature and the specification of the liquid that it will measure in routine operation. Several meter factors may be required where normal operations change significantly. The proving device should be installed so that the temperature and pressure within the prover and meter coincide as closely as possible. Should meter and prover temperatures or pressures vary, the prover volume shall be corrected to meter operating conditions according to Chapters 4, 11, and 12 or as agreed to by the contracting parties. Factors shall be adjusted as required between proving dates as a result of significant changes in metering pressure and/or temperature since the last proving.

14.8.4.6 SAMPLING

Sampling shall be accomplished to yield a sample that is proportional to, and representative of, the flowing stream during the measuring interval. Proportional samplers take small samples of the flowing stream proportional to the flow rate. Time incremental sampling may be used only when the flow rate is constant.

The sample collecting system shall be designed to contain the collected sample in the liquid state. This may be done using a piston cylinder or a cylinder with a bladder. Both the piston cylinder and bladder cylinder normally use inert gas vapor, hydraulic oil, or pipeline fluid to oppose the liquid injection and maintain a pressure level above the vapor pressure of the sample. A typical proportional sampler is described in the appendix to this publication.

Precautions shall be taken to avoid vaporization in sample loop lines when operating near the product vapor pressure. In some instances, insulating sample lines and sample containers or controlling the pressure or temperature of sample containers containing volatile materials may be necessary.

Sample loops should be short and of small diameter, sampling from the center of the stream. Adequate sample loop flow rates should be maintained to keep fresh product at the sample valve and to reduce the time lag between the meter and the sampler to a minimum.

All sample lines, pumps, and related equipment should be purged or bled down when sample collection cylinders are emptied to avoid contamination or distortion of the flowing sample. Sampler systems should be designed to minimize dead product areas, which could distort samples.

Obtaining a representative sample for transport to the laboratory shall be in accordance with GPA 2174, Appendix B of Chapter 14.1, or other recognized safety procedures. Sample containers must be adequately sized. If samples are to be shipped by common carrier, containers must comply with the latest hazardous materials regulations of the United States Department of Transportation.

Products or mixtures that have equilibrium vapor pressures above atmospheric pressure shall be maintained at a pressure where vaporization cannot occur within the on-line sample system or transfer containers.

Use of sample collection and transportation containers equipped with floating pistons or bladders (and equipped to maintain sample storage pressures above vapor pressure) is one effective way to avoid liquid-vapor separation. When using this type of equipment, adequate precautions must be observed to allow for thermal expansion of the product so that excessive pressure or release of product does not occur. Procedures described in the appendix of this publication may be used.

Sample handling procedures outlined in API Chapter 14.1, Appendix B, using immiscible fluid outage cylinders, may also be used. Water used with this method may result in removal of carbon dioxide or other water-soluble components from the sample.

Sample injection pumps or devices that inject the sample into containers shall be designed to deliver a constant volume per stroke over their normal operating pressure range. Procedures as outlined in Chapter 14.1, the appendix to this publication, and GPA Publication 2174 shall be followed, as applicable.

Samples taken over a period of time using a proportional sampler must be mixed to be truly representative before they are transferred to portable sample containers. Product mixing should not be attempted until the sampler has been isolated from the source. Procedures for thorough mixing of samples shall be provided to ensure that samples transferred to transportation cylinders and the analysis obtained are representative of the flowing stream during the measured interval.

After mixing, the sampled product is transferred to a portable piston cylinder or a double valved sample cylinder, using the immiscible fluid displacement method. Transfer the sampler to the portable cylinder using the same procedure used to take spot samples. When the required number of portable cylinders has been filled, the remaining product in the sampler must be vented back into the pipeline or disposed of before the sampler is returned to service.

Obtaining a representative sample of the stream liquid for transport to the laboratory shall be in accordance with GPA Publication 2174 or Appendix B of Chapter 14.1. Provisions shall be made for thermal expansion. Department of Transportation approved containers shall be used.

14.8.4.7 SAMPLE ANALYSIS

Depending upon the composition of the stream, liquid sample analysis shall follow the chromatographic procedures described in GPA Publications 2165, 2177, and 2261, or other methods agreed upon by the contracting parties.

Where applicable, such as with liquefied petroleum gas mixtures, special efforts shall be made to accurately determine the molecular weight and the density of the heptanes plus fraction (or of the last significant fraction determined by agreement).

14.8.5 Mass Determination in Dynamic Systems (Density Range 0.30 to 0.70 g/cm^3)

Mass measurement is applicable to liquefied petroleum gas mixtures and to components that are affected by compositional changes, intermolecular adhesions, solution mixing, or extreme pressure and temperature conditions where accurate physical correction factors have not been determined

Mass measurement in a dynamic state normally utilizes (1) a volumetric measuring device at flowing conditions, (2) a density or relative density (specific gravity) measuring device for determining density or relative density at the same flowing conditions as the measuring device, and (3) a representative sample of the fluid flowing through the measuring system, collected proportional to flow, as presented in Chapter 14.7.

Mass measurement is accomplished by multiplying the measured volume at flowing conditions times flowing density measured at the same conditions, using consistent units. The equivalent volume at standard conditions of each component in the mixture may be

obtained by using a compositional analysis of the representative sample and the density of each component at 60°F and the equilibrium pressure at 60°F.

Liquids with densities below 0.3 and above 0.7 grams per cubic centimetre and cryogenic fluids are excluded from the scope of this document. However, the principles can apply to these fluids with modified application techniques.

Equipment exists which uses diverse principles for measuring volume, sampling the product, and determining the composition and density of the product. This publication does not advocate the preferential use of any particular type of equipment. It is not the intention of this publication to restrict future development or improvement of equipment.

14.8.5.1 BASE CONDITIONS

Density is defined as mass per unit volume:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

Mass is an absolute measure of the quantity of matter. Weight is the force resulting from an acceleration due to gravity acting upon a mass. Changes of gravity acceleration from one locality to another will affect the resulting weight force observed. Therefore, quantities determined in accordance with Chapter 14.7 shall be *mass* rather than weight. This may be accomplished through procedures in Chapter 14.6 by referral to weighing devices used to calibrate density meters to test weights of known mass. This referral or calibration is done at or near the densitometer location, eliminating the need for further correction for local gravitational force variances.

Weight observations to determine fluid density shall be corrected for air bouyancy (commonly called "weighed in vacuum") and for local gravity, as necessary. Such observations can be used in conjunction with the calibration of density meters or for checking the performance of equation of state correlations. Procedures are outlined in Chapter 14.6.

Volumes and densities for mass measurement shall be determined at operating temperature and pressure to eliminate temperature and compressibility corrections. However, equivalent volumes of components are often computed for the determined mass flow. These volumes will be stated as follows: temperature, 15°C (or 60°F); pressure, 101.325 kilopascals (14.696 pounds per square inch absolute), or the product equilibrium vapor pressure at 15°C (or 60°F), whichever is higher.

14.8.5.2 MASS MEASUREMENT USING DISPLACEMENT TYPE OR TURBINE METERS

The equation for determining mass using displacement-type or turbine meters is:

$$\text{Mass} = \begin{bmatrix}\text{Metered volume}\\ \text{at meter}\\ \text{operating}\\ \text{conditions}\end{bmatrix} \times \begin{bmatrix}\text{Meter factor}\\ \text{at meter}\\ \text{operating}\\ \text{conditions}\end{bmatrix} \times \begin{bmatrix}\text{Density per}\\ \text{unit volume at}\\ \text{meter operating}\\ \text{conditions}\end{bmatrix} \times \begin{bmatrix}\text{Densitometer}\\ \text{correction}\\ \text{factor (if}\\ \text{applicable)}\end{bmatrix}$$

14.8.5.3 MASS MEASUREMENT USING ORIFICE METERS

The equation for determining mass using orifice meters is:

$$Q_m = C' \sqrt{h_w \rho_f} = \text{flow rate expressed in units of mass/units of time.}$$

The terms for this equation are defined and discussed in 14.8.5.1.

14.8.5.4 DENSITY DETERMINATION

14.8.5.4.1 Empirical Density

Liquid density may be calculated as a function of composition, temperature, and pressure. It is preferred that the calculated or measured density be applied in real time to the flow meter. This provides for the maximum mass measurement precision, that is, the incremental volume of measured liquid is always in direct time relation to the density measured or calculated. However, it is common practice to use the composition of a sample taken continuously during the delivery period proportional to the volume delivered, and to use the average temperature and pressure for the delivery period.

Calculations may be made by means of empirical correlations or by generalized equations of state. The empirical correlations are derived from fitting experimental data covering specific ranges of compositions, temperatures, and pressures and can be inaccurate outside these ranges. Gas Processors Association procedure TP-1 for ethane/propane mix and TP-2 for high ethane raw make streams are examples. TP-3 is a more theoretical procedure for application to liquefied natural gas.

Generalized equations of state do not have strict limitations on ranges of compositions and conditions and can be applied to a wide variety of systems; however, empirical correlations are much more accurate when applied to the specific systems for which they were derived. The Rackett equation, the Starling-Han modification of the BWR equation of state, and several modified Redlich-Kwong equations of state (Soave, Mark V, Peng-Robinson) are examples.

It is the responsibility of the contracting parties to verify the validity and limits of the accuracy of methods considered for empirical density determination on the particular fluids to be measured.

Significant errors can occur from inaccuracies in temperature and pressure measurement, recording, or integration. Products with a density of less than 0.6 grams per cubic metre are particularly susceptible to errors and require a higher level of precision. See Chapter 14.6 for recommended precision levels of temperature and pressure.

14.8.5.4.2 Measured Density

Measured density of products between 0.3 and 0.7 grams per cubic centimetre shall be determined using density meters installed and calibrated in accordance with Chapter 14.6 or as otherwise agreed between the contracting parties.

Density instruments or probes shall be installed as follows·

1. No interaction that would adversely affect the flow or density measurement shall exist between the flow meter and the density transducer or probe.
2. Temperature and pressure differences among the fluid in the flow meter, the density measuring device, and the calibrating devices must be minimized and must be within specified limits for the fluid being measured and the mass measurement accuracy expected or required.
3 Density meters may be installed either upstream or downstream of primary flow devices in accordance with Chapter 14.6 but should not be located between flow straightening devices and meters and must not bypass the primary flow measurement device.

Densitometer accuracy will be seriously affected by the accumulation of foreign material from the flowing stream. The possibility of accumulation should be considered in selecting density measurement equipment and in determining the frequency of density equipment calibration and maintenance. Accuracy of the data recording, transmission, and computation equipment and methods should also be considered in system selection. See Chapter 14.6 for further comments.

14.8.5.5 CONVERSION OF MEASURED MASS TO VOLUME

Conversion from mass determined into equivalent volumes of components shall be in accordance with the latest revision of GPA Publication 8173, as described below. In this procedure, a chromatographic analysis representative of the delivered product is used to determine the mass of each individual component that comprised the total mass. The individual component masses are then converted to their respective equivalent liquid volumes at 15°C (or 60°F) and equilibrium vapor pressure at 15°C (or 60°F), using component density values from GPA Publication 2145.

The calculation of total mass flowing must be performed continuously on-line by a suitable device or by off-line integration of charts on which metered volume and density are continuously recorded so that at all times the density corresponds to the volume measured.

Conversion of the determined mass into an equivalent volume of each component at base or standard conditions at equilibrium vapor pressure at 15°C (60°F) or 101.325 kilopascals (14.696 pounds per square inch absolute), whichever is higher, shall be in accordance with Chapter 14.4. In this procedure a chromatographic analysis, representative of the delivered product, is used to determine the mass of each individual component comprising the total mass. The individual component masses are then converted to their respective equivalent liquid volumes at 15°C (or 60°F) and the equilibrium vapor pressure at 15°C (or 60°F) using component density values in vacuum from Chapter 11 or GPA Publication 2145. Example calculations, repeated from Chapter 14.4, are provided in 14.8.5.6.

14.8.5.6 CALCULATIONS FOR LIQUID-VAPOR CONVERSION

The density of pure hydrocarbons in pounds mass per gallon (weight in vacuum) shall be as stated in GPA Standard 2145. Should constants be required for a hydrocarbon component that is not presented in GPA Standard 2145, the constants contained in the GPSA *Engineering Data Book*, Section 16, "Physical Properties," shall be used. If the required constants are not contained in the GPSA *Engineering Data Book*, the ASTM Data Series Publication, DS 4A, constants shall be used. The steps described in Figure 1 are required.

14.8.5.7 SPECIAL PRECAUTIONS FOR MASS MEASUREMENT

Volume measurement must be made at flowing conditions. The measuring device must be proven at flowing conditions.

Density or relative density (specific gravity) measurements must be made at the same flowing conditions as the volume measurements.

Temperature compensated metering devices shall not be used in the mass measurement method.

14.8.6 Volumetric Measurement in Static Systems

The liquid volume of liquefied petroleum gas consists of the sum of the liquid volume and the volume of the vapor above the liquid converted to its liquid equivalent.

Volumetric measurement is accomplished by using calibrated vessels or tanks with gaging devices that can be read at the vessel operating pressures to determine the liquid level. The volume of vapor above the liquid is determined by using the ideal gas law ($PV = NRT$) corrected by the gas compressibility factor. The liquid and vapor are corrected for temperature and pressure to standard or base conditions of temperature and the vapor pressure of the product at standard or base temperature. The vapor volume can be converted to equivalent liquid volume by using the appropriate factors.

Step 1—Convert to mass analysis. Given: 825,300 = Total pounds mass.

Component	Mole Percent	Mole Weight	Mole Percent × Mole Weight	Weight of Fraction of Component
CO_2	0.11	44.01	4.84	0.001107
C_1	2.14	16.043	34.33	0.007852
C_2	38.97	30.069	1171.79	0.268010
C_3	36.48	44.096	1608.62	0.367921
IC_4	2.94	58.123	170.88	0.039083
nC_4	8.77	58.123	509.74	0.116587
iC_5	1.71	72.15	123.38	0.028219
nC_5	1.82	72.15	131.31	0.030033
C_6+	7.06	87.436	617.30	0.141188
	100.00		4372.19	1.000000

Step 2—Calculate the mass of each component as follows: Weight fraction times total pounds mass equals pounds mass each component:

Component	Weight Fraction of Component	Total Pounds Mass	Pounds Mass of Component
CO_2	0.001107	825,300	914
C_1	0.007852	825,300	6,480
C_2	0.268010	825,300	221,189
C_3	0.367920	825,300	303,645
IC_4	0.0339083	825,300	32,255
nC_4	0.116587	825,300	96,219
IC_5	0.028219	825,300	23,289
nC_5	0.030033	825,300	24,786
C_6+	0.141188	825,300	116,523
			825,300

Step 3—Calculate the volume of each component at equilibrium pressure and 60°F as follows:

Component	Component Pounds Mass	Density Pounds/Gallon (In vacuum)	U.S. Gallons
CO_2	914	6.817	134
C_1	6,480	2.50	2,592
C_2	221,189	2.97	74,474
C_3	303,645	4.231	71,767
IC_4	32,255	4 694	6,872
nC_4	96,219	4.871	19,785
IC_5	23,289	5.206	4,473
nC_5	24,786	5.262	4,710
C_6+	116,523	5.951*	19,580
			204,355

*From analysis

Figure 1—Calculations for Liquid Vapor Conversion

A pressure vessel or container must be able to safely withstand the vapor pressures of the contained product at the maximum operating temperature.

14.8.6.1 TANK CALIBRATION

Procedures for calibrating tanks and vessels are presented in Chapter 2.

14.8.6.2 TANK GAGING OF LIQUEFIED PETROLEUM GAS

Procedures for gaging liquefied petroleum gas in storage tanks are presented in Chapter 3. Special precautions are necessary to accurately account for the vapors above the liquid.

The composition and volume of the vapors are dependent upon the temperature and pressure conditions of the liquid.

14.8.6.3 TEMPERATURE MEASUREMENT

Chapter 5.4 contains general requirements for temperature measurement. Procedures for measuring the temperature of liquefied petroleum gas in storage vessels under static conditions are presented in Chapter 7.

14.8.6.4 RELATIVE DENSITY MEASUREMENT

Procedures for determining relative density of liquefied petroleum gas are presented in Chapters 9, 11, 12, 14.6, and 14.7. Observed relative densities (specific gravities) are corrected to standard or base conditions by using tables in Chapter 11.1.

14.8.6.5 WATER AND FOREIGN MATERIAL

Water and sediment content is not as serious a problem with liquefied petroleum gases as with crude oil. Product specifications in contracts for custody transfer should contain a section on product quality to provide for testing propane by the freeze valve method (ANSI/ASTM D 2713-76), the cobal bromide method, or the Bureau of Mines method. Other mutually acceptable methods for determining dryness may be used for other liquefied petroleum gases having a high vapor pressure.

14.8.6.6 SAMPLING

The scope of Chapter 8 does not include sampling of liquefied petroleum gases; however, GPA Publication 2140 contains a section on sampling this type of product. GPA Publication 2140 is also designated as ASTM D 1265. Its scope covers the procedure for obtaining representative samples of liquefied petroleum gases, such as propane, butane, or mixtures thereof, in containers other than those used in laboratory testing apparatus. A liquid sample is transferred from the source into a sample container by purging the container and filling it with liquid to 80 percent of capacity.

Considerable effort may be required to obtain a representative sample, especially if the material being sampled is a mixture of liquefied petroleum gases. The following factors must be considered:

1. Samples must be obtained in the liquid phase
2. When it is definitely known that the material being sampled is composed predominantly of only one liquefied petroleum gas, a liquid sample may be taken from any part of the vessel
3. When the material being sampled has been agitated until uniformity is assured, a liquid sample may be taken from any part of the vessel.
4. Because of wide variations in the construction details of containers for liquefied petroleum gases, it is difficult to specify a uniform method for obtaining representative samples of heterogeneous mixtures. If it is not practicable to agitate a mixture for homogeneity, obtain liquid samples by a procedure that has been agreed upon by the contracting parties

Directions for sampling cannot be explicit enough to cover all cases. They must be supplemented by judgment, skill, and sampling experience. Extreme care and good judgment are necessary to ensure that samples represent the general character and average condition of the material. Because of the hazards involved, liquefied petroleum gases should be sampled by, or under the supervision of, persons familiar with the necessary safety precautions.

14.8.6.7 VOLUMETRIC CALCULATION

When product is removed from or added to a tank, the beginning and ending liquid levels are obtained along with corresponding temperatures and pressures. The volumes of liquid and vapor are calculated for the beginning and ending conditions, and the difference between the beginning and ending calculations of the total volume of the vapor and liquid is the volume change in the vessel.

$$\begin{bmatrix}\text{Total volume}\\ \text{at standard}\\ \text{conditions}\end{bmatrix} = \begin{bmatrix}\text{Volume of liquid}\\ \text{at standard}\\ \text{conditions}\end{bmatrix} + \begin{bmatrix}\text{Volume of vapor}\\ \text{above the liquid}\\ \text{in equivalent}\\ \text{liquid units at}\\ \text{standard conditions}\end{bmatrix}$$

$$\begin{bmatrix}\text{Volume of}\\ \text{liquid at}\\ \text{standard}\\ \text{conditions}\end{bmatrix} = \begin{bmatrix}\text{Liquid volume}\\ \text{at tank}\\ \text{conditions}\end{bmatrix} \times \begin{bmatrix}\text{Volume correction}\\ \text{factor for}\\ \text{temperature and}\\ \text{gravity}\end{bmatrix}$$

$$\begin{bmatrix}\text{Volume of vapor}\\ \text{above liquid in}\\ \text{equivalent liquid}\\ \text{units at base}\\ \text{conditions}\end{bmatrix} = \begin{bmatrix}\text{Volume of}\\ \text{vapor above}\\ \text{the liquid}\end{bmatrix} \times \frac{P_o}{P_s} \times \frac{T_s}{T_o} \times \begin{bmatrix}\text{Factor for liquid}\\ \text{volume per vapor}\\ \text{volume}\end{bmatrix}$$

Where:

Total volume = (volume of product in the vessel as a liquid) + (vapor above the liquid converted to its liquid volume equivalent). Volume measured at standard conditions.

Volume of liquid at standard conditions = volume measured at standard temperature and vapor pressure of the liquid at standard temperature.

Volume of liquid at tank conditions = volume of vessel at liquid level determined by tank calibration and gaging device.

Volume of vapor above the liquid = volume of vessel above the liquid level determined by tank calibration and gaging device.

Volume correction factor = factor used to correct the liquid volume to standard temperature. Refer to tables in Chapters 11 and 12.

P_o = observed pressure, in absolute units.

P_s = standard pressure, in absolute units.

T_o = observed temperature, in kelvins (K) or degrees Rankine (°R).

T_s = standard temperature, in kelvins (K) or degrees Rankine (°R)

Factor for liquid volume per vapor volume = standard conversion unit for product being measured

14.8.6.8 MIXTURE CALCULATION

When mixtures are measured, the composition of the liquid and vapor will be different for varying conditions of temperature and pressure. The composition of each phase can be determined by sampling and analysis of each. Refer to Chapter 14.4 for the procedure for calculating liquid equivalent of the vapor volume above stored natural gas liquid mixtures.

14.8.7 Mass Measurement in Static Systems

Mass is determined by weighing the container or vessel before and after product has been added to, or removed from, the vessel. The difference in weight provides the basis

for total mass of the product contained in the vessel.

To calculate the volume using mass units:

$$V_b = \frac{\text{Mass}}{\text{Density}}$$

Where:

V_b = volume at standard temperature and vapor pressure of the product at standard temperature.

Mass = difference between before and after mass determination.

Density = density in vacuum of liquid product at standard conditions in same units as mass.

Refer to Chapter 11 to determine relative density at standard conditions.

APPENDIX—INSTALLATION AND OPERATION OF FLOATING PISTON SAMPLERS

The procedures included here are presented to supplement other existing procedures, specifications, and standards in sampling higher than atmospheric vapor pressure products where flashing of lighter components within the container may cause distortion of the sample composition.

All samples should be obtained using some type of probe from the center of the flowing stream. A bypass around a device that causes a differential pressure, such as an orifice plate or small pump, is used to supply fresh product to bypass-type sample injection valves. See Figures A-1 and A-2. Bypass lines must not bypass primary volume measurement devices.

Figure A-3 provides an example of a typical proportional sampler.

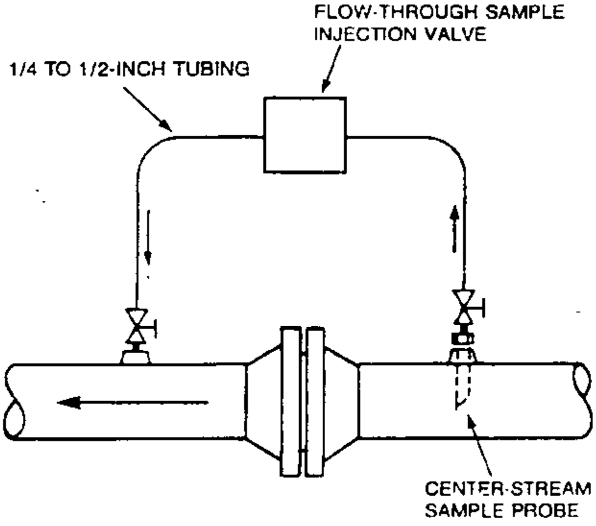

Figure A-1—Typical Sample Probe Installation on an Orifice Flange

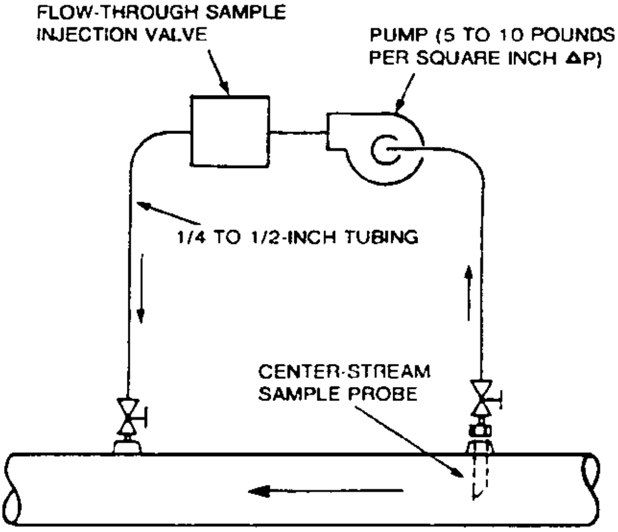

Figure A-2—Typical Sample Probe Installation for a Pump

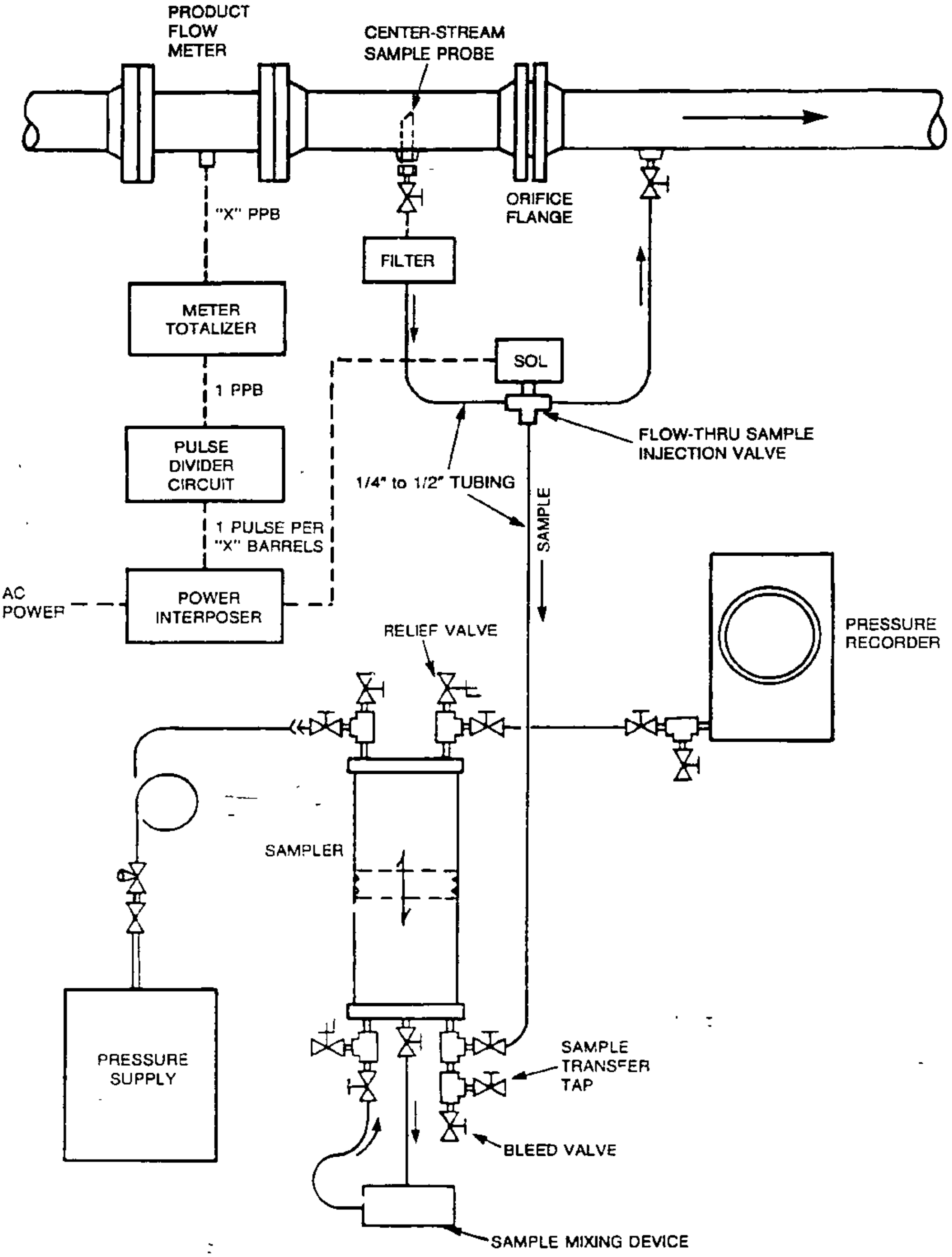

Figure A-3—Typical Proportional Sampler

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Table 3-B-5—Conversion of $Re_D/10^6$ to $Q_v/1000$ (Q_v in Thousands of Cubic Feet per Hour): $Q_v/1000 = Re_D/1000D/28.2435$

	Nominal Pipe Diameter										
	2 Inches			3 Inches				4 Inches			
$Re_D/10^6$	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.020	1.2	1.4	1.5	1.6	1.9	2.1	2.2	2.2	2.4	2.7	2.9
0.030	1.8	2.1	2.2	2.4	2.8	3.1	3.3	3.3	3.7	4.1	4.3
0.040	2.4	2.7	2.9	3.3	3.7	4.1	4.3	4.5	4.9	5.4	5.7
0.050	3.0	3.4	3.7	4.1	4.6	5.1	5.4	5.6	6.1	6.8	7.1
0.060	3.6	4.1	4.4	4.9	5.6	6.2	6.5	6.7	7.3	8.1	8.6
0.070	4.2	4.8	5.1	5.7	6.5	7.2	7.6	7.8	8.5	9.5	10.0
0.080	4.8	5.5	5.9	6.5	7.4	8.2	8.7	8.9	9.7	10.8	11.4
0.090	5.4	6.2	6.6	7.3	8.4	9.2	9.8	10.0	11.0	12.2	12.8
0.100	6.0	6.9	7.3	8.1	9.3	10.3	10.9	11.2	12.2	13.5	14.3
0.150	9.0	10.3	11.0	12.2	13.9	15.4	16.3	16.7	18.3	20.3	21.4
0.200	11.9	13.7	14.6	16.3	18.6	20.5	21.7	22.3	24.3	27.1	28.5
0.250	14.9	17.2	18.3	20.4	23.2	25.7	27.2	27.9	30.4	33.9	35.6
0.300	17.9	20.6	22.0	24.4	27.9	30.8	32.6	33.5	36.5	40.6	42.8
0.350	20.9	24.0	25.6	28.5	32.5	35.9	38.0	39.1	42.6	47.4	49.9
0.400	23.9	27.5	29.3	32.6	37.2	41.1	43.5	44.6	48.7	54.2	57.0
0.450	26.9	30.9	32.9	36.6	41.8	46.2	48.9	50.2	54.8	61.0	64.1
0.500	29.9	34.3	36.6	40.7	46.5	51.3	54.3	55.8	60.9	67.7	71.3
0.600	35.8	41.2	43.9	48.9	55.7	61.6	65.2	67.0	73.0	81.3	85.5
0.700	41.8	48.1	51.2	57.0	65.0	71.9	76.0	78.1	85.2	94.8	99.8
0.800	47.8	54.9	58.5	65.2	74.3	82.1	86.9	89.3	97.4	108	114
0.900	53.8	61.8	65.9	73.3	83.6	92.4	97.8	100	110	122	128
1.000	59.7	68.7	73.2	81.4	92.9	103	109	112	122	135	143
1.500	89.6	103	110	122	139	154	163	167	183	203	214
2.000	119	137	146	163	186	205	217	223	243	271	285
2.500	149	172	183	204	232	257	272	279	304	339	356
3.000	179	206	220	244	279	308	326	335	365	406	428
3.500	209	240	256	285	325	359	380	391	426	474	499
4.000	239	275	293	326	372	411	435	446	487	542	570
4.500	269	309	329	366	418	462	489	502	548	610	641
5.000	299	343	365	407	465	513	543	558	609	677	713
5.500	329	378	403	448	511	565	597	614	670	745	784
6.000	358	412	439	489	557	616	652	670	730	813	855
6.500	388	446	476	529	604	667	706	725	791	881	927
7.000	418	481	512	570	650	719	760	781	852	948	998
7.500	448	515	549	611	697	770	815	837	913	1,016	1,069
8.000	478	549	585	651	743	821	869	893	974	1,084	1,140
8.500	508	584	622	692	790	873	923	949	1,035	1,151	1,212
9.000	538	618	659	733	836	924	978	1,004	1,096	1,219	1,283
9.500	567	652	695	774	883	975	1,032	1,060	1,156	1,287	1,354
10.000	597	687	732	814	929	1,027	1,086	1,116	1,217	1,355	1,425

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6, μ = 0.000069; k = 1.3; P_b = 14.73, and T_b = 519.67°R

Table 3-B-5—Continued

	Nominal Pipe Diameter									
	6 Inches				8 Inches			10 Inches		
$Re_D/10^6$	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.036
0.020	3.5	3.7	4.1	4.3	5.4	5.7	5.7	6.8	7.1	7.1
0.030	5.2	5.5	6.1	6.4	8.1	8.5	8.6	10.2	10.6	10.7
0.040	6.9	7.3	8.2	8.6	10.8	11.3	11.4	13.5	14.2	14.2
0.050	8.7	9.2	10.2	10.7	13.5	14.1	14.3	16.9	17.7	17.8
0.060	10.4	11.0	12.2	12.9	16.2	17.0	17.1	20.3	21.3	21.3
0.070	12.1	12.9	14.3	15.0	18.9	19.8	20.0	23.7	24.8	24.9
0.080	13.9	14.7	16.3	17.2	21.6	22.6	22.9	27.1	28.4	28.4
0.090	15.6	16.5	18.4	19.3	24.3	25.4	25.7	30.5	31.9	32.0
0.100	17.3	18.4	20.4	21.5	27.0	28.3	28.6	33.9	35.5	35.5
0.150	26.0	27.5	30.6	32.2	40.5	42.4	42.9	50.8	53.2	53.3
0.200	34.7	36.7	40.8	42.9	54.0	56.5	57.2	67.7	71.0	71.1
0.250	43.3	45.9	51.0	53.7	67.5	70.6	71.4	84.6	88.7	88.8
0.300	52.0	55.1	61.2	64.4	81.0	84.8	85.7	102	106	107
0.350	60.7	64.3	71.4	75.2	94.5	98.9	100	118	124	124
0.400	69.4	73.5	81.6	85.9	108	113	114	135	142	142
0.450	78.0	82.6	91.8	96.6	121	127	129	152	160	160
0.500	86.7	91.8	102	107	135	141	143	169	177	178
0.600	104	110	122	129	162	170	171	203	213	213
0.700	121	129	143	150	189	198	200	237	248	249
0.800	139	147	163	172	216	226	229	271	284	284
0.900	156	165	184	193	243	254	257	305	319	320
1.000	173	184	204	215	270	283	286	339	355	355
1.500	260	275	306	322	405	424	429	508	532	533
2.000	347	367	408	429	540	565	572	677	710	711
2.500	433	459	510	537	675	706	714	846	887	888
3.000	520	551	612	644	810	848	857	1,016	1,064	1,066
3.500	607	643	714	752	945	989	1,000	1,185	1,242	1,244
4.000	694	735	816	859	1,080	1,130	1,143	1,354	1,419	1,421
4.500	780	826	918	966	1,215	1,272	1,286	1,524	1,596	1,599
5.000	867	918	1,020	1,074	1,350	1,413	1,429	1,693	1,774	1,777
5.500	954	1,010	1,122	1,181	1,485	1,554	1,572	1,862	1,951	1,954
6.000	1,040	1,102	1,224	1,288	1,620	1,695	1,715	2,031	2,129	2,132
6.500	1,127	1,194	1,326	1,396	1,755	1,837	1,857	2,201	2,306	2,310
7.000	1,214	1,286	1,428	1,503	1,890	1,978	2,000	2,370	2,483	2,487
7.500	1,300	1,377	1,530	1,611	2,025	2,119	2,143	2,539	2,661	2,665
8.000	1,387	1,469	1,632	1,718	2,160	2,261	2,286	2,708	2,838	2,843
8.500	1,474	1,561	1,734	1,825	2,295	2,402	2,429	2,878	3,016	3,020
9.000	1,560	1,653	1,836	1,933	2,430	2,543	2,572	3,047	3,193	3,198
9.500	1,647	1,745	1,938	2,043	2,565	2,685	2,715	3,216	3,370	3,376
10.000	1,734	1,837	2,040	2,147	2,700	2,826	2,858	3,386	3,548	3,553

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73, and T_b = 519.67°R

Table 3-B-5—Continued

	Nominal Pipe Diameter														
	12 Inches			16 Inches			20 Inches			24 Inches			30 Inches		
$Re_D/10^6$	11.374	11.938	12.090	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
0.150	60.4	63.4	64.2	78.0	79.7	81.0	99.9	101	102	120	122	123	153	154	155
0.200	80.5	84.5	85.6	104	106	108	133	135	136	160	163	165	204	205	207
0.250	101	106	107	130	133	135	167	168	170	200	204	206	254	257	259
0.300	121	127	128	156	159	162	200	202	204	240	244	247	305	308	311
0.350	141	148	150	182	186	189	233	235	239	280	285	288	356	359	362
0.400	161	169	171	208	212	216	266	269	273	320	326	329	407	411	414
0.450	181	190	193	234	239	243	300	303	307	360	366	370	458	462	466
0.500	201	211	214	260	266	270	333	336	341	401	407	412	509	513	518
0.600	242	254	257	312	319	324	400	404	409	481	489	494	611	616	621
0.700	282	296	300	364	372	378	466	471	477	561	570	576	713	719	725
0.800	322	338	342	416	425	432	533	538	545	641	651	659	814	821	829
0.900	362	380	385	468	478	486	599	605	613	721	733	741	916	924	932
1.000	403	423	428	520	531	540	666	673	682	801	814	823	1,018	1,027	1,036
1.500	604	634	642	780	797	810	999	1,009	1,022	1,202	1,222	1,235	1,527	1,540	1,553
2.000	805	845	856	1,040	1,062	1,080	1,332	1,345	1,363	1,602	1,629	1,646	2,036	2,054	2,071
2.500	1,007	1,057	1,070	1,300	1,328	1,350	1,665	1,682	1,704	2,003	2,036	2,058	2,545	2,567	2,589
3.000	1,208	1,268	1,284	1,560	1,593	1,620	1,998	2,018	2,045	2,403	2,443	2,470	3,054	3,080	3,107
3.500	1,409	1,479	1,498	1,820	1,859	1,890	2,331	2,355	2,386	2,804	2,850	2,881	3,563	3,594	3,625
4.000	1,611	1,691	1,712	2,080	2,124	2,160	2,664	2,691	2,726	3,204	3,257	3,293	4,072	4,107	4,143
4.500	1,812	1,902	1,926	2,340	2,399	2,430	2,997	3,027	3,067	3,605	3,665	3,704	4,581	4,621	4,660
5.000	2,014	2,113	2,140	2,600	2,655	2,700	3,330	3,364	3,408	4,005	4,072	4,116	5,090	5,134	5,178
5.500	2,215	2,325	2,354	2,860	2,921	2,970	3,663	3,700	3,749	4,406	4,479	4,528	5,599	5,647	5,696
6.000	2,416	2,536	2,568	3,120	3,187	3,240	3,996	4,036	4,089	4,806	4,886	4,939	6,108	6,161	6,214
6.500	2,618	2,747	2,782	3,380	3,452	3,510	4,329	4,373	4,430	5,207	5,293	5,351	6,617	6,674	6,732
7.000	2,819	2,959	2,996	3,640	3,718	3,780	4,662	4,709	4,771	5,607	5,700	5,762	7,126	7,188	7,249
7.500	3,020	3,170	3,210	3,900	3,983	4,050	4,996	5,045	5,112	6,008	6,108	6,174	7,635	7,701	7,767
8.000	3,222	3,381	3,425	4,160	4,249	4,320	5,329	5,382	5,453	6,408	6,515	6,586	8,143	8,214	8,285
8.500	3,423	3,593	3,639	4,420	4,514	4,590	5,662	5,718	5,793	6,809	6,922	6,997	8,652	8,728	8,803
9.000	3,624	3,804	3,853	4,680	4,780	4,860	5,995	6,055	6,134	7,209	7,329	7,409	9,161	9,241	9,321
9.500	3,826	4,015	4,067	4,940	5,045	5,130	6,328	6,391	6,475	7,610	7,736	7,820	9,670	9,754	9,839
10.000	4,027	4,227	4,281	5,201	5,311	5,399	6,661	6,727	6,816	8,010	8,143	8,232	10,179	10,268	10,356
12.000	4,833	5,072	5,137	6,241	6,373	6,479	7,993	8,073	8,179	9,612	9,772	9,878	12,215	12,321	12,428
15.000	6,041	6,340	6,421	7,801	7,966	8,099	9,991	10,091	10,224	12,016	12,215	12,348	15,269	15,402	15,535
18.000	7,249	7,608	7,705	9,361	9,560	9,719	11,989	12,109	12,268	14,419	14,658	14,818	18,323	18,482	18,642
21.000	8,457	8,876	8,989	10,921	11,153	11,339	13,987	14,127	14,313	16,822	17,101	17,287	21,377	21,563	21,748
24.000	9,665	10,144	10,274	12,481	12,746	12,959	15,986	16,145	16,358	19,225	19,544	19,757	24,430	24,643	24,855
27.000	10,873	11,412	11,558	14,041	14,340	14,579	17,984	18,164	18,403	21,628	21,987	22,226	27,484	27,723	27,962
30.000	12,081	12,680	12,842	15,602	15,933	16,198	19,982	20,182	20,447	24,031	24,430	24,696	30,538	30,804	31,069

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-6—Expansion Factors for Flange Taps (Y_1): Static Pressure Taken From Upstream Taps

	$\beta = d/D$												
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60	0.61	0.62
0.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.1	0.9989	0.9989	0.9989	0.9988	0.9988	0.9988	0.9988	0.9988	0.9988	0.9988	0.9987	0.9987	0.9987
0.2	0.9977	0.9977	0.9977	0.9977	0.9976	0.9976	0.9976	0.9976	0.9975	0.9975	0.9975	0.9975	0.9974
0.3	0.9966	0.9966	0.9966	0.9965	0.9965	0.9964	0.9964	0.9963	0.9963	0.9963	0.9962	0.9962	0.9962
0.4	0.9954	0.9954	0.9954	0.9953	0.9953	0.9952	0.9952	0.9951	0.9951	0.9950	0.9949	0.9949	0.9949
0.5	0.9943	0.9943	0.9943	0.9942	0.9941	0.9940	0.9940	0.9939	0.9938	0.9938	0.9937	0.9936	0.9936
0.6	0.9932	0.9932	0.9931	0.9930	0.9929	0.9928	0.9927	0.9927	0.9926	0.9925	0.9924	0.9924	0.9923
0.7	0.9920	0.9920	0.9920	0.9919	0.9918	0.9916	0.9915	0.9915	0.9914	0.9913	0.9912	0.9911	0.9910
0.8	0.9909	0.9909	0.9908	0.9907	0.9906	0.9904	0.9903	0.9902	0.9901	0.9900	0.9899	0.9898	0.9897
0.9	0.9898	0.9897	0.9897	0.9895	0.9894	0.9892	0.9891	0.9890	0.9889	0.9888	0.9886	0.9885	0.9885
1.0	0.9886	0.9886	0.9885	0.9884	0.9882	0.9880	0.9879	0.9878	0.9877	0.9875	0.9874	0.9873	0.9872
1.1	0.9875	0.9875	0.9874	0.9872	0.9870	0.9868	0.9867	0.9866	0.9864	0.9863	0.9861	0.9860	0.9859
1.2	0.9863	0.9863	0.9862	0.9860	0.9859	0.9856	0.9855	0.9853	0.9852	0.9850	0.9848	0.9847	0.9846
1.3	0.9852	0.9852	0.9851	0.9849	0.9847	0.9844	0.9843	0.9841	0.9840	0.9838	0.9836	0.9835	0.9833
1.4	0.9841	0.9840	0.9840	0.9837	0.9835	0.9832	0.9831	0.9829	0.9827	0.9825	0.9823	0.9822	0.9821
1.5	0.9829	0.9829	0.9828	0.9826	0.9823	0.9820	0.9819	0.9817	0.9815	0.9813	0.9810	0.9809	0.9808
1.6	0.9818	0.9818	0.9817	0.9814	0.9811	0.9808	0.9806	0.9805	0.9803	0.9800	0.9798	0.9796	0.9795
1.7	0.9806	0.9806	0.9805	0.9802	0.9800	0.9796	0.9794	0.9792	0.9790	0.9788	0.9785	0.9784	0.9782
1.8	0.9795	0.9795	0.9794	0.9791	0.9788	0.9784	0.9782	0.9780	0.9778	0.9775	0.9772	0.9771	0.9769
1.9	0.9784	0.9783	0.9782	0.9779	0.9776	0.9772	0.9770	0.9768	0.9766	0.9763	0.9760	0.9758	0.9756
2.0	0.9772	0.9772	0.9771	0.9767	0.9764	0.9760	0.9758	0.9756	0.9753	0.9750	0.9747	0.9745	0.9744
2.1	0.9761	0.9761	0.9759	0.9756	0.9753	0.9748	0.9746	0.9744	0.9741	0.9738	0.9734	0.9733	0.9731
2.2	0.9750	0.9749	0.9748	0.9744	0.9741	0.9736	0.9734	0.9731	0.9729	0.9725	0.9722	0.9720	0.9718
2.3	0.9738	0.9738	0.9736	0.9732	0.9729	0.9724	0.9722	0.9719	0.9716	0.9713	0.9709	0.9707	0.9705
2.4	0.9727	0.9726	0.9725	0.9721	0.9717	0.9712	0.9710	0.9707	0.9704	0.9700	0.9697	0.9694	0.9692
2.5	0.9715	0.9715	0.9713	0.9709	0.9705	0.9700	0.9698	0.9695	0.9692	0.9688	0.9684	0.9682	0.9680
2.6	0.9704	0.9704	0.9702	0.9698	0.9694	0.9688	0.9686	0.9683	0.9679	0.9675	0.9671	0.9669	0.9667
2.7	0.9693	0.9692	0.9691	0.9686	0.9682	0.9676	0.9673	0.9670	0.9667	0.9663	0.9659	0.9656	0.9654
2.8	0.9681	0.9681	0.9679	0.9674	0.9670	0.9664	0.9661	0.9658	0.9654	0.9650	0.9646	0.9644	0.9641
2.9	0.9670	0.9669	0.9668	0.9663	0.9658	0.9652	0.9649	0.9646	0.9642	0.9638	0.9633	0.9631	0.9628
3.0	0.9658	0.9658	0.9656	0.9651	0.9647	0.9640	0.9637	0.9634	0.9630	0.9626	0.9621	0.9618	0.9615
3.1	0.9647	0.9647	0.9645	0.9639	0.9635	0.9628	0.9625	0.9622	0.9617	0.9613	0.9608	0.9605	0.9603
3.2	0.9636	0.9635	0.9633	0.9628	0.9623	0.9616	0.9613	0.9609	0.9605	0.9601	0.9595	0.9593	0.9590
3.3	0.9624	0.9624	0.9622	0.9616	0.9611	0.9604	0.9601	0.9597	0.9593	0.9588	0.9583	0.9580	0.9577
3.4	0.9613	0.9612	0.9610	0.9604	0.9599	0.9592	0.9589	0.9585	0.9580	0.9576	0.9570	0.9567	0.9564
3.5	0.9602	0.9601	0.9599	0.9593	0.9588	0.9580	0.9577	0.9573	0.9568	0.9563	0.9558	0.9554	0.9551
3.6	0.9590	0.9590	0.9587	0.9581	0.9576	0.9568	0.9565	0.9560	0.9556	0.9551	0.9545	0.9542	0.9538
3.7	0.9579	0.9578	0.9576	0.9570	0.9564	0.9556	0.9553	0.9548	0.9543	0.9538	0.9532	0.9529	0.9526
3.8	0.9567	0.9567	0.9564	0.9558	0.9552	0.9544	0.9540	0.9536	0.9531	0.9526	0.9520	0.9516	0.9513
3.9	0.9556	0.9555	0.9553	0.9545	0.9540	0.9532	0.9528	0.9524	0.9519	0.9513	0.9507	0.9504	0.9500
4.0	0.9545	0.9544	0.9542	0.9536	0.9529	0.9520	0.9516	0.9512	0.9506	0.9501	0.9494	0.9491	0.9487

Table 3-B-6—Continued

	$\beta = d/D$												
h_w/P_{f_1}	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70	0.71	0.72	0.73	0.74	0.75
0.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.1	0.9987	0.9987	0.9987	0.9987	0.9987	0.9987	0.9986	0.9986	0.9986	0.9986	0.9986	0.9986	0.9986
0.2	0.9974	0.9974	0.9974	0.9974	0.9973	0.9973	0.9973	0.9973	0.9972	0.9972	0.9972	0.9971	0.9971
0.3	0.9961	0.9961	0.9961	0.9960	0.9960	0.9960	0.9959	0.9959	0.9958	0.9958	0.9958	0.9957	0.9957
0.4	0.9948	0.9948	0.9948	0.9947	0.9947	0.9946	0.9946	0.9945	0.9945	0.9944	0.9943	0.9943	0.9942
0.5	0.9935	0.9935	0.9934	0.9934	0.9933	0.9933	0.9932	0.9931	0.9931	0.9930	0.9929	0.9929	0.9928
0.6	0.9923	0.9922	0.9921	0.9921	0.9920	0.9919	0.9918	0.9918	0.9917	0.9916	0.9915	0.9914	0.9913
0.7	0.9910	0.9909	0.9908	0.9907	0.9907	0.9906	0.9905	0.9904	0.9903	0.9902	0.9901	0.9900	0.9899
0.8	0.9897	0.9896	0.9895	0.9894	0.9893	0.9892	0.9891	0.9890	0.9889	0.9888	0.9887	0.9886	0.9884
0.9	0.9884	0.9883	0.9882	0.9881	0.9880	0.9879	0.9878	0.9877	0.9875	0.9874	0.9873	0.9871	0.9870
1.0	0.9871	0.9870	0.9869	0.9868	0.9867	0.9865	0.9864	0.9863	0.9861	0.9860	0.9859	0.9857	0.9855
1.1	0.9858	0.9857	0.9856	0.9854	0.9853	0.9852	0.9851	0.9849	0.9848	0.9846	0.9844	0.9843	0.9841
1.2	0.9845	0.9844	0.9843	0.9841	0.9840	0.9838	0.9837	0.9835	0.9834	0.9832	0.9830	0.9828	0.9826
1.3	0.9832	0.9831	0.9829	0.9828	0.9827	0.9825	0.9823	0.9822	0.9820	0.9818	0.9816	0.9814	0.9812
1.4	0.9819	0.9818	0.9816	0.9815	0.9813	0.9812	0.9810	0.9808	0.9806	0.9804	0.9802	0.9800	0.9798
1.5	0.9806	0.9805	0.9803	0.9802	0.9800	0.9798	0.9796	0.9794	0.9792	0.9790	0.9788	0.9786	0.9783
1.6	0.9793	0.9792	0.9790	0.9788	0.9787	0.9785	0.9783	0.9781	0.9778	0.9776	0.9774	0.9771	0.9769
1.7	0.9780	0.9779	0.9777	0.9775	0.9773	0.9771	0.9769	0.9767	0.9764	0.9762	0.9760	0.9757	0.9754
1.8	0.9768	0.9766	0.9764	0.9762	0.9760	0.9758	0.9755	0.9753	0.9751	0.9748	0.9745	0.9743	0.9740
1.9	0.9755	0.9753	0.9751	0.9749	0.9747	0.9744	0.9742	0.9739	0.9737	0.9734	0.9731	0.9728	0.9725
2.0	0.9742	0.9740	0.9738	0.9735	0.9733	0.9731	0.9728	0.9726	0.9723	0.9720	0.9717	0.9714	0.9711
2.1	0.9729	0.9727	0.9725	0.9722	0.9720	0.9717	0.9715	0.9712	0.9709	0.9706	0.9703	0.9700	0.9696
2.2	0.9716	0.9714	0.9711	0.9709	0.9706	0.9704	0.9701	0.9698	0.9695	0.9692	0.9689	0.9685	0.9682
2.3	0.9703	0.9701	0.9698	0.9696	0.9693	0.9690	0.9688	0.9685	0.9681	0.9678	0.9675	0.9671	0.9667
2.4	0.9690	0.9688	0.9685	0.9683	0.9680	0.9677	0.9674	0.9671	0.9668	0.9664	0.9661	0.9657	0.9653
2.5	0.9677	0.9675	0.9672	0.9669	0.9666	0.9663	0.9660	0.9657	0.9654	0.9650	0.9646	0.9643	0.9639
2.6	0.9664	0.9662	0.9659	0.9656	0.9653	0.9650	0.9647	0.9643	0.9640	0.9636	0.9632	0.9628	0.9624
2.7	0.9651	0.9649	0.9646	0.9643	0.9640	0.9637	0.9633	0.9630	0.9626	0.9622	0.9618	0.9614	0.9610
2.8	0.9638	0.9636	0.9633	0.9630	0.9626	0.9623	0.9620	0.9616	0.9612	0.9608	0.9604	0.9600	0.9595
2.9	0.9625	0.9623	0.9620	0.9616	0.9613	0.9610	0.9606	0.9602	0.9598	0.9594	0.9590	0.9585	0.9581
3.0	0.9613	0.9610	0.9606	0.9603	0.9600	0.9596	0.9592	0.9588	0.9584	0.9580	0.9576	0.9571	0.9566
3.1	0.9600	0.9597	0.9593	0.9590	0.9586	0.9583	0.9579	0.9575	0.9571	0.9566	0.9562	0.9557	0.9552
3.2	0.9587	0.9584	0.9580	0.9577	0.9573	0.9569	0.9567	0.9561	0.9557	0.9552	0.9547	0.9542	0.9537
3.3	0.9574	0.9571	0.9567	0.9564	0.9560	0.9556	0.9552	0.9547	0.9543	0.9538	0.9533	0.9528	0.9525
3.4	0.9561	0.9558	0.9554	0.9550	0.9546	0.9542	0.9538	0.9534	0.9529	0.9524	0.9519	0.9514	0.9508
3.5	0.9548	0.9545	0.9541	0.9537	0.9533	0.9529	0.9524	0.9520	0.9515	0.9510	0.9505	0.9500	0.9494
3.6	0.9535	0.9532	0.9528	0.9524	0.9520	0.9515	0.9511	0.9506	0.9501	0.9496	0.9491	0.9485	0.9480
3.7	0.9552	0.9518	0.9515	0.9511	0.9506	0.9502	0.9497	0.9492	0.9487	0.9482	0.9477	0.9471	0.9465
3.8	0.9509	0.9505	0.9502	0.9497	0.9493	0.9488	0.9484	0.9479	0.9474	0.9468	0.9463	0.9457	0.9451
3.9	0.9496	0.9492	0.9488	0.9484	0.9480	0.9475	0.9470	0.9465	0.9460	0.9454	0.9448	0.9442	0.9436
4.0	0.9483	0.9479	0.9475	0.9471	0.9465	0.9462	0.9457	0.9451	0.9446	0.9440	0.9434	0.9428	0.9422

Table 3-B-7—F_{pb} Factors Used to Change From a Pressure Base of 14.73 Pounds Force per Square Inch Absolute to Other Pressure Bases

$$F_{pb} = \frac{14.73}{\text{Contract pressure base, psia}}$$

Pressure Base (pounds force per square inch absolute)	F_{pb}
14.4	1.0229
14.525	1.0141
14.65	1.0055
14.696	1.0023
14.70	1.0020
14.725	1.0003
14.73	1.0000
14.735	0.9997
14.775	0.9970
14.90	0.9886
15.025	0.9804
15.15	0.9723
15.225	0.9675
15.275	0.9643
15.325	0.9612
15.40	0.9565
15.525	0.9488
15.65	0.9412
15.775	0.9338
15.90	0.9264
16.025	0.9192
16.15	0.9121
16.275	0.9051
16.40	0.8982
16.70	0.8820

Table 3-B-8—F_{tb} Factors Used to Change From a Temperature Base of 60°F to Other Temperature Bases

$$F_{tb} = \frac{\text{Base °F} + 459.67}{60 + 459.67}$$

Temperature (°F)	F_{tb}	Temperature (°F)	F_{tb}
40	0.9615	65	1.0096
41	0.9634	66	1.0115
42	0.9654	67	1.0135
43	0.9673	68	1.0154
44	0.9692	69	1.0173
45	0.9711	70	1.0192
46	0.9731	71	1.0212
47	0.9750	72	1.0231
48	0.9769	73	1.0250
49	0.9788	74	1.0269
50	0.9808	75	1.0289
51	0.9827	76	1.0308
52	0.9846	77	1.0327
53	0.9865	78	1.0346
54	0.9885	79	1.0366
55	0.9904	80	1.0385
56	0.9923	81	1.0404
57	0.9942	82	1.0423
58	0.9962	83	1.0443
59	0.9981	84	1.0462
60	1.0000	85	1.0481
61	1.0019	86	1.0500
62	1.0038	87	1.0520
63	1.0058	88	1.0539
64	1.0077	89	1.0558
		90	1.0577

Table 3-B-9—F_{tf} Factors Used to Change From a Flowing Temperature of 60°F to Actual Flowing Temperature

$$F_{tf} = \sqrt{\frac{60 + 459.67}{T_f + 459.67}}$$

Temperature (°F)	F_{tf}	Temperature (°F)	F_{tf}	Temperature (°F)	F_{tf}
−20	1.0872	37	1.0229	94	0.9688
−19	1.0859	38	1.0219	95	0.9679
−18	1.0847	39	1.0208	96	0.9671
−17	1.0835	40	1.0198	97	0.9662
−16	1.0823	41	1.0188	98	0.9653
−15	1.0810	42	1.0178	99	0.9645
−14	1.0798	43	1.0168	100	0.9636
−13	1.0786	44	1.0158	101	0.9627
−12	1.0774	45	1.0148	102	0.9619
−11	1.0762	46	1.0137	103	0.9610
−10	1.0750	47	1.0127	104	0.9602
−9	1.0738	48	1.0117	105	0.9593
−8	1.0726	49	1.0108	106	0.9585
−7	1.0715	50	1.0098	107	0.9576
−6	1.0703	51	1.0088	108	0.9568
−5	1.0691	52	1.0078	109	0.9559
−4	1.0679	53	1.0068	110	0.9551
−3	1.0668	54	1.0058	111	0.9543
−2	1.0656	55	1.0048	112	0.9534
−1	1.0644	56	1.0039	113	0.9526
0	1.0633	57	1.0029	114	0.9518
1	1.0621	58	1.0019	115	0.9509
2	1.0610	59	1.0010	116	0.9501
3	1.0598	60	1.0000	117	0.9493
4	1.0587	61	0.9990	118	0.9485
5	1.0575	62	0.9981	119	0.9477
6	1.0564	63	0.9971	120	0.9468
7	1.0553	64	0.9962	121	0.9460
8	1.0541	65	0.9952	122	0.9452
9	1.0530	66	0.9943	123	0.9444
10	1.0519	67	0.9933	124	0.9436
11	1.0508	68	0.9924	125	0.9428
12	1.0497	69	0.9915	126	0.9420
13	1.0485	70	0.9905	127	0.9412
14	1.0474	71	0.9896	128	0.9404
15	1.0463	72	0.9887	129	0.9396
16	1.0452	73	0.9877	130	0.9388
17	1.0441	74	0.9868	131	0.9380
18	1.0430	75	0.9859	132	0.9372
19	1.0419	76	0.9850	133	0.9364
20	1.0409	77	0.9840	134	0.9356
21	1.0398	78	0.9831	135	0.9348
22	1.0387	79	0.9822	136	0.9340
23	1.0376	80	0.9813	137	0.9332
24	1.0365	81	0.9804	138	0.9325
25	1.0355	82	0.9795	139	0.9317
26	1.0344	83	0.9786	140	0.9309
27	1.0333	84	0.9777	141	0.9301
28	1.0323	85	0.9768	142	0.9294
29	1.0312	86	0.9759	143	0.9286
30	1.0302	87	0.9750	144	0.9278
31	1.0291	88	0.9741	145	0.9271
32	1.0281	89	0.9732	146	0.9263
33	1.0270	90	0.9723	147	0.9255
34	1.0260	91	0.9714	148	0.9248
35	1.0250	92	0.9706	149	0.9240
36	1.0239	93	0.9697	150	0.9232

Table 3-B-10—F_{gr} Factors Used to Adjust for Real Gas Relative Density (G_r): Base Conditions of 60°F and 14.73 Pounds Force per Square Inch Absolute

$$F_{gr} = \sqrt{\frac{1}{G_r}}$$

	F_{gr}									
G_r	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.550	1.3484	1.3472	0.3460	1.3447	1.3435	1.3423	1.3411	1.3399	1.3387	1.3375
0.560	1.3363	1.3351	1.3339	1.3327	1.3316	1.3304	1.3292	1.3280	1.3269	1.3257
0.570	1.3245	1.3234	1.3222	1.3211	1.3199	1.3188	1.3176	1.3165	1.3153	1.3142
0.580	1.3131	1.3119	1.3108	1.3097	1.3086	1.3074	1.3063	1.3052	1.3041	1.3030
0.590	1.3019	1.3008	1.2997	1.2986	1.2975	1.2964	1.2953	1.2942	1.2932	1.2921
0.600	1.2910	1.2899	1.2888	1.2878	1.2867	1.2856	1.2846	1.2835	1.2825	1.2814
0.610	1.2804	1.2793	1.2783	1.2772	1.2762	1.2752	1.2741	1.2731	1.2720	1.2710
0.620	1.2700	1.2690	1.2680	1.2669	1.2659	1.2649	1.2639	1.2629	1.2619	1.2609
0.630	1.2599	1.2589	1.2579	1.2569	1.2559	1.2549	1.2539	1.2529	1.2520	1.2510
0.640	1.2500	1.2490	1.2480	1.2471	1.2461	1.2451	1.2442	1.2432	1.2423	1.2413
0.650	1.2403	1.2394	1.2384	1.2375	1.2365	1.2356	1.2347	1.2337	1.2328	1.2318
0.660	1.2309	1.2300	1.2290	1.2281	1.2272	1.2263	1.2254	1.2244	1.2235	1.2226
0.670	1.2217	1.2208	1.2199	1.2190	1.2181	1.2172	1.2163	1.2154	1.2145	1.2136
0.680	1.2127	1.2118	1.2109	1.2100	1.2091	1.2082	1.2074	1.2065	1.2056	1.2047
0.690	1.2039	1.2030	1.2021	1.2012	1.2004	1.1995	1.1986	1.1978	1.1969	1.1961
0.700	1.1952	1.1944	1.1935	1.1927	1.1918	1.1910	1.1901	1.1893	1.1884	1.1876
0.710	1.1868	1.1859	1.1851	1.1843	1.1834	1.1826	1.1818	1.1810	1.1802	1.1793
0.720	1.1785	1.1777	1.1769	1.1761	1.1752	1.1744	1.1736	1.1728	1.1720	1.1712
0.730	1.1704	1.1696	1.1688	1.1680	1.1672	1.1664	1.1656	1.1648	1.1640	1.1633
0.740	1.1625	1.1617	1.1609	1.1601	1.1593	1.1586	1.1578	1.1570	1.1562	1.1555
0.750	1.1547	1.1539	1.1532	1.1524	1.1516	1.1509	1.1501	1.1493	1.1486	1.1478
0.760	1.1471	1.1463	1.1456	1.1448	1.1441	1.1433	1.1426	1.1418	1.1411	1.1403
0.770	1.1396	1.1389	1.1381	1.1374	1.1366	1.1359	1.1352	1.1345	1.1337	1.1330
0.780	1.1323	1.1316	1.1308	1.1301	1.1294	1.1287	1.1279	1.1272	1.1265	1.1258
0.790	1.1251	1.1244	1.1237	1.1230	1.1222	1.1215	1.1208	1.1201	1.1194	1.1187
0.800	1.1180	1.1173	1.1166	1.1159	1.1152	1.1146	1.1139	1.1132	1.1125	1.1118
0.810	1.1111	1.1104	1.1097	1.1090	1.1084	1.1077	1.1070	1.1063	1.1057	1.1050
0.820	1.1043	1.1036	1.1030	1.1023	1.1016	1.1010	1.1003	1.0996	1.0990	1.0983
0.830	1.0976	1.0970	1.0963	1.0957	1.0950	1.0944	1.0937	1.0930	1.0924	1.0917
0.840	1.0911	1.0904	1.0898	1.0891	1.0885	1.0878	1.0872	1.0866	1.0859	1.0853
0.850	1.0846	1.0840	1.0834	1.0827	1.0821	1.0815	1.0808	1.0802	1.0796	1.0790
0.860	1.0783	1.0777	1.0771	1.0764	1.0758	1.0752	1.0746	1.0740	1.0733	1.0727
0.870	1.0721	1.0715	1.0709	1.0703	1.0696	1.0690	1.0684	1.0678	1.0672	1.0666
0.880	1.0660	1.0654	1.0648	1.0642	1.0636	1.0630	1.0624	1.0618	1.0612	1.0606
0.890	1.0600	1.0594	1.0588	1.0582	1.0576	1.0570	1.0564	1.0558	1.0553	1.0547
0.900	1.0541	1.0535	1.0529	1.0523	1.0518	1.0512	1.0506	1.0500	1.0494	1.0489
0.910	1.0483	1.0477	1.0471	1.0466	1.0460	1.0454	1.0448	1.0443	1.0437	1.0431
0.920	1.0426	1.0420	1.0414	1.0409	1.0403	1.0398	1.0392	1.0386	1.0381	1.0375
0.930	1.0370	1.0364	1.0358	1.0353	1.0347	1.0342	1.0336	1.0331	1.0325	1.0320
0.940	1.0314	1.0309	1.0303	1.0298	1.0292	1.0287	1.0281	1.0276	1.0270	1.0265
0.950	1.0260	1.0254	1.0249	1.0244	1.0238	1.0233	1.0228	1.0222	1.0217	1.0212
0.960	1.0206	1.0201	1.0196	1.0190	1.0185	1.0180	1.0174	1.0169	1.0164	1.0159
0.970	1.0153	1.0148	1.0143	1.0138	1.0132	1.0127	1.0122	1.0117	1.0112	1.0107
0.980	1.0102	1.0096	1.0091	1.0086	1.0081	1.0076	1.0071	1.0066	1.0060	1.0055
0.990	1.0050	1.0045	1.0040	1.0035	1.0030	1.0025	1.0020	1.0015	1.0010	1.0005
1.000	1.0000									

Table 3-B-11—Supercompressibility Factors (F_{pv}) for G_r = 0.6 Without Nitrogen or Carbon Dioxide

Pressure (psia)	Temperature (°F)					
	20	40	60	80	100	120
100	1.00947	1.00807	1.00687	1.00504	1.00496	1.00419
200	1.02058	1.01762	1.01512	1.01294	1.01116	1.00958
300	1.03218	1.02748	1.02355	1.02022	1.01740	1.01497
400	1.04427	1.03764	1.03216	1.02756	1.02367	1.02035
500	1.05688	1.04810	1.04093	1.03497	1.02996	1.02572
600	1.06999	1.05884	1.04983	1.04243	1.03625	1.03104
700	1.08360	1.06983	1.05885	1.04990	1.04251	1.03631
800	1.09766	1.08103	1.06793	1.05737	1.04871	1.04149
900	1.11209	1.09237	1.07703	1.06479	1.05482	1.04656
1000	1.12679	1.10375	1.08608	1.07211	1.06081	1.05150
1100	1.14156	1.11508	1.09501	1.07927	1.06663	1.05628
1200	1.15616	1.12621	1.10372	1.08622	1.07225	1.06087
1300	1.17029	1.13696	1.11211	1.09289	1.07763	1.06524
1400	1.18358	1.14715	1.12007	1.09922	1.08271	1.06935
1500	1.19565	1.15657	1.12749	1.10512	1.08745	1.07318
1600	1.20615	1.16504	1.13425	1.11054	1.09180	1.07669
1700	1.21481	1.17237	1.14025	1.11540	1.09573	1.07986
1800	1.22146	1.17845	1.14541	1.11965	1.09919	1.08267
1900	1.22606	1.18318	1.14965	1.12324	1.10216	1.08509
2000	1.22868	1.18655	1.15294	1.12615	1.10462	1.08710

Note: The data in this table were generated using the A.G.A. Gas Measurement Program. Copyright © 1988 American Gas Association. All rights reserved. Gas input data are as follows: % CO_2 = 0; % N_2 = 0; specific gravity = 0.6. This table was developed for informational purposes only and is specific to the gas quality listed. The data in this table are *not* subject to adjustment for nitrogen or carbon dioxide content and, because of their broad range, should not be interpolated. With the A.G.A Program, the user establishes the gas composition parameters and specifies the table range that is consistent with field or measurement conditions.

APPENDIX 3-C—FLOW CALCULATION EXAMPLES

3-C.1 General

This appendix presents two methods for calculating the volume flow rate of natural gas through an orifice meter equipped with flange taps. The first method uses the equations presented in 3.3 through 3.5. The second method is based on the more traditional calculation format, which involves the computation of various factors. The equations used for the factor approach are presented in Appendix 3-B.

To assist the user in interpreting the calculation methodology, the data set given below, which is for a single orifice meter, is used consistently throughout the flow calculation examples. The volume flow rate is computed under the assumption that the measurements are absolute and without error. It should be noted that depending on the type of instrumentation used and the calibration methods employed, calibration and correction factors may need to be applied. *For simplicity in using hand calculations and for ease of interpretation in the following examples, intermediate values are rounded to six significant digits. Part 4 should be used for any implementation of the equations.*

3-C.2 Given Data

The orifice meter consists of a carbon steel meter tube equipped with flange taps and a Type 304 stainless steel orifice plate. Static pressure measurements are taken from the upstream tap.

d_r = mean orifice bore diameter at T_r of 68°F, in inches
= 4.000.
D_r = mean meter tube internal diameter at T_r of 68°F, in inches
= 8.071.
G_r = real gas relative density (specific gravity)
= 0.570.
h_w = average differential pressure, in inches of water at 60°F
= 50.0.
P_b = contract base pressure, in pounds force per square inch absolute
= 14.65
P_{f_1} = average upstream absolute static pressure, in pounds force per square inch absolute
= 370.0.
T_b = contract base temperature of 50°F, in degrees Rankine (50°F + 459.67)
= 509.67.
T_f = flowing temperature of 65°F, in degrees Rankine (65°F + 459.67)
= 524.67.
xc = carbon dioxide content, in mole percent
= 0.00
xn = nitrogen content, in mole percent
= 1.10.
k = isentropic exponent (c_p/c_v)
= 1.3.
α_1 = linear coefficient of thermal expansion for a stainless steel orifice plate, in inches per inch-°F
= 0.00000925.
α_2 = linear coefficient of thermal expansion for a carbon steel meter tube, in inches per inch-°F
= 0.00000620.
μ = dynamic viscosity, in pounds mass per foot-second
= 0.0000069.

3–C.3 Calculation Examples

3–C.3.1 METHOD 1: VOLUME FLOW RATE CALCULATION BASED ON 3.3 THROUGH 3.5

3–C.3.1.1 General

Using the given data set, the volume flow rate of natural gas, in cubic feet per hour at standard conditions, can be calculated using Equation 3-6b:

$$Q_v = 7709.61 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \qquad (3\text{-}6b)$$

Note: Since the given data contain values for the contract base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate at standard conditions will require conversion to the flow rate at base conditions of 14.65 pounds force per square inch absolute and 50°F.

The systematic approach to solving the volume flow rate equation above involves the calculation of the intermediate values described 3-C.3.1.2 through 3-C.3.1.7.

3–C.3.1.2 Flange–Tapped Orifice Meter Coefficient of Discharge [C_d(FT)]

The following equations are used to calculate the coefficient of discharge, C_d(FT):

$$C_d(FT) = C_i(FT) + 0.000511\left(\frac{10^6 \beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4 C \qquad (3\text{-}11)$$

$$C_i(FT) = C_i(CT) + Tap\ Term \qquad (3\text{-}12)$$

$$C_i(CT) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1 - \beta)M_1 \qquad (3\text{-}13)$$

$$Tap\ Term = Upstrm + Dnstrm \qquad (3\text{-}14)$$

$$Upstrm = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \qquad (3\text{-}15)$$

$$Dnstrm = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \qquad (3\text{-}16)$$

Also,

$$B = \frac{\beta^4}{1 - \beta^4} \qquad (3\text{-}17)$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4},\ 0.0\right) \qquad (3\text{-}18)$$

$$M_2 = \frac{2L_2}{1 - \beta} \qquad (3\text{-}19)$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \qquad (3\text{-}20)$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \qquad (3\text{-}21)$$

Where

C_d(FT) = coefficient of discharge at a specified pipe Reynolds number for a flange-tapped orifice meter

C_i(CT) = coefficient of discharge at an infinite pipe Reynolds number for corner-tapped orifice meter.

C_i(FT) = coefficient of discharge at an infinite pipe Reynolds number for a flange-tapped orifice meter.

d = orifice plate bore diameter calculated at T_f, in inches.
D = meter tube internal diameter calculated at T_f, in inches.
e = Napierian constant
= 2.71828.
$L_1 = L_2$
= dimensionless correction for tap location
= N_4/D for flange taps.
N_4 = 1.0 when D is in inches.
Re_D = pipe Reynolds number.
β = diameter ratio
= d/D.

Note: For this example, M_1 is equal to 0.0, since the given meter tube diameter (D) is greater than or equal to 2.8 inches. For meter tube diameters (D) less than 2.8 inches, $M_1 = 2.8 - D$. The solution of the intermediate equations presented above for the flow coefficient calculation follows.

3–C.3.1.3 Meter Tube Diameter, Orifice Plate Bore Diameter, and Diameter Ratio (D, d, and β)

Calculate the values of d, D, and β at a flowing temperature of 65°F from the given diameters d_r and D_r:

$$\begin{aligned} d &= d_r[1 + \alpha_1(T_f - T_r)] \qquad (3\text{-}9) \\ &= 4.000[1 + 0.00000925(524.67 - 527.67)] \\ &= 3.99989 \end{aligned}$$

And

$$\begin{aligned} D &= D_r[1 + \alpha_2(T_f - T_r)] \qquad (3\text{-}10) \\ &= 8.071[1 + 0.00000620(524.67 - 527.67)] \\ &= 8.07085 \end{aligned}$$

Substitute the given values of d and D at 65°F into Equation 3-8:

$$\begin{aligned} \beta &= d / D \qquad (3\text{-}8) \\ &= 3.99989 / 8.07085 \\ &= 0.495597 \end{aligned}$$

3–C.3.1.4 Velocity of Approach Factor (E_v)

The following equation is used to calculate the velocity of approach factor:

$$\begin{aligned} E_v &= \frac{1}{\sqrt{1 - \beta^4}} \qquad (3\text{-}22) \\ &= \frac{1}{\sqrt{1 - 0.495597^4}} \\ &= 1.03160 \end{aligned}$$

3–C.3.1.5 Expansion Factor (Y)

The following equation is used to calculate the expansion factor:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \qquad (3\text{-}32)$$

The intermediate value, x_1, is calculated as follows:

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\,P_{f_1}} \qquad (3\text{-}33)$$

Substitute the given values of h_w and P_{f_1} into Equation 3-32:

$$x_1 = \frac{50.0}{(27.707)(370.0)}$$
$$= 0.00487729$$

Substitute the values for k, x_1, and β into Equation 3-32:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \qquad (3\text{-}32)$$
$$= 1 - [0.41 + 0.35(0.495597)^4]\left(\frac{0.00487729}{1.3}\right)$$
$$= 0.998383$$

3–C.3.1.6 Compressibility (Z_b, Z_s, and Z_{f_1})

The derivation of the equation for compressibility is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the calculation procedures necessary for determining the compressibility at base conditions (Z_b), standard conditions (Z_s), or flowing conditions (Z_{f_1}). The following values for gas compressibility at the conditions given in the data set were obtained from the A.G.A. computer program that uses the calculation given in A.G.A. Transmission Measurement Committee Report No. 8. At $G_r = 0.57$,

$Z_b = 0.997839$ at 14.65 pounds force per square inch absolute and 509.67°R (50°F)
$Z_s = 0.997971$ at 14.73 pounds force per square inch absolute and 519.67°R (60°F)
$Z_{f_1} = 0.951308$ at 370 pounds force per square inch absolute and 524.67°R (65°F)

3–C.3.1.7 Reynolds Number (Re_D)

The following equation is used to calculate the pipe Reynolds number:

$$Re_D = 0.0114541\left(\frac{Q_b P_b G_r}{\mu D T_b Z_{b_{air}}}\right) \qquad (3\text{-}28)$$

Substituting the calculated value for D, standard conditions for P_b and T_b, a value of 0.999590 for $Z_{b_{air}}$, and the data set values for G_r and μ in Equation 3-28 produce the following

$$Re_D = (0.0114541)\left(\frac{Q_v(14.73)(0.570)}{(0.0000069)(8.07085)(519.67)(0.999590)}\right)$$
$$= 3.32449Q_v$$

When the flow rate is not known, the Reynolds number can be developed by assuming an initial value for the flange-tapped orifice meter coefficient of discharge, C_d(FT), and iterating for the correct values, as stated in 3.4.5. The following flow rate calculation provides the initial iteration of the Reynolds number. This initial iteration is based on an assumed value for C_d(FT) of 0.60. Based on experience, from three to five iterations should provide results consistent with the requirements of Part 4.

3–C.3.1.8 Volume Flow Rate (Q_v and Q_b)

The volume flow rate can be calculated by substituting the given parameters, the intermediate calculated values, and an assumed value of 0.60 for C_d(FT) in Equation 3-6b and iterating for the final solution:

$$Q_v = 7709.61 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \qquad (3\text{-}6b)$$

$$= 7709.61(0.60)(1.03160)(0.998383)(3.99989)^2$$

$$\times \sqrt{\frac{(370.0)(0.997971)(50.0)}{(0.951308)(0.570)(524.67)}}$$

$$= 614{,}033 \text{ cubic feet per hour at standard conditions}$$

[This is an estimate of the initial flow rate based on an assumed $C_d(FT)$ of 0.60.]

Substitute the estimate of initial flow rate into the Reynolds number equation and calculate the estimated initial Reynolds number:

$$Re_D = 3.32449 Q_v$$

$$= 3.32449(614{,}033)$$

$$= 2{,}041{,}347 \text{ (initial estimate of Reynolds number)}$$

Substitute the calculated value of β into Equation 3-17:

$$B = \frac{\beta^4}{1 - \beta^4} \qquad (3\text{-}17)$$

$$= \frac{0.495597^4}{1 - 0.495597^4}$$

$$= 0.0642005$$

Substitute the calculated values of β and D into Equation 3-19:

$$M_2 = \frac{2L_2}{1 - \beta} \qquad (3\text{-}19)$$

$$= \frac{2}{8.07085(1 - 0.495597)}$$

$$= 0.491284$$

Substitute the calculated values of Re_D and β into Equation 3-20:

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \qquad (3\text{-}20)$$

$$= \left[\frac{19{,}000(0.495597)}{2{,}041{,}347}\right]^{0.8}$$

$$= 0.0135261$$

Substitute the calculated value of Re_D into Equation 3-21:

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \qquad (3\text{-}21)$$

$$= \left(\frac{10^6}{2{,}041{,}347}\right)^{0.35}$$

$$= 0.778985$$

Substitute the appropriate calculated values into Equation 3-13 to determine the $C_i(CT)$ term of the coefficient of discharge, $C_d(FT)$:

$$C_i(CT) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1 - \beta)M_1 \qquad (3\text{-}13)$$

$$= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8$$

$$+ 0.003(1 - 0.495597)(0.0)$$

$$= 0.602414$$

Substitute the applicable calculated values into Equation 3-15 to compute the *Upstrm* term of the coefficient of discharge, C_d(FT):

$$Upstrm = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \qquad (3\text{-}15)$$
$$= [0.0433 + 0.0712e^{-8.5/\text{[illegible]}} - 0.1145e^{-6.0/\text{[illegible]}}]$$
$$\times [1 - 0.23(0.0135269)](0.0642005)$$
$$= 0.000851774$$

Substitute the applicable calculated values into Equation 3-16 to compute the *Dnstrm* term of the coefficient of discharge, C_d(FT):

$$Dnstrm = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \qquad (3\text{-}16)$$
$$= -0.0116[0.491284 - 0.52(0.491284)^{1.3}](0.495597)^{1.1}$$
$$\times [1 - 0.14(0.0134223)]$$
$$= -0.00149777$$

Substitute the applicable calculated values into Equation 3-14 to compute the *Tap Term* of the coefficient of discharge, C_d(FT):

$$Tap\ Term = Upstrm + Dnstrm \qquad (3\text{-}14)$$
$$= 0.000851774 + (-0.00149777)$$
$$= -0.000645999$$

Substitute the applicable calculated values into Equation 3-13 to compute the C_i(FT) term of the coefficient of discharge, C_i(FT):

$$C_i(\text{FT}) = C_i(\text{CT}) + Tap\ Term \qquad (3\text{-}12)$$
$$= 0.602414 - 0.000645999$$
$$= 0.601768$$

Substitute the value for C_i(FT) and the intermediate values into Equation 3-11 to calculate the discharge coefficient, C_d(FT):

$$C_d(\text{FT}) = C_i(\text{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4C \qquad (3\text{-}11)$$
$$= 0.601768 + 0.000511\left[\frac{10^6(0.495597)}{2{,}041{,}347}\right]^{0.7}$$
$$+ [0.0210 + 0.0049(0.0135261)](0.495597)^4(0.778985)$$
$$= 0.602947 \text{ (second estimate of the coefficient of discharge)}$$

By substituting the value of C_d(FT) into the applicable equations, the volume flow rate can be recalculated following the same process outlined in this example. The resulting volume flow rate value is as follows:

$$Q_v = 617{,}049 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(\text{FT}) = 0.602947]$$

And

$$Re_D = 3.32449Q_v = 3.32449(617{,}049)$$
$$= 2{,}051{,}373 \text{ (second estimate of Reynolds number)}$$

Resulting in

$$C_d(\text{FT}) = 0.602944 \text{ (third estimate of coefficient of discharge)}$$

On page 57, Equation 3-20 should read as follows:

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}$$

$$= \left[\frac{19{,}000(0.495597)}{2{,}041{,}328}\right]^{0.8} \qquad (3\text{-}20)$$

$$= 0.0135262$$

On page 57, Equation 3-21 should read as follows:

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35}$$

$$= \left(\frac{10^6}{2{,}041{,}328}\right)^{0.35} \qquad (3\text{-}21)$$

$$= 0.778988$$

On page 58, Equation 3-15 should read as follows:

$$Upstrm = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B$$

$$= [0.0433 + 0.0712e^{-8.5/\text{[illegible]}} - 0.1145e^{-6.0/\text{[illegible]}}]$$

$$\times [1 - 0.23(0.0135262)](0.0642005) \qquad (3\text{-}15)$$

$$= 0.000876388$$

On page 58, Equation 3-16 shoud read as follows:

$$Dnstrm = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A)$$

$$= -0.0116[0.491284 - 0.52(0.491284)^{1.3}](0.495597)^{1.1}$$

$$\times [1 - 0.14(0.0135262)] \qquad (3\text{-}16)$$

$$= -0.00152379$$

On page 58, Equation 3-14 should read as follows.

$$Tap\ Term = Upstrm + Dnstrm$$

$$= 0.000876388 + (-0.00152379) \qquad (3\text{-}14)$$

$$= -0.000647402$$

On page 58, Equation 3-12 should read as follows,

$$C(\text{FT}) = C(\text{CT}) + Tap\ Term$$

$$= 0.602414 - 0.000647402 \qquad (3\text{-}12)$$

$$= 0.601767$$

On page 58, Equation 3-11 should read as follows.

$$C_d(\text{FT}) = C(\text{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4C$$

$$= 0.601767 + 0.000511\left[\frac{10^6(0.495597)}{2{,}041{,}328}\right]^{0.7} \qquad (3\text{-}11)$$

$$+ [0.0210 + 0.0049(0.0135262)](0.495597)^4(0.778988)$$

$$= 0.602947 \text{ (second estimate of the coefficient of discharge)}$$

Following the same calculation procedure for iteration of flow rate, the resulting volumetric flow rate is as follows:

$$Q_v = 617{,}046 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(FT) = 0.602944]$$

And

$$Re_D = 3.32449Q_v = 3.32449(617{,}046)$$
$$= 2{,}051{,}363 \text{ (third estimate of Reynolds number)}$$

Resulting in

$$C_d(FT) = 0.602944 \text{ (fourth estimate of coefficient of discharge)}$$

The volume flow rate calculation based on the fourth estimate of $C_d(FT)$ follows. As stated above, three estimates of $C_d(FT)$ should normally provide volume flow rate calculation results that are consistent with the requirements of Part 4.

$$Q_v = 617{,}046 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(FT) = 0.602944]$$

Since the given data contain values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate is the standard volume flow rate. To calculate the flow rate at the given base conditions (P_b = 14.65 pounds force per square inch absolute and T_b = 509.67°R), the standard volume flow rate and the appropriate values for P, T, and Z are substituted into Equation 3-7 as follows:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \tag{3-7}$$

$$= 617{,}046\left(\frac{509.67}{519.67}\right)\left(\frac{14.73}{14.65}\right)\left(\frac{0.997839}{0.997971}\right)$$

$$= 608{,}396 \text{ cubic feet per hour at base conditions}$$

3–C.3.2 METHOD 2: VOLUME FLOW RATE CALCULATION BASED ON THE FACTOR APPROACH PRESENTED IN APPENDIX 3–B

3–C.3.2.1 General

Using the given data, the volume flow rate of natural gas, in cubic feet per hour at standard conditions, can be calculated using Equation 3-B-2, as stated in Appendix 3-B:

$$Q_v = F_n(F_c + F_{sl})Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv}\sqrt{P_{f1} h_w} \tag{3-B-2}$$

Since the given data contain values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate requires conversion to the flow rate at base conditions of 14.65 pounds force per square inch absolute and 60°F.

The systematic approach to solving Equation 3-B-2 involves calculation of the individual factors as shown in 3-C.3.2.2 through 3-C.3.2.10.

3–C.3.2.2 Numeric Conversion Factor (F_n)

Equation 3-B-5b is used to calculate the numeric conversion factor:

$$F_n = 338.196E_vD^2\beta^2 \tag{3-B-5b}$$

Where

$$E_v = \frac{1}{\sqrt{1 - \beta^4}} \qquad (3\text{-}22)$$

Calculate the value of d, D, and β at a flowing temperature of 65°F from the given diameters d_r and D_r:

$$\begin{aligned} d &= d_r[1 + \alpha_1(T_f - T_r)] && (3\text{-}9) \\ &= 4.000[1 + 0.00000925(524.67 - 527.67)] \\ &= 3.99989 \end{aligned}$$

And

$$\begin{aligned} D &= D_r[1 + \alpha_2(T_f - T_r)] && (3\text{-}10) \\ &= 8.071[1 + 0.00000620(524.67 - 527.67)] \\ &= 8.07085 \end{aligned}$$

$$\begin{aligned} \beta &= d / D && (3\text{-}8) \\ &= 3.99989 / 8.07085 \\ &= 0.495597 \end{aligned}$$

Substitute the values for β and D into Equation 3-B-5:

$$\begin{aligned} F_n &= 338.196 E_v D^2 \beta^2 && (3\text{-B-}5) \\ &= 338.196 \frac{1}{\sqrt{1 - \beta^4}} D^2 \beta^2 \\ &= 338.196 \frac{1}{\sqrt{1 - (0.495597)^4}} (8.07085)^2 (0.495597)^2 \\ &= 5581.82 \end{aligned}$$

3–C.3.2.3 Flange–Tapped Orifice Meter Coefficient of Discharge [C_d(FT)]

The following equation is used to calculate the coefficient of discharge:

$$C_d(\mathrm{FT}) = F_c + F_{sl} \qquad (3\text{-B-}6)$$

Where:

$$\begin{aligned} F_c &= 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 \\ &\quad + \left(0.0433 - 0.0712e^{-8.5/D} - 0.1145e^{-6.0/D}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1 - \beta^4} \\ &\quad - 0.0116\left[\frac{2}{D(1 - \beta)} - 0.52\left(\frac{2}{D(1 - \beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right] && (3\text{-B-}7) \\ F_{sl} &= 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} \\ &\quad + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.35} && (3\text{-B-}9) \\ Re_D &= 0.0114541\left(\frac{Q_v P_b G_r}{\mu D T_b Z_{b_{air}}}\right) && (3\text{-}28) \end{aligned}$$

On page 58, the third to the last equation should read as follows:

Q_v = 617,048 cubic feet per hour at standard conditions

[based on $C_d(FT)$ = 0.602947]

On page 58, the second to the last equation should read as follows:

$$Re_D = 3.32446 Q_v = 3.32446(617{,}048)$$

$$= 2{,}051{,}351 \text{ (second estimate of Reynolds number)}$$

On page 59, the second equation should read as follows:

$$Re_D = 3.32446 Q_v = 3.32446(617{,}046)$$

$$= 2{,}051{,}345 \text{ (third estimate of Reynolds number)}$$

On page 59, Equation 3-7 should read as follows:

$$Q_b = Q_v\left(\frac{P_f}{P_b}\right)\left(\frac{T_b}{T_f}\right)\left(\frac{Z_b}{Z_f}\right)$$

$$= 617{,}046\left(\frac{14.73}{14.65}\right)\left(\frac{509.67}{519.67}\right)\left(\frac{0.997839}{0.997971}\right) \qquad (3\text{-}7)$$

$$= 608{,}396 \text{ cubic feet per hour at base conditions}$$

On page 60, Equation 3-B-9 should read as follows:

$$F_c = 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7}$$

$$+ \left[0.0210 - 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000}{Re_D}\right)^{0.35} \qquad (3\text{-}B\text{-}9)$$

On page 62, the first equation should read as follows:

$$F_c = 0.5961 - 0.0291\beta^2 - 0.2290\beta^8$$

$$+ (0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1})\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4}$$

$$- 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]$$

$$= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8$$

$$+ (0.0433 + 0.0712e^{[illegible]} - 0.1145e^{[illegible]})[1 - 0.23(0.0137493)](0.0642005)$$

$$- 0.0116[0.491284 - 0.52(0.491284^{1.3})](0.495597)^{1.1}[1 - 0.14(0.0137493)]$$

$$= 0.601767$$

$$B = \frac{\beta^4}{1 - \beta^4} \tag{3-17}$$

$$M_2 = \frac{2L_2}{1 - \beta} \tag{3-19}$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \tag{3-20}$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \tag{3-21}$$

Note: In this example, since the given meter tube diameter (D) is greater than 2.8 inches, Equation 3-B-7 is used to calculate the F_c term. For meter tube diameters (D) less than 2.8 inches, Equation 3-B-8 must be used to calculate the F_c term. The solution of the intermediate equations presented above for the flow coefficient calculation follows.

Substituting the calculated values of β and D gives the following:

$$\frac{\beta^4}{1 - \beta^4} = \frac{(0.495597)^4}{1 - (0.495597)^4}$$
$$= 0.0642005$$

$$\frac{2}{D(1 - \beta)} = \frac{2}{8.07085(1 - 0.495597)}$$
$$= 0.491284$$

As discussed in 3.4.5, the Reynolds number (Re_D) for natural gas can be approximated using Equation 3-28. Note that the parameters of this example are within the recommended tolerances for viscosity, temperature, and specific gravity. Furthermore, 3.4.5 states that when the flow rate is not known, a more precise value for the Reynolds number can be determined through iteration of Equation 3-28 and that three to five iterations will provide results that are consistent with the requirements of Part 4. The initial assumption needed for the first iteration can come from assuming a value for C_d(FT) as in the previous example or from assuming an initial Reynolds number for the pipe Reynolds number. Table 3-B-1, Appendix 3-B, provides values for pipe Reynolds numbers versus nominal pipe diameters for the purpose of initiating the iteration process. This example uses Table 3-B-1 for the initial estimate of pipe Reynolds number.

$$Re_D = 2{,}000{,}000 \quad \text{(initial assumption from Table 3-B-1)}$$

Substituting the values of Re_D and β gives the following:

$$\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} = \left[\frac{19{,}000(0.495597)}{2{,}000{,}000}\right]^{0.8}$$
$$= 0.0137493$$

$$\left(\frac{10^6}{Re_D}\right)^{0.35} = \left(\frac{10^6}{2{,}000{,}000}\right)^{0.35}$$
$$= 0.784584$$

Substitute the appropriate calculated values into Equation 3-B-7 to determine the orifice calculation factor, F_c:

$$
\begin{aligned}
F_c &= 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 \\
&\quad + \left(0.0433 + 0.0712e^{-4/D} - 0.1145e^{-4/D}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4} \\
&\quad - 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right] \\
&= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8 \\
&\quad + \left(0.0433 + 0.0712e^{-4/\text{[illegible]}} - 0.1145e^{-4/\text{[illegible]}}\right)[1 - 0.23(0.0137493)](0.0642005) \\
&\quad - 0.0116[0.491284 - 0.52(0.491284)]^{1.3}(0.495597)^{1.1}[1 - 0.14(0.0137493)] \\
&= 0.601767
\end{aligned}
$$

Substitute the applicable calculated values into Equation 3-B-9 to compute the orifice slope factor, F_{sl}:

$$
\begin{aligned}
F_{sl} &= 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} \\
&\quad + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.35} \qquad \text{(3-B-9)} \\
&= 0.000511\left(\frac{1{,}000{,}000(0.4955972)}{2{,}000{,}000}\right)^{0.7} \\
&\quad + [0.0210 + 0.0049(0.0137493)](0.495597)^4(0.784584) \\
&= 0.00118960
\end{aligned}
$$

Substitute the values for F_c and F in Equation 3-B-6 to calculate the discharge coefficient, C_d(FT):

$$
\begin{aligned}
C_d(\text{FT}) &= F_c + F_{sl} \\
&= 0.601767 + 0.00118960 \\
&= 0.602957
\end{aligned}
$$

3-C.3.2.4 Expansion Factor (Y_1)

The following equation is used to calculate the expansion factor:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \qquad \text{(3-32)}$$

The intermediate value, x_1, is calculated as follows:

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\,P_{f_1}} \qquad \text{(3-33)}$$

Substitute the given values of h_w and P_{f_1} into Equation 3-33:

$$
\begin{aligned}
x_1 &= \frac{50.0}{27.707(370.0)} \\
&= 0.00487729
\end{aligned}
$$

Substitute the values for k, x_1, and β into Equation 3-32:

On page 62, Equation 3-B-9 should read as follows:

$$
\begin{aligned}
F_{sl} &= 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} \\
&\quad + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000}{Re_D}\right)^{0.35} \qquad (3\text{-}B\text{-}9) \\
&= 0.000511\left(\frac{1{,}000{,}000(0.495597)}{2{,}000{,}000}\right)^{0.7} \\
&\quad + [0.0210 + 0.0049(0.0137493)](0.495597)^4(0.784584) \\
&= 0.00118960
\end{aligned}
$$

On page 65, the first equation should read as follows:

$$
\begin{aligned}
Re_D &= 0.0114588\left(\frac{Q_v P_b G_r}{\mu D T_b}\right) \\
&= 3.32446Q_v \\
&= 3.32446(617{,}057) \\
&= 2{,}051{,}400 \text{ (second iteration)}
\end{aligned}
$$

On page 80, Equation 3-D-9 should read as follows (that is, Kpipe, *should be inserted in the equation and the second line of the equation should be deleted):*

$$Re_d = 220{,}858\, d F_{pv} \sqrt{\rho h_w}\ x\ (K\text{pipe}) \qquad (3\text{-}D\text{-}9)$$

On page 80, the nomenclature should read as follows (that is, Kpipe, *should be inserted in the list):*

Where:

G = specific gravity.
Kpipe = values from Table 3-D-4.
Re_d = orifice bore Reynolds number.
T_f = absolute flowing temperature, in degrees Rankine
ρ = specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F

On page 97, Equations 3-F-4 and 3-F-5 should read as follows:

$$H_v^{id} = \phi_1(H_v^{id})_1 + \phi_2(H_v^{id})_2 + \ldots + \phi_n(H_v^{id})_n \qquad (3\text{-}F\text{-}4)$$

$$H_v^{id} = \sum_{i=1}^{n} \phi_i (H_v^{id})_i \qquad (3\text{-}F\text{-}5)$$

On page 102, the second line of Equation 3-4a should read as follows:

$$Q_r = 359.072 C_d(FT) E_v Y d^2 \sqrt{\frac{P_f G_i (28.9625)(144) h_w}{Z_f R T_f}}\ \frac{Z_b R T_b}{P_b G_i (28.9625)(144)}$$

$$\begin{aligned} Y_1 &= 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \qquad (3\text{-}32) \\ &= 1 - [0.41 + 0.35(0.495597)^4]\left(\frac{0.00487729}{1.3}\right) \\ &= 0.998383 \end{aligned}$$

3–C.3.2.5 Compressibility (Z_b, Z_s, and Z_{f_1})

The derivation of the compressibility equation is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the procedures necessary for calculating the compressibility at base conditions (Z_b), standard conditions (Z_s), or flowing conditions (Z_{f_1}). The following values for gas compressibility at the given conditions were obtained from the A.G.A. computer program, using the A.G.A. Transmission Measurement Committee Report No. 8 calculation.

At $G_r = 0.57$,

$Z_b = 0.997839$ at 14.65 pounds force per square inch absolute and 509.67°R (50°F)
$Z_s = 0.997971$ at 14.73 pounds force per square inch absolute and 519.67°R (60°F)
$Z_{f_1} = 0.951308$ at 370 pounds force per square inch absolute and 524.67°R (65°F)

3–C.3.2.6 Base Pressure Factor (F_{pb})

The base pressure factor is calculated using Equation 3-B-10 as follows:

$$\begin{aligned} F_{pb} &= \frac{14.73}{P_b} \qquad (3\text{-B-}10) \\ &= \frac{14.73}{14.73} \\ &= 1.00000 \end{aligned}$$

In this example, F_{pb} has been calculated for a base pressure of 14.73 pounds force per square inch absolute, instead of 14.65 pounds force per square inch absolute as in the given data, and a base volume at the given base conditions has been calculated after the standard volume was determined. This procedure was necessary because of the use of the base compressibility of air ($Z_{b_{air}}$) of 0.999590 at 14.73 pounds force per square inch absolute and 60°F in the development of the numerical constant 338.196 in the F_n factor (see Appendix 3-G).

3–C.3.2.7 Base Temperature Factor (F_{tb})

Equation 3-B-11 is used to calculate the base temperature factor:

$$\begin{aligned} F_{tb} &= \frac{T_b}{519.67} \qquad (3\text{-B-}11) \\ &= \frac{519.67}{519.67} \\ &= 1.00000 \end{aligned}$$

In this example, F_{tb} has been calculated for a base temperature of 519.67°R (60°F) instead of 509.67°R(50°F) as in the given data, and a base volume at the given base conditions has been calculated after the standard volume was determined. This procedure was necessary because of the use of the base compressibility of air ($Z_{b_{air}}$) of 0.999590 at 14.73 pounds force per square inch absolute and 60°F in the development of the numerical constant 338.196 in the F_n factor (see Appendix 3-G).

3–C.3.2.8 Flowing Temperature Factor (F_{tf})

The flowing temperature factor is calculated using Equation 3-B-12 as follows:

$$F_{tf} = \sqrt{\frac{519.67}{T_f}} \qquad \text{(3-B-12)}$$

Substitute the given flowing temperature, T_f, into Equation 3-B-12:

$$\begin{aligned} F_{tf} &= \sqrt{\frac{519.67}{T_f}} \\ &= \sqrt{\frac{519.67}{524.67}} \\ &= 0.995224 \end{aligned}$$

3–C.3.2.9 Real Gas Relative Density Factor (F_{gr})

Equation 3-B-13 is used to calculate the real gas relative density factor.

$$F_{gr} = \sqrt{\frac{1}{G_r}} \qquad \text{(3-B-13)}$$

Substitute the given specific gravity, G_r, into Equation 3-B-13:

$$\begin{aligned} F_{gr} &= \sqrt{\frac{1}{G_r}} \\ &= \sqrt{\frac{1}{0.570}} \\ &= 1.32453 \end{aligned}$$

3–C.3.2.10 Supercompressibility Factor (F_{pv})

As stated in the calculations in 3-C.3.1, the derivation of the equation for compressibility is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the procedures necessary for calculating the compressibility at standard conditions (Z_s) or at flowing conditions (Z_{f_1})

$$\begin{aligned} Z_s &= 0.997971 \\ Z_{f_1} &= 0.951308 \end{aligned}$$

Equation 3-B-14 is used to calculate the supercompressibility factor:

$$\begin{aligned} F_{pv} &= \sqrt{\frac{Z_s}{Z_f}} \\ &= \sqrt{\frac{0.997971}{0.951308}} \\ &= 1.02423 \end{aligned}$$

3–C.3.2.11 Volume Flow Rate (Q_v)

The volume flow rate is calculated by substituting the given parameters and the intermediate calculated factors into Equation 3-B-2:

$$\begin{aligned} Q_v &= F_n (F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \sqrt{P_{f_1} h_w} \qquad \text{(3-B-2)} \\ &= 617.057 \end{aligned}$$

The calculated flow rate above is based on an initial assumed value for the Reynolds number (Re_D) of 2,000,000. For the second estimate, the value of Re_D is calculated as follows:

$$
\begin{aligned}
Re_D &= 0.0114588\left(\frac{Q_v P_s G_r}{\mu D T_s}\right) \\
&= 3.32449 Q_v \\
&= 3.32449(617{,}057) \\
&= 2{,}051{,}400 \text{ (second iteration)}
\end{aligned}
$$

By substituting the second estimate of Re_D into the applicable equations, the volume flow rate can be recalculated by following the process outlined in 3-C.3.1. The resulting volume flow rate is as follows:

$$Q_v = 617{,}013 \quad \text{(based on the second estimate of } Re_D\text{)}$$

The same calculation procedures are used to obtain the third estimate of Re_D:

$$
\begin{aligned}
Re_D &= 3.32449 Q_v \\
&= 3.32449(617{,}013) \\
&= 2{,}051{,}254 \text{ (third iteration)}
\end{aligned}
$$

The volume flow rate calculation based on the third estimate of Re_D follows. As stated above, three to five estimates of Re_D will provide calculation results that are consistent with the requirements of Par 4.

$$
\begin{aligned}
Q_v &= F_n (F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \sqrt{P_{f_1} h_w} \\
&= (5581.82)(0.601767 + 0.00117736)(0.998383)(1.00000)(1.00000) \\
&\quad \times (0.995224)(1.32453)(1.02423)\sqrt{(370.0)(50.0)} \\
&= 617{,}044 \text{ cubic feet per hour}
\end{aligned}
$$

Note: The calculated volume flow rate is based on the third estimate of Re_D. The small discrepancy between the calculated volume flow rate, Q_v, in Methods 1 and 2 results from the rounding techniques used in the series of equations in the examples

Since the given data included values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differed from the values established in Part 3 for standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate is the standard volume flow rate. To calculate the flow rate at base conditions (P_b = 14.65 pounds force per square inch absolute and T_b = 509.67°R), the standard volume flow rate and the appropriate values for P, T, and Z are substituted into Equation 3-7 as follows:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \qquad (3\text{-}7)$$

$$
\begin{aligned}
&= 617{,}044\left(\frac{509.67}{519.67}\right)\left(\frac{14.73}{14.65}\right)\left(\frac{0.997839}{0.997971}\right) \\
&= 608\ 394 \text{ cubic feet per hour at base conditions}
\end{aligned}
$$

APPENDIX 3-D—PIPE TAP ORIFICE METERING

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3–D.1 Symbols, Units, and Terminology

3–D.1.1 GENERAL

Some of the symbols listed in 3-D.1.2 are specific to this appendix. Unless otherwise noted, all of these symbols are dimensionless. Symbols that are used in this appendix but not listed in 3-D.1.2 are defined in 3.2.2.

3–D.1.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
C'	Orifice flow constant	—
F_b	Basic orifice factor	—
K_e	Coefficient of discharge when Reynolds number = $(1{,}000{,}000d)/15$	—
K_o	Coefficient of discharge for infinite Reynolds number	—
ρ	Specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F	lbm/ft^3

3–D.2 Scope

3–D.2.1 INTRODUCTION

Recent research work on orifice measurement has been restricted to flange, corner, and radius tap meters. It is recognized that a number of "pipe tap" meters continue in operation in natural gas measurement in the United States. The provisions of the second (1985) edition of Chapter 14, Section 3, that are applicable to pipe tap configurations are included in this appendix. The dimensional information, tolerances, and computation methods in this appendix are only applicable to pipe tap meters.

This appendix provides recommendations and specifications relating to the measurement of natural gas and other related hydrocarbon fluids by means of orifice meters equipped with pipe taps. It includes definitions, construction and installation specifications, and instructions for computing flow rate and volume. Also included are equations and tables that provide factors necessary to apply adjustments to the basic pipe tap orifice flow.

This appendix covers the measurement of natural gas by pipe tap orifice meters, including the primary element and the methods of calculation. It does not cover the equipment used to determine the pressure, temperature, specific gravity, and other variances that must be known for the accurate measurement of natural gas.

3–D.2.2 GENERAL

Unless specifically noted in this appendix, all information and data presented in the body of this standard—including recommendations, specifications, and symbols—are applicable to pipe tap orifice metering.

3–D.2.3 TYPE OF METER

This appendix is limited to orifice meters that have circular orifices located concentrically in the meter tube, having upstream and downstream pressure taps as specified for pipe taps.

3–D.2.4 DEFINITION OF *PIPE TAP PRESSURE MEASUREMENT*

The definition of *pipe tap pressure measurement* is based on the position of the pair of tap holes. The upstream tap center is located 2.5 times the inside pipe diameter upstream from the nearest plate face, and the downstream tap center is located 8 times the inside pipe diameter downstream from the nearest plate face (see 3-D.3.4.1).

3–D.3 Construction and Installation Specifications

3–D.3.1 BETA RATIO LIMITATIONS OF ORIFICE PLATES

The orifice-to-meter-tube (pipe) diameter ratio ($\beta = d/D$) should fall within the range from 0.20 to 0.67 inclusive. These limits, with an uncertainty as high as ±0.75 percent, may be exceeded when additional flow uncertainty is acceptable. Beta ratios that exceed the range from 0.20 to 0.67, with an uncertainty as high as ±1.5 percent, may be used; however, the flow constants for these extreme values of β are subject to higher tolerances, and the use of these extremes should be avoided.

3–D.3.2 METER TUBE SPECIFICATIONS

3–D.3.2.1 Definition

The term *meter tube* refers to the straight upstream pipe of length A or A' on the installation sketches in Part 2 (including the straightening vanes, if used), the orifice flanges or fittings, and the downstream pipe (length B on the installation sketches in Part 2) beyond the orifice. The length of upstream and downstream pipe is specified in Part 2. The tolerances for the diameter and the restrictions on the inside surface of the meter tube are specified in 3-D.3.2.4. There shall be no pipe connections within these distances other than straightening vanes, the thermometer wells specified in Part 2, and the pressure taps specified in 3-D.2.4 and Part 2.

3–D.3.2.2 Inside Surface

The sections of pipe to which the orifice flanges or fittings are attached and the adjacent pipe sections that constitute the meter tube, as defined in 3-D.3.2.1, shall comply with the following:

a. The roughness of the inside pipe walls shall not exceed 300 microinches. Carefully selected smooth commercial pipe may be used. Seamless pipe or cold drawn seamless pressure tubing may be used, provided its inside wall is smooth. Drawn-over-mandrel (DOM), electric-resistance-welded (ERW), straight-seam tubing manufactured to the requirements of ASTM A 513, T-5, may also be used. To improve smoothness inside the meter tube, the inside pipe walls may be machined, ground, or coated.
b. Grooves, scoring, pits, and ridges resulting from seams; distortion caused by welding; offsets; and other irregularities (regardless of their size) that affect the inside diameter at the points identified in Figure 3-D-1 by more than the tolerances shown are not permitted. When these tolerances are exceeded, the irregularities must be corrected.
c. The interior of the meter tube shall be kept clean and free from accumulations of contaminants, such as dirt and liquids, at all times.

3–D.3.2.3 Meter Tube Diameter

The mean inside diameter of the meter tube shall be determined as follows:

a. Measurements shall be made on at least four diameters equally spaced in a plane 1 inch upstream from the upstream face of the orifice plate. The mean (arithmetic average) of these measurements is defined as the mean meter tube diameter to be used in calculating the flow coefficient when minimum uncertainty of this variable is desired.
b. Check measurements of the upstream inside diameter of the meter tube shall be made at two or more additional cross-sections. The actual locations of the check measurements of the diameter, circumferentially and axially along the tube, are not specified. These checks should be taken at points that will indicate the maximum and minimum diameters that exist and should cover at least two pipe diameters from the face of the orifice plate or extend past the flange or fitting weld, whichever distance is greater. Check measurements are used to verify the uniformity of the upstream meter tube but do not become a part of the mean meter tube diameter.

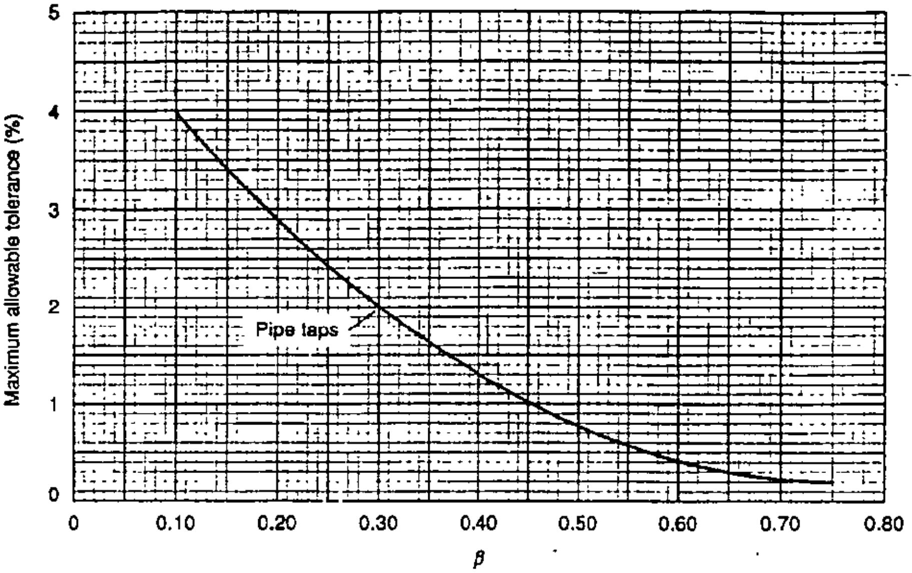


Figure 3-D-1—Maximum Percentage Allowable Meter Tube Tolerance Versus Beta Ratio

c. The inside diameter of the downstream section of the meter tube shall be measured in a plane 1 inch downstream from the downstream face of the orifice plate. Check measurements of the diameter of the downstream section of the meter tube, similar to those described in Item b above, shall be made at two additional cross-sections.

3–D.3.2.4 Tolerances and Restrictions

The tolerances for the diameter and the restrictions on the inside surface of the meter tube are as follows:

a. The difference between the maximum measured diameter and the minimum measured diameter on the inlet section shall not exceed the tolerance shown in Figure 3-D-1 as a percentage of the mean diameter defined in 3-D.3.2.3. The relationship below may be used to calculate the variance of the diameter of the upstream section of the meter tube:

$$\frac{\text{Maximum diameter} - \text{Minimum diameter}}{D} \times 100 \leq \text{Percent tolerance in Figure 3-D-1}$$

b. Abrupt changes in diameter (shoulders, offsets, ridges, and so forth) shall not exist in the meter tube (see 3-D.3.2.3, Item b).

c. When Table 3-D-1 is used for flow measurement estimation, the meter tube diameter, as defined in 3-D.3.2.3, shall agree with the inside diameters listed in the tables within the tolerance shown in Figure 3-D-1.

d. Any diameter measurement in the downstream section shall not vary from the mean diameter of the meter tube, as defined in 3-D.3.2.3, by more than the tolerance shown in Figure 3-D-1. The following relationship may be used to calculate the variance of the diameter of the downstream section of the meter tube:

$$\left|\frac{\text{Any diameter} - D}{D}\right| \times 100 \leq \text{Percent tolerance in Figure 3-D-1}$$

Application of this equation doubles the tolerance for the downstream section of the meter tube.

e. The temperature at which the meter tube measurements are made should be recorded for correction to the operating conditions.

For new installations, in which the beta ratio is likely to be changed, the tolerance permitted for variations in pipe size, as shown in Figure 3-D-1, should be the same as that given for a maximum orifice plate diameter ratio (β) of 0.75.

3–D.3.2.5 Use of Table 3–D–1

If Table 3-D-1 is used for flow estimation, the mean inside diameter of the upstream section of the meter tube should be as nearly the same as the published inside diameter given in Table 3-D-1 as is possible. The inside diameters given in the table were used to calculate the constants in the table. If the mean meter tube diameter differs from the table inside diameter by an amount greater than the tolerance set forth in Figure 3-D-1 or if minimum uncertainty is desired, the mean meter tube diameter should be used to compute the orifice-to-meter-tube diameter ratio, β, as well as the flow coefficient. Other factors should be calculated for this exact value of β.

3–D.3.3 LENGTH OF PIPE PRECEDING AND FOLLOWING THE ORIFICE

The installation sketches and accompanying graphs are not duplicated in this appendix but are available in Part 2, Figures 2-5 through 2-9. The graphs show the minimum lengths of straight pipe required (expressed in nominal pipe diameters) versus beta ratio. It must be noted that when pipe taps are used, lengths *A*, *A'*, and *C* shall be increased by two nominal pipe diameters and length *B* shall be increased by eight nominal pipe diameters. The lengths of straight pipe should be those required for the maximum beta ratio that may be used.

3–D.3.4 PRESSURE TAP HOLES

3–D.3.4.1 Location

Meter tubes that use pipe taps shall have the center of the upstream tap hole located 2.5 times the published or actual inside diameter from the upstream face of the orifice plate.

Table 3-D-1—Basic Orifice Factors (F_b) for Pipe Taps (All Dimensions in Inches)

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 2 Inches			Published Inside Diameters at Nominal Pipe Size of 3 Inches				Published Inside Diameters at Nominal Pipe Size of 4 Inches			
	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.250	12.850	12.813	12.800	12.782	22.765	12.754	12.748	12.745	12.737	12.727	12.723
0.375	29.362	29.098	29.006	28.883	28.772	28.711	28.682	28.670	28.635	26.599	28.585
0.500	53.713	52.817	52.482	52.020	51.594	51.354	51.244	51.197	51.065	50.937	50.887
0.625	87.237	84.920	84.085	82.924	81.802	81.143	80.837	80.704	80.334	79.976	79.837
0.750	132.29	126.87	124.99	122.45	120.08	118.67	118.00	117.70	116.87	116.05	115.73
0.875	192.87	181.02	177.09	171.93	167.26	164.58	163.31	162.76	161.17	159.58	158.94
1.000	275.73	251.11	243.25	233.30	224.61	219.77	217.53	216.55	213.79	211.03	209.92
1.125	392.50	342.99	327.99	309.44	293.87	285.49	281.67	280.03	275.43	270.91	269.10
1.250		466.00	438.00	404.53	377.[illegible]0	363.41	357.13	354.45	347.04	339.88	337.06
1.375			583.98	524.69	478.89	455.83	445.75	441.49	429.84	418.80	414.51
1.500				679.11	602.80	565.80	549.95	543.32	525.41	508.77	502.39
1.625					755.89	697.45	672.96	662.83	635.77	611.12	601.81
1.750					947.87	856.39	819.07	803.79	763.53	727.55	714.17
1.875						1,050.4	994.01	971.22	912.00	860.19	841.21
2.000						1,290.7	1,205.6	1,171.9	1,085.5	1,011.7	985.07
2.125							1,465.1	1,415.0	1,289.7	1,185.4	1,148.4
2.250									1,532.0	1,385.4	1,334.5
2.375									1,822.9	1,617.2	1,547.4
2.500										1,887.7	1,792.3
2.625										2,206.1	2,076.0
2.750											2,407.0

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 6 Inches				Published Inside Diameters at Nominal Pipe Size of 8 Inches			Published Inside Diameters at Nominal Pipe Size of 10 Inches			Published Inside Diameters at Nominal Pipe Size of 12 Inches		
	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.136	11.374	11.938	12.090
0.500	50.740	50.707	50.653	50.629									
0.625	79.438	79.351	79.219	79.164									
0.750	114.81	114.62	114.32	114.20									
0.875	157.11	156.72	156.13	155.89	155.11	154.99	154.97						
1.000	206.63	205.92	204.85	204.41	203.01	202.80	202.76	202.16					
1.125	263.71	262.52	260.72	259.99	257.62	257.28	257.20	256.23	256.01	255.96			
1.250	328.73	326.87	324.03	322.87	319.10	318.57	318.44	316.90	316.57	316.49	315.82	315.57	315.51
1.375	402.07	399.32	395.09	393.34	387.63	386.81	386.63	384.30	383.80	383.68	382.67	382.31	382.22
1.500	484.21	480.26	474.21	471.70	463.40	462.20	461.93	458.53	457.80	457.64	456.17	455.65	455.53
1.625	575.75	570.19	561.74	558.25	546.62	544.93	544.54	539.73	538.70	538.47	536.40	535.67	535.49
1.750	677.39	669.69	658.09	653.34	637.52	635.20	634.67	628.05	626.63	626.30	623.46	622.46	622.22
1.875	790.00	779.49	763.79	757.41	736.36	733.25	732.53	723.63	721.72	721.28	717.45	716.12	715.79
2.000	914.59	900.39	879.40	870.95	843.36	839.31	838.37	826.66	824.14	823.56	818.51	816.75	816.32
2.125	1,052.3	1,033.4	1,005.6	994.54	958.80	953.61	952.40	937.31	934.04	933.29	926.74	924.46	923.90
2.250	1,204.7	1,179.6	1,143.2	1,128.9	1,083.0	1,076.4	1,074.9	1,055.8	1,051.6	1,050.7	1,042.3	1,039.4	1,038.7
2.375	1,373.4	1,340.5	1,293.2	1,274.6	1,216.3	1,208.0	1,206.1	1,182.3	1,177.0	1,175.8	1,165.3	1,161.7	1,160.8
2.500	1,560.5	1,517.5	1,456.5	1,432.8	1,359.2	1,348.9	1,346.5	1,316.9	1,310.5	1,309.0	1,296.0	1,291.4	1,290.3
2.625	1,768.3	1,712.6	1,634.4	1,604.3	1,512.1	1,499.3	1,496.4	1,460.1	1,452.2	1,450.4	1,434.4	1,428.8	1,427.4
2.750	1,999.9	1,928.1	1,828.3	1,790.4	1,675.4	1,659.7	1,656.1	1,611.8	1,602.3	1,600.1	1,580.7	1,573.9	1,572.2
2.875	2,258.6	2,166.5	2,040.0	1,992.3	1,849.9	1,830.7	1,826.3	1,771.6	1,761.1	1,758.4	1,735.2	1,727.0	1,725.0
3.000	2,548.6	2,431.0	2,271.2	2,211.6	2,036.1	2,012.7	2,007.4	1,942.6	1,928.8	1,925.6	1,897.9	1,888.2	1,885.8
3.125	2,875.3	2,725.3	2,524.3	2,450.2	2,234.7	2,206.4	2,200.0	2,122.2	2,105.8	2,102.0	2,069.1	2,057.6	2,054.7
3.250	3,244.9	3,054.0	2,801.9	2,710.0	2,446.6	2,412.5	2,404.8	2,311.8	2,292.3	2,287.8	2,249.0	2,235.4	2,232.1
3.375	3,665.7	3,422.4	3,106.9	2,993.4	2,672.6	2,631.7	2,622.4	2,511.7	2,488.7	2,483.4	2,437.8	2,421.9	2,418.0
3.500		3,837.6	3,443.1	3,303.1	2,913.7	2,864.8	2,853.7	2,722.5	2,695.4	2,689.2	2,635.8	2,617.2	2,612.7
3.625		4,308.1	3,814.5	3,642.4	3,171.2	3,112.8	3,099.6	2,944.5	2,912.8	2,905.5	2,843.2	2,821.6	2,816.4
3.750			4,226.4	4,014.9	3,446.1	3,376.7	3,361.1	3,178.4	3,141.3	3,132.8	3,060.3	3,035.4	3,029.3
3.875			4,685.0	4,425.2	3,739.9	3,657.7	3,639.3	3,424.6	3,381.4	3,371.5	3,287.5	3,258.8	3,251.8
4.000			5,197.9	4,878.5	4,054.3	3,957.1	3,935.3	3,683.9	3,633.6	3,622.2	3,525.2	3,492.1	3,484.0
4.250					4,751.6	4,616.7	4,586.7	4,244.2	4,176.9	4,161.7	4,033.1	3,989.6	3,979.1
4.500					5,554.8	5,369.1	5,328.1	4,865.6	4,776.3	4,756.2	4,587.4	4,530.9	4,517.3
4.750					6,485.5	6,231.3	6,175.4	5,555.6	5,438.0	5,411.6	5,191.9	5,119.1	5,101.6
5.000					7,571.6	7,224.5	7,148.8	6,323.1	6,169.4	6,135.0	5,851.1	5,757.9	5,735.6
5.250					8,850.5	8,376.6	8,274.2	7,178.8	6,979.1	6,934.6	6,570.1	6,451.7	6,423.4
5.500						9,724.0	9,585.4	8,135.5	7,877.4	7,820.2	7,354.9	7,205.3	7,169.7
5.750								9,208.8	8,876.6	8,803.3	8,212.4	8,024.4	7,979.8
6.000								10,418	9,991.5	9,898.0	9,150.7	8,915.6	8,860.0
6.250								11,786	11,240	11,121	10,179	9,886.4	9,817.5
6.500								13,344	12,644	12,493	11,309	10,946	10,860
6.750									14,231	14,038	12,552	12,103	11,998
7.000									16,035	15,790	13,925	13,371	13,242
7.250											15,446	14,763	14,605
7.500											17,135	16,295	16,102
7.750											19,021	17,986	17,750
8.000												19,861	19,572
8.250												21,948	21,594

The center of the downstream tap hole shall be located eight times the published or actual inside diameter from the downstream face of the orifice plate. Figure 3-D-2 shows the allowable tolerances. A maximum beta ratio of 0.75 should be used in the design of new installations.

3–D.3.4.2 Fabrication

Meter tubes that use pipe taps shall have a hole of the proper size drilled through the pipe wall. Proper hole sizes are listed in Table 3-D-2. The hole shall not be threaded. A fitting

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
1.500	453.93	453.79										
1.625	533.28	533.09	532.94									
1.750	619.20	618.94	618.74									
1.875	711.75	711.41	711.14									
2.000	811.01	810.55	810.21	806.73	806.59	806.42						
2.125	917.03	916.45	916.01	911.54	911.37	911.15						
2.250	1,029.9	1,029.2	1,028.6	1,022.9	1,022.7	1,022.5						
2.375	1,149.7	1,148.8	1,148.1	1,141.0	1,140.7	1,140.4	1,136.8	1,136.5	1,136.3			
2.500	1,276.6	1,275.4	1,274.5	1,265.7	1,265.4	1,265.0	1,260.6	1,260.2	1,260.0			
2.625	1,410.5	1,409.1	1,408.0	1,397.2	1,396.8	1,396.3	1,390.9	1,390.5	1,390.2			
2.750	1,551.7	1,550.0	1,548.6	1,535.5	1,535.0	1,534.4	1,527.9	1,527.4	1,527.0			
2.875	1,700.2	1,698.1	1,696.5	1,680.7	1,680.1	1,679.4	1,671.6	1,670.9	1,670.5	1,663.7		
3.000	1,856.1	1,853.6	1,851.7	1,832.8	1,832.1	1,831.2	1,821.9	1,821.1	1,820.6	1,821.6	1,812.3	1,812.1
3.125	2,019.6	2,016.6	2,014.4	1,991.9	1,991.1	1,990.0	1,979.0	1,978.1	1,977.5	1,968.0	1,967.7	1,967.4
3.250	2,190.7	2,187.2	2,184.6	2,158.1	2,157.1	2,155.8	2,142.9	2,141.8	2,141.1	2,130.0	2,129.7	2,129.3
3.375	2,369.7	2,365.6	2,362.5	2,331.4	2,330.3	2,328.8	2,313.6	2,312.3	2,311.5	2,298.6	2,298.2	2,297.8
3.500	2,556.5	2,551.7	2,548.1	2,512.0	2,510.6	2,508.9	2,491.2	2,489.8	2,488.8	2,473.9	2,473.4	2,472.9
3.625	2,751.5	2,745.9	2,741.7	2,699.8	2,698.3	2,696.3	2,675.8	2,674.1	2,673.0	2,655.8	2,655.2	2,654.7
3.750	2,954.6	2,948.2	2,943.4	2,895.1	2,893.3	2,891.0	2,867.4	2,865.5	2,864.2	2,844.4	2,843.7	2,843.1
3.875	3,166.0	3,158.7	3,153.2	3,097.8	3,095.7	3,093.1	3,066.1	3,063.8	3,062.4	3,039.7	3,039.0	3,038.3
4.000	3,385.8	3,377.5	3,371.3	3,308.1	3,305.7	3,302.7	3,271.9	3,269.3	3,267.7	3,241.8	3,241.0	3,240.2
4.250	3,851.7	3,841.0	3,832.9	3,751.8	3,748.8	3,744.9	3,705.1	3,701.8	3,699.7	3,666.5	3,665.4	3,664.4
4.500	4,353.5	4,339.9	4,329.7	4,226.9	4,223.1	4,218.2	4,167.7	4,163.5	4,160.8	4,118.7	4,117.4	4,116.1
4.750	4,893.0	4,875.9	4,863.0	4,734.3	4,729.5	4,723.4	4,660.2	4,654.9	4,651.5	4,598.9	4,597.2	4,595.5
5.000	5,472.1	5,450.6	5,434.5	5,274.7	5,268.8	5,261.3	5,183.1	5,176.6	5,172.4	5,107.3	5,105.2	5,103.1
5.250	6,092.7	6,066.0	6,046.0	5,849.2	5,842.0	5,832.8	5,737.2	5,729.2	5,724.1	5,644.3	5,641.8	5,639.3
5.500	6,757.2	6,724.3	6,699.6	6,458.8	6,450.1	6,438.8	6,323.1	6,313.4	6,307.2	6,210.4	6,207.3	6,204.3
5.750	7,468.2	7,427.8	7,397.6	7,104.7	7,094.2	7,080.6	6,941.5	6,929.8	6,922.4	6,806.0	6,802.3	6,798.7
6.000	8,228.7	8,179.4	8,142.5	7,778.2	7,775.5	7,759.3	7,593.1	7,579.2	7,570.3	7,431.5	7,427.1	7,422.8
6.250	9,041.9	8,981.9	8,937.2	8,510.8	8,495.6	8,476.2	8,278.6	8,262.2	8,251.7	8,087.5	8,082.2	8,077.1
6.500	9,911.4	9,838.9	9,784.9	9,273.8	9,255.8	9,232.7	8,999.1	8,979.7	8,967.3	8,774.3	8,768.1	8,762.1
6.750	10,842	10,754	10,689	10,079	10,058	10,031	9,755.4	9,732.6	9,718.1	9,492.6	9,485.4	9,478.4
7.000	11,837	11,732	11,654	10,929	10,903	10,871	10,548	10,522	10,505	10,243	10,234	10,226
7.250	12,902	12,777	12,684	11,824	11,795	11,757	11,380	11,349	11,329	11,026	11,016	11,007
7.500	14,044	13,894	13,784	12,768	12,733	12,689	12,250	12,214	12,191	11,841	11,830	11,819
7.750	15,269	15,091	14,959	13,763	13,722	13,671	13,161	13,119	13,093	12,691	12,678	12,666
8.000	16,583	16,372	16,216	14,811	14,764	14,704	14,113	14,065	14,036	13,575	13,560	13,546

should be fastened to the pipe at this point, and great care must be exercised to ensure that the inside of the pipe is not distorted in any way.

The diameter of the tap hole shall not be reduced within a length equal to 2.5 times the tap hole diameter as measured from the inside surface of the meter tube. If the fitting is welded to the pipe used to fabricate the meter tube, the tap hole shall not be drilled until after the welding is done

In Table 3-D-2, the finished tap hole shall be ±1/64 inch from the selected nominal tap hole diameter along the drilled length of the hole.

3–D.4 Computing the Flow of Natural Gas and Other Related Hydrocarbon Fluids Through Orifice Meters Equipped With Pipe Taps

3–D.4.1 GENERAL

The recommendations in 3-D 4 2 through 3-D.4.8 concerning calculations and computations are confined strictly to pipe tap orifice meters installed and operated according to the provisions of this appendix. The equations use inch-pound units and absolute values

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
8.250	17,996	17,746	17,562	15,915	15,861	15,791	15,109	15,055	15,020	14,494	14,477	14,461
8.500	19,517	19,221	19,004	17,079	17,016	16,935	16,150	16,088	16,048	15,448	15,429	15,411
8.750	21,157	20,807	20,551	18,306	18,233	18,140	17,238	17,166	17,121	16,439	16,418	16,398
9.000	22,927	22,515	22,214	19,600	19,515	19,408	18,374	18,293	18,241	17,468	17,444	17,421
9.250	24,842	24,357	24,004	20,964	20,867	20,744	19,561	19,468	19,410	18,535	18,508	18,482
9.500	26,917	26,347	25,932	22,404	22,293	22,151	20,801	20,695	20,629	19,642	19,612	19,582
9.750	29,173	28,502	28,015	23,925	12,797	23,635	22,096	21,976	21,901	20,789	20,755	20,722
10.000	31,630	30,840	30,269	25,531	25,384	25,199	23,448	23,313	23,228	21,977	21,939	21,902
10.250	34,316	33,384	32,714	27,229	27,062	26,850	24,861	24,708	24,612	23,208	23,165	23,124
10.500		36,161	35,373	29,026	28,834	28,593	26,337	26,165	26,057	24,482	24,435	24,389
10.750				30,928	30,710	30,435	27,879	27,686	27,564	25,802	25,749	25,698
11.000				32,944	32,695	32,382	29,492	29,274	29,137	27,168	27,109	27,053
11.250				35,082	34,799	34,444	31,177	30,933	30,780	28,582	28,517	28,454
11.500				37,353	37,031	36,627	32,941	32,667	32,495	30,045	29,973	29,904
11.750				39,766	39,401	38,942	34,786	34,479	34,286	31,559	31,480	31,403
12.000				42,336	41,921	41,400	36,717	36,374	36,158	33,126	33,038	32,953
12.500				47,998	47,462	46,791	40,859	40,430	40,162	36,426	36,319	36,216
13.000				54,472	53,779	52,915	45,410	44,878	44,545	39,960	39,830	39,705
13.500							50,425	49,765	49,353	43,746	43,590	43,438
14.000							55,965	55,148	54,640	47,805	47,617	47,435
14.500							62,106	61,096	60,469	52,159	51,933	51,715
15.000							68,938	67,689	66,917	56,833	56,563	56,303
15.500							76,572	75,027	74,075	61,857	61,535	61,225
16.000								83,233	82,057	67,263	66,879	66,511
16.500										73,087	72,632	72,195
17.000										79,372	78,833	78,315
17.500										86,165	85,227	84,915
18.000										93,522	92,767	92,044
18.500										101,506	100,614	99,761
19.000										110,192	109,137	108,130
19.500										119,667	118,420	117,231
20.000										130,036	128,559	127,153

throughout. Constants and variables that have a subscript of 1 indicate upstream measurements; those that have a subscript of 2 indicate downstream measurements.

3–D.4.2 EQUATION

In the measurement of most gases, especially natural gas, the general practice is to express the flow rate in cubic feet per hour at some specified reference or base conditions of pressure and temperature (that is, in standard cubic feet per hour). To calculate the quantity of gas, the following equation shall be used:

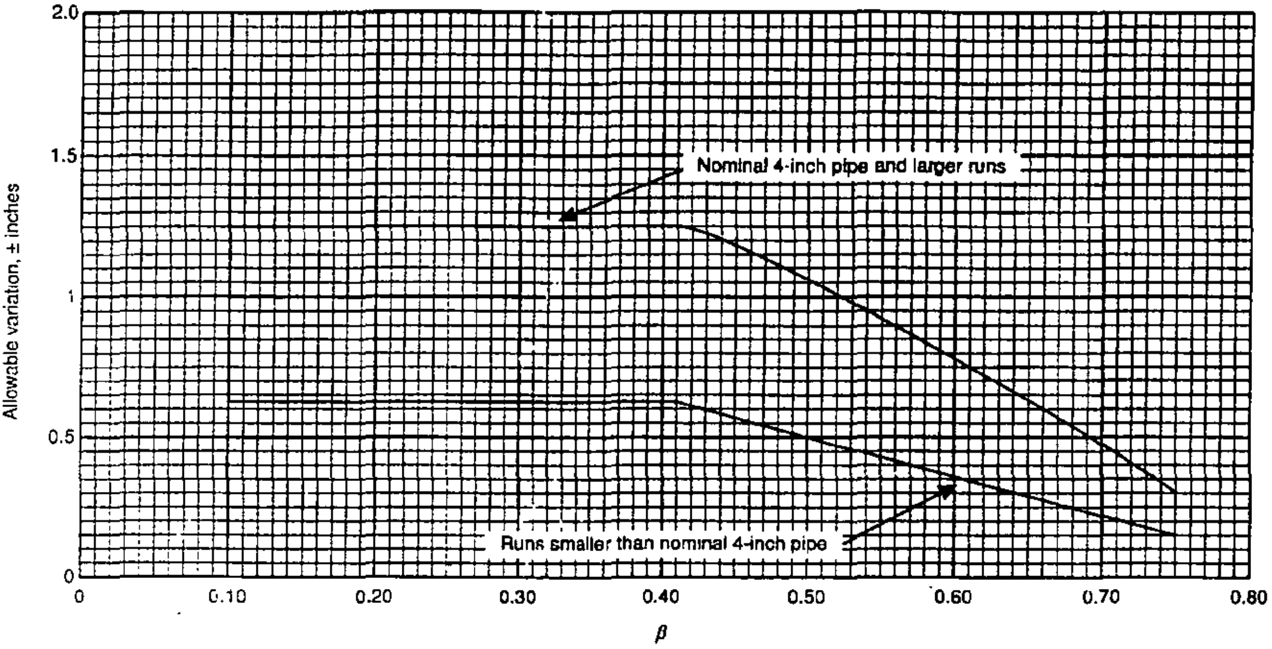
$$Q_s = C'\sqrt{h_w P_f} \tag{3-D-1}$$

Where:

C' = orifice flow constant
h_w = differential pressure at 60°F, in inches of water
P_f = static pressure, in pounds force per square inch absolute.
Q_s = volume flow rate at base conditions, in standard cubic feet per hour.

3–D.4.3 ORIFICE FLOW CONSTANT (C')

The orifice flow constant, C', is defined as the rate of airflow as a real gas, in standard cubic feet per hour, when the extension, $(h_w P_f)^{0.5}$, equals unity. The orifice flow constant



Note: A maximum β ratio of 0.75 should be used in the design of new installations.

Figure 3-D-2—Allowable Variations in Pressure Tap Hole Location

should not be confused with the flow coefficient or coefficient of discharge (K). The following equation is used to calculate the orifice flow constant:

$$C' = F_b F_r Y F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \tag{3-D-2}$$

Where:

F_b = basic orifice factor.
F_{gr} = real specific gravity (relative density) factor.
F_{pb} = base pressure factor.
F_{pv} = supercompressibility factor (from A.G.A Transmission Measurement Committee Report No. 8).
F_r = Reynolds number factor.
F_{tb} = base temperature factor
F_{tf} = flowing temperature factor.
Y = expansion factor

Table 3-D-2—Meter Tube Pressure Tap Holes
(Dimensions in Inches)

Meter Tube Nominal Inside Diameter	Nominal Tap Hole Diameter		
	Recommended	Maximum	Minimum
<2	¼	¼	¼
2 or 3	⅜	⅜	¼
≥4	½	½	¼

Note: The finished tap hole shall be ±1/64 inch from the selected nominal tap hole diameter along the drilled length of the hole.

The sequence of multiplication in Equation 2 is not binding; however, to duplicate the results obtained using Equation 2, the sequence of multiplication and the manner of rounding or truncation should be agreed upon and practiced. Trim factors to compensate for the type of instrumentation used, the calibration methods, and the elements of meter location are treated separately (see Appendix 3-A). These trim factors may be applied as a multiplier to C'.

The values of all the C' factors are detailed in subsequent sections of this appendix. Both equations and tabular data based on the equations are provided. The tables are to be used as an alternative to calculations by equations or to check computed results.

3–D.4.4 COEFFICIENTS OF DISCHARGE (K)

To calculate the coefficients of discharge, K, the following empirical equations are used:

$$K_o = \frac{K_e}{1 + \dfrac{15E}{1{,}000{,}000d}} \qquad \text{(3-D-3)}$$

Where

$$K_e = 0.5925 + \frac{0.0182}{D} + \left(0.44 - \frac{0.06}{D}\right)\beta^2 + \left(0.935 + \frac{0.225}{D}\right)\beta^5$$
$$+ 1.35\beta^{14} + \frac{1.43}{\sqrt{D}}(0.25 - \beta)^{5/2} \qquad \text{(3-D-4)}$$

$$E = d(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + B) \qquad \text{(3-D-5)}$$

$$B = \frac{875}{D} + 75 \qquad \text{(3-D-6)}$$

Note: In Equation 3-D-4, the signs of some of the terms with fractional exponents become negative for some values of β. In such cases, these terms are to be neglected or their value treated as zero, and where these terms are a factor to another term, the whole product is to be treated as zero.

Where:

d = measured orifice diameter, in inches.
D = measured inside meter tube diameter, in inches.
K_e = coefficient of discharge when Reynolds number is equal to $(1{,}000{,}000d)/15$.
K_o = coefficient of discharge when Reynolds number equals infinity, which will be the minimum value for any particular orifice and meter tube size.
β = beta ratio
= d/D.

These values will be used in subsequent intermediate calculations of the orifice flow constant factors

3–D.4.5 BASIC ORIFICE FACTOR (F_b)

To calculate the basic orifice factor, F_b, use the following equation and note the standard conditions:

$$F_b = 338.178d^2K_o \qquad \text{(3-D-7)}$$

When

P_b (base pressure) = 14.73 pounds force per square inch absolute
Specific gravity = 1.000
T_b (base temperature) = 60°F (519.67°R)

Table 3-D-1 was developed using Equation 3-D-7 and various combinations of d and D; to use it, however, the measured inside diameter (D) of the meter tube must be within the limits specified in 3-D.3.2 and Figure 3-D-1. Table 3-D-2 may not be interpolated.

3–D.4.6 REYNOLDS NUMBER FACTOR (F_r)

To calculate the Reynolds number factor, F_r, use the following equations:

$$F_r = 1 + \frac{E}{Re_d} \qquad \text{(3-D-8)}$$

$$Re_d = 220{,}858\, dF_{pv}\sqrt{\rho h_w} \times (0.613408 - 0.152756\beta + 0.803833\beta^2 - 1.701111\beta^3 + 1.569336\beta^4) \qquad \text{(3-D-9)}$$

$$\rho = \left(\frac{P_f}{14.7}\right)\left(\frac{491.67}{T_f}\right)G \qquad \text{(3-D-10)}$$

Where:

G = specific gravity.
Re_d = orifice bore Reynolds number.
T_f = absolute flowing temperature, in degrees Rankine.
ρ = specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F.

Table 3-D-3, which may not be interpolated, may be used to determine the value of b; this value may then be applied to Equation 3-D-11:

Table 3-D-3—b Values for Determining Reynolds Number Factor F_r for Pipe Taps (All Dimensions in Inches)

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 2 Inches			Published Inside Diameters at Nominal Pipe Size of 3 Inches				Published Inside Diameters at Nominal Pipe Size of 4 Inches			
	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.250	0.1106	0.1091	0.1087	0.1081	0.1078	0.1078	0.1079	0.1079	0.1081	0.1084	0.1085
0.375	0.0890	0.0878	0.0877	0.0879	0.0888	0.0898	0.0905	0.0908	0.0918	0.0932	0.0939
0.500	0.0758	0.0734	0.0729	0.0728	0.0737	0.0750	0.0758	0.0763	0.0778	0.0800	0.0810
0.625	0.0694	0.0647	0.0635	0.0624	0.0624	0.0634	0.0642	0.0646	0.0662	0.0685	0.0697
0.750	0.0676	0.0608	0.0586	0.0559	0.0546	0.0548	0.0552	0.0555	0.0568	0.0590	0.0602
0.875	0.0684	0.0602	0.0570	0.0528	0.0497	0.0488	0.0488	0.0489	0.0496	0.0513	0.0524
1.000	0.0702	0.0614	0.0576	0.0522	0.0473	0.0452	0.0445	0.0443	0.0443	0.0453	0.0461
1.125	0.0709	0.0635	0.0595	0.0532	0.0469	0.0435	0.0422	0.0417	0.0407	0.0408	0.0412
1.250		0.0650	0.0617	0.0552	0.0478	0.0434	0.0414	0.0406	0.0387	0.0376	0.0377
1.375			0.0629	0.0575	0.0496	0.0443	0.0418	0.0408	0.0379	0.0358	0.0353
1.500				0.0590	0.0518	0.0461	0.0431	0.0418	0.0382	0.0350	0.0341
1.625					0.0539	0.0482	0.0450	0.0435	0.0392	0.0351	0.0336
1.750					0.0554	0.0504	0.0471	0.0456	0.0408	0.0359	0.0340
1.875						0.0521	0.0492	0.0477	0.0427	0.0372	0.0349
2.000						0.0532	0.0508	0.0495	0.0448	0.0388	0.0363
2.125							0.0519	0.0509	0.0467	0.0407	0.0380
2.250									0.0483	0.0427	0.0398
2.375									0.0494	0.0445	0.0417
2.500										0.0461	0.0435
2.625										0.0472	0.0450
2.750											0.0462

Note: The b values are calculated from the following equation:

$$b = \frac{E}{12{,}835dK}$$

Where

d = mean orifice diameter, in inches.
E = value from Equation 3-D-5.
K = value approximated from Table 3-D-4.

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}} \qquad (3\text{-D-11})$$

$$b = \frac{E}{12{,}835dK} \qquad (3\text{-D-12})$$

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

	Published Inside Diameters at Nominal Pipe Size of 6 Inches				Published Inside Diameters at Nominal Pipe Size of 8 Inches			Published Inside Diameters at Nominal Pipe Size of 10 Inches			Published Inside Diameters at Nominal Pipe Size of 12 Inches		
Orifice Diameter	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.136	11.374	11.938	12.090
0.500	0.0850	0.0862	0.0883	0.0893									
0.625	0.0747	0.0762	0.0789	0.0802									
0.750	0.0655	0.0672	0.0703	0.0719									
0.875	0.0575	0.0592	0.0625	0.0642	0.0716	0.0730	0.0734						
1.000	0.0506	0.0523	0.0556	0.0573	0.0652	0.0668	0.0672	0.0728					
1.125	0.0448	0.0464	0.0495	0.0512	0.0593	0.0609	0.0613	0.0674	0.0691	0.0695			
1.250	0.0401	0.0414	0.0442	0.0458	0.0538	0.0555	0.0560	0.0624	0.0641	0.0646	0.0687	0.0704	0.0708
1.375	0.0363	0.0373	0.0397	0.0412	0.0489	0.0506	0.0511	0.0576	0.0594	0.0599	0.0643	0.0661	0.0666
1.500	0.0334	0.0341	0.0360	0.0372	0.0445	0.0462	0.0466	0.0532	0.0550	0.0555	0.0601	0.0620	0.0625
1.625	0.0313	0.0315	0.0329	0.0339	0.0405	0.0421	0.0425	0.0490	0.0509	0.0514	0.0561	0.0580	0.0585
1.750	0.0300	0.0298	0.0304	0.0311	0.0369	0.0384	0.0388	0.0452	0.0471	0.0476	0.0523	0.0543	0.0548
1.875	0.0293	0.0287	0.0285	0.0290	0.0338	0.0352	0.0355	0.0417	0.0436	0.0440	0.0488	0.0508	0.0513
2.000	0.0292	0.0281	0.0273	0.0273	0.0311	0.0323	0.0327	0.0385	0.0403	0.0407	0.0454	0.0475	0.0480
2.125	0.0297	0.0281	0.0265	0.0262	0.0288	0.0299	0.0301	0.0355	0.0373	0.0377	0.0423	0.0443	0.0449
2.250	0.0305	0.0285	0.0261	0.0256	0.0268	0.0277	0.0280	0.0329	0.0345	0.0349	0.0394	0.0414	0.0419
2.375	0.0316	0.0293	0.0262	0.0253	0.0252	0.0259	0.0261	0.0305	0.0320	0.0324	0.0367	0.0387	0.0392
2.500	0.0330	0.0304	0.0267	0.0254	0.0239	0.0244	0.0246	0.0283	0.0298	0.0301	0.0342	0.0361	0.0366
2.625	0.0345	0.0317	0.0274	0.0258	0.0230	0.0232	0.0233	0.0265	0.0277	0.0281	0.0319	0.0337	0.0342
2.750	0.0362	0.0332	0.0284	0.0265	0.0224	0.0224	0.0224	0.0248	0.0260	0.0263	0.0298	0.0316	0.0320
2.875	0.0379	0.0348	0.0295	0.0274	0.0220	0.0218	0.0218	0.0234	0.0244	0.0246	0.0279	0.0295	0.0300
3.000	0.0395	0.0364	0.0308	0.0285	0.0219	0.0214	0.0213	0.0222	0.0230	0.0233	0.0262	0.0277	0.0281
3.125	0.0410	0.0380	0.0323	0.0297	0.0220	0.0213	0.0211	0.0212	0.0218	0.0220	0.0246	0.0260	0.0264
3.250	0.0422	0.0394	0.0338	0.0311	0.0223	0.0214	0.0212	0.0205	0.0209	0.0210	0.0232	0.0245	0.0249
3.375	0.0433	0.0408	0.0353	0.0325	0.0228	0.0217	0.0214	0.0199	0.0201	0.0202	0.0220	0.0232	0.0235
3.500		0.0419	0.0367	0.0339	0.0235	0.0221	0.0218	0.0195	0.0195	0.0196	0.0210	0.0220	0.0223
3.625		0.0428	0.0381	0.0354	0.0243	0.0227	0.0224	0.0193	0.0191	0.0191	0.0200	0.0209	0.0212
3.750			0.0393	0.0367	0.0252	0.0234	0.0230	0.0192	0.0188	0.0188	0.0193	0.0200	0.0202
3.875			0.0404	0.0380	0.0262	0.0243	0.0238	0.0193	0.0187	0.0186	0.0187	0.0192	0.0194
4.000			0.0413	0.0391	0.0273	0.0252	0.0248	0.0195	0.0187	0.0186	0.0182	0.0185	0.0187
4.250					0.0297	0.0273	0.0268	0.0203	0.0192	0.0189	0.0176	0.0176	0.0177
4.500					0.0321	0.0296	0.0290	0.0215	0.0200	0.0197	0.0175	0.0172	0.0171
4.750					0.0344	0.0320	0.0314	0.0230	0.0212	0.0208	0.0178	0.0171	0.0170
5.000					0.0364	0.0342	0.0336	0.0248	0.0228	0.0223	0.0185	0.0175	0.0172
5.250					0.0381	0.0361	0.0356	0.0267	0.0245	0.0239	0.0195	0.0181	0.0178
5.500						0.0377	0.0373	0.0287	0.0263	0.0257	0.0207	0.0190	0.0186
5.750								0.0307	0.0282	0.0276	0.0221	0.0202	0.0197
6.000								0.0326	0.0302	0.0295	0.0236	0.0215	0.0210
6.250								0.0343	0.0320	0.0314	0.0253	0.0230	0.0224
6.500								0.0358	0.0336	0.0331	0.0270	0.0246	0.0240
6.750									0.0351	0.0346	0.0288	0.0262	0.0256
7.000									0.0363	0.0359	0.0304	0.0279	0.0272
7.250											0.0320	0.0295	0.0288
7.500											0.0334	0.0310	0.0304
7.750											0.0347	0.0325	0.0318
8.000												0.0338	0.0332
8.250												0.0349	0.0344

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
Orifice Diameter	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
1.500	0.0697	0.0705										
1.625	0.0662	0.0670	0.0676									
1.750	0.0628	0.0636	0.0642									
1.875	0.0595	0.0603	0.0610									
2.000	0.0563	0.0571	0.0578	0.0663	0.0667	0.0672						
2.125	0.0532	0.0541	0.0548	0.0635	0.0639	0.0645						
2.250	0.0503	0.0512	0.0519	0.0609	0.0613	0.0618						
2.375	0.0475	0.0485	0.0492	0.0583	0.0588	0.0593	0.0658	0.0665	0.0669			
2.500	0.0449	0.0458	0.0466	0.0558	0.0562	0.0568	0.0635	0.0642	0.0646			
2.625	0.0424	0.0433	0.0441	0.0534	0.0538	0.0544	0.0613	0.0620	0.0624			
2.750	0.0400	0.0409	0.0417	0.0510	0.0515	0.0520	0.0591	0.0598	0.0603			
2.875	0.0378	0.0387	0.0394	0.0488	0.0492	0.0498	0.0570	0.0577	0.0582	0.0669		
3.000	0.0356	0.0365	0.0372	0.0466	0.0470	0.0476	0.0549	0.0556	0.0561	0.0650	0.0654	0.0657
3.125	0.0336	0.0345	0.0352	0.0445	0.0449	0.0455	0.0529	0.0536	0.0541	0.0632	0.0636	0.0639
3.250	0.0317	0.0326	0.0333	0.0425	0.0429	0.0435	0.0509	0.0517	0.0521	0.0615	0.0618	0.0622
3.375	0.0300	0.0308	0.0314	0.0405	0.0410	0.0416	0.0490	0.0497	0.0502	0.0597	0.0601	0.0604
3.500	0.0283	0.0291	0.0297	0.0387	0.0391	0.0397	0.0471	0.0479	0.0484	0.0580	0.0584	0.0587
3.625	0.0268	0.0275	0.0281	0.0369	0.0373	0.0379	0.0453	0.0461	0.0466	0.0563	0.0567	0.0571
3.750	0.0254	0.0261	0.0267	0.0352	0.0356	0.0362	0.0436	0.0444	0.0449	0.0547	0.0551	0.0554
3.875	0.0240	0.0247	0.0253	0.0336	0.0340	0.0346	0.0419	0.0427	0.0432	0.0530	0.0534	0.0538
4.000	0.0228	0.0235	0.0240	0.0320	0.0324	0.0330	0.0403	0.0411	0.0416	0.0515	0.0519	0.0523
4.250	0.0207	0.0213	0.0217	0.0291	0.0295	0.0301	0.0372	0.0380	0.0385	0.0484	0.0488	0.0492
4.500	0.0190	0.0194	0.0198	0.0265	0.0269	0.0274	0.0343	0.0351	0.0356	0.0455	0.0459	0.0463
4.750	0.0176	0.0180	0.0183	0.0242	0.0246	0.0250	0.0316	0.0324	0.0329	0.0427	0.0431	0.0435
5.000	0.0166	0.0168	0.0171	0.0221	0.0225	0.0229	0.0292	0.0299	0.0303	0.0401	0.0405	0.0409
5.250	0.0160	0.0161	0.0162	0.0203	0.0206	0.0210	0.0269	0.0276	0.0280	0.0376	0.0380	0.0384
5.500	0.0156	0.0156	0.0156	0.0188	0.0190	0.0194	0.0248	0.0255	0.0259	0.0352	0.0356	0.0360
5.750	0.0155	0.0154	0.0153	0.0175	0.0177	0.0180	0.0230	0.0236	0.0240	0.0330	0.0334	0.0338
6.000	0.0157	0.0154	0.0153	0.0164	0.0165	0.0168	0.0213	0.0218	0.0222	0.0309	0.0313	0.0317
6.250	0.0161	0.0157	0.0154	0.0155	0.0156	0.0158	0.0197	0.0203	0.0206	0.0289	0.0293	0.0297
6.500	0.0167	0.0162	0.0159	0.0148	0.0149	0.0151	0.0184	0.0189	0.0192	0.0271	0.0274	0.0278
6.750	0.0175	0.0169	0.0164	0.0144	0.0144	0.0145	0.0172	0.0176	0.0179	0.0253	0.0257	0.0261
7.000	0.0184	0.0177	0.0172	0.0141	0.0141	0.0141	0.0162	0.0166	0.0168	0.0237	0.0241	0.0244
7.250	0.0195	0.0187	0.0181	0.0140	0.0140	0.0139	0.0153	0.0156	0.0159	0.0223	0.0226	0.0229
7.500	0.0206	0.0198	0.0191	0.0140	0.0140	0.0139	0.0146	0.0149	0.0150	0.0209	0.0212	0.0215
7.750	0.0219	0.0209	0.0202	0.0143	0.0141	0.0140	0.0140	0.0142	0.0144	0.0196	0.0199	0.0202
8.000	0.0232	0.0222	0.0214	0.0146	0.0144	0.0142	0.0136	0.0138	0.0139	0.0185	0.0187	0.0190

Table 3-D-4 must be used to determine the value of *K* in Equation 3-D-12. First-order linear interpolation of Table 3-D-4 is permissible. In calculating the extension for determinations of F_r, average or estimated values may be used.

3–D.4.7 EXPANSION FACTOR (*Y*)

3–D.4.7.1 Expansion Factor Based on Upstream Static Pressure (Y_1)

If the static pressure is measured at the upstream pressure tap, the calculations for the expansion factor, Y_1, use the following equations:

$$Y_1 = 1 - [0.333 + 1.145(\beta^2 + 0.7\beta^5 + 12\beta^{13})]\frac{x_1}{k} \qquad \text{(3-D-13)}$$

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
8.250	0.0246	0.0235	0.0227	0.0151	0.0149	0.0146	0.0133	0.0134	0.0135	0.0174	0.0177	0.0179
8.500	0.0260	0.0249	0.0240	0.0157	0.0154	0.0151	0.0132	0.0132	0.0132	0.0165	0.0167	0.0170
8.750	0.0273	0.0262	0.0253	0.0163	0.0160	0.0157	0.0131	0.0130	0.0130	0.0156	0.0158	0.0161
9.000	0.0286	0.0276	0.0267	0.0171	0.0168	0.0163	0.0131	0.0130	0.0130	0.0149	0.0151	0.0153
9.250	0.0299	0.0288	0.0280	0.0180	0.0176	0.0171	0.0133	0.0131	0.0130	0.0142	0.0144	0.0146
9.500	0.0311	0.0301	0.0292	0.0189	0.0185	0.0180	0.0136	0.0133	0.0132	0.0137	0.0138	0.0140
9.750	0.0322	0.0312	0.0304	0.0198	0.0194	0.0189	0.0139	0.0136	0.0134	0.0132	0.0133	0.0135
10.000	0.0332	0.0323	0.0315	0.0209	0.0204	0.0198	0.0143	0.0140	0.0138	0.0129	0.0129	0.0130
10.250	0.0341	0.0333	0.0326	0.0219	0.0214	0.0208	0.0149	0.0144	0.0142	0.0126	0.0126	0.0127
10.500		0.0341	0.0335	0.0230	0.0225	0.0219	0.0154	0.0150	0.0147	0.0123	0.0124	0.0124
10.750				0.0241	0.0236	0.0229	0.0161	0.0155	0.0152	0.0122	0.0122	0.0122
11.000				0.0252	0.0247	0.0240	0.0168	0.0162	0.0158	0.0121	0.0121	0.0121
11.250				0.0263	0.0258	0.0251	0.0175	0.0169	0.0165	0.0121	0.0121	0.0121
11.500				0.0273	0.0268	0.0261	0.0183	0.0176	0.0172	0.0122	0.0122	0.0121
11.750				0.0284	0.0278	0.0272	0.0191	0.0184	0.0180	0.0124	0.0123	0.0122
12.000				0.0293	0.0288	0.0282	0.0200	0.0192	0.0188	0.0126	0.0124	0.0123
12.500				0.0312	0.0307	0.0301	0.0218	0.0210	0.0205	0.0131	0.0130	0.0128
13.000				0.0327	0.0323	0.0318	0.0236	0.0228	0.0222	0.0139	0.0137	0.0135
13.500							0.0255	0.0246	0.0240	0.0148	0.0146	0.0143
14.000							0.0272	0.0264	0.0258	0.0159	0.0156	0.0153
14.500							0.0289	0.0280	0.0275	0.0172	0.0168	0.0165
15.000							0.0304	0.0296	0.0291	0.0185	0.0181	0.0177
15.500							0.0318	0.0311	0.0306	0.0199	0.0194	0.0191
16.000								0.0323	0.0319	0.0213	0.0209	0.0205
16.500										0.0228	0.0223	0.0219
17.000										0.0242	0.0238	0.0233
17.500										0.0257	0.0252	0.0248
18.000										0.0270	0.0266	0.0261
18.500										0.0283	0.0279	0.0275
19.000										0.0296	0.0292	0.0288
19.500										0.0307	0.0303	0.0299
20.000										0.0317	0.0313	0.0310

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707 P_{f_1}} \qquad (3\text{-D-}14)$$

Where:

k = ratio of specific heats, c_p/c_v (that is, the ratio of the specific heat of a gas at constant pressure to the specific heat of the gas at constant volume at standard conditions).

x_1/k = acoustic ratio.

Table 3-D-5 was developed using Equations 3-D-13 and 3-D-14 with a value of $k = 1.3$. First- or second-order linear interpolation of Table 3-D-5 is permissible.

The values of Y_1 are subject to an uncertainty varying from 0 when $x_1 = 0$ to ±0.5 percent when $x_1 = 0.2$. For larger values of x_1, a somewhat larger uncertainity can be expected. Equation 3-D-13 may be used over a range of $0.1 \leq \beta \leq 0.7$.

Table 3-D-4—Values of *K* to Be Used in Determining R_d for Calculation of F_r Factor

β	*K* (pipe)
0.100	0.607
0.125	0.608
0.150	0.611
0.175	0.614
0.200	0.618
0.225	0.623
0.250	0.628
0.275	0.634
0.300	0.641
0.325	0.650
0.350	0.658
0.375	0.668
0.400	0.680
0.425	0.692
0.450	0.707
0.475	0.724
0.500	0.742
0.525	0.763
0.550	0.785
0.575	0.810
0.600	0.837
0.625	0.869
0.650	0.904
0.675	0.943
0.700	0.988

3–D.4.7.2 Expansion Factor Based on Downstream Static Pressure (Y_2)

If the static pressure is measured at the downstream pressure tap, the calculations for the expansion factor, Y_2, use the following equations:

$$Y_2 = \sqrt{1 + x_2} - [0.333 + 1.145(\beta^2 + 0.7\beta^5 + 12\beta^{13})]\frac{x_2}{k\sqrt{1 + x_2}} \quad (3\text{-D-}15)$$

$$x_2 = \frac{P_{f_1} - P_{f_2}}{P_{f_2}} = \frac{h_w}{27.707\,P_{f_2}} \quad (3\text{-D-}16)$$

Table 3-D-6 was developed using Equations 3-D-15 and 3-D-16 with a value of $k = 1.3$. First- or second-order linear interpolation of Table 3-D-6 is permissible.

3–D.4.8 OTHER *C'* FACTORS

The remaining orifice flow constant *C'* factors (namely, F_{pb}, F_{tb}, F_{tf}, F_{gr}, and F_{pv}) are calculated exactly as described in the body of this standard. Computations using equations or tables are permissible with these factors when calculating the flow of natural gas through orifice meters equipped with pipe taps.

3–D.4.9 EXAMPLES

3–D.4.9.1 Example 1

Given the following physical parameters and flowing conditions, calculate the flow rate for a pipe tap orifice meter through one meter tube:

Tube diameter	2.067 in
Orifice diameter	1 in
Static pressure	500 psig (measured upstream)
Differential pressure	50 inches of water at 60°F

Base pressure	14.73 psia
Atmospheric pressure	14.7 psia (barometric)
Flowing temperature	100°F
Base temperature	60°F
Relative density (specific gravity)	0.600
Carbon dioxide	0.5 mole percent
Nitrogen	0.5 mole percent
Differential pressure device	Bellows (recorder, dry)

The solution is calculated as follows:

Diameter ratio (β) = 0.483793

Extension = 160.421

Basic orifice factor (F_b) = 243.279
(from Equations 3-D-3, 3-D-4, 3-D-5, 3-D-6, and 3-D-7; or Table 3-D-2)

Table 3-D-5—Expansion Factors for Pipe Taps (Y_1): Static Pressure Taken From Upstream Taps

	$\beta = d/D$										
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9990	0.9989	0.9988	0.9985	0.9984	0.9982	0.9981	0.9980	0.9979	0.9978	0.9977
0.2	0.9981	0.9979	0.9976	0.9971	0.9968	0.9964	0.9962	0.9961	0.9959	0.9957	0.9954
0.3	0.9971	0.9968	0.9964	0.9956	0.9952	0.9946	0.9944	0.9941	0.9938	0.9935	0.9931
0.4	0.9962	0.9958	0.9951	0.9942	0.9936	0.9928	0.9925	0.9921	0.9917	0.9913	0.9908
0.5	0.9952	0.9947	0.9939	0.9927	0.9919	0.9910	0.9906	0.9902	0.9897	0.9891	0.9885
0.6	0.9943	0.9937	0.9927	0.9913	0.9903	0.9892	0.9887	0.9882	0.9876	0.9870	0.9862
0.7	0.9933	0.9926	0.9915	0.9898	0.9887	0.9874	0.9869	0.9862	0.9856	0.9848	0.9840
0.8	0.9923	0.9916	0.9903	0.9883	0.9871	0.9857	0.9850	0.9843	0.9835	0.9826	0.9817
0.9	0.9914	0.9905	0.9891	0.9869	0.9855	0.9839	0.9831	0.9823	0.9814	0.9805	0.9794
1.0	0.9904	0.9895	0.9878	0.9854	0.9839	0.9821	0.9812	0.9803	0.9794	0.9783	0.9771
1.1	0.9895	0.9884	0.9866	0.9840	0.9823	0.9803	0.9794	0.9784	0.9773	0.9761	0.9748
1.2	0.9885	0.9874	0.9854	0.9825	0.9807	0.9785	0.9775	0.9764	0.9752	0.9739	0.9725
1.3	0.9876	0.9863	0.9842	0.9811	0.9791	0.9767	0.9756	0.9744	0.9732	0.9718	0.9702
1.4	0.9866	0.9853	0.9830	0.9796	0.9775	0.9749	0.9737	0.9725	0.9711	0.9696	0.9679
1.5	0.9857	0.9842	0.9818	0.9782	0.9758	0.9731	0.9719	0.9705	0.9690	0.9674	0.9656
1.6	0.9847	0.9832	0.9805	0.9767	0.9742	0.9713	0.9700	0.9685	0.9670	0.9652	0.9633
1.7	0.9837	0.9821	0.9793	0.9752	0.9726	0.9695	0.9681	0.9666	0.9649	0.9631	0.9610
1.8	0.9828	0.9811	0.9781	0.9738	0.9710	0.9677	0.9662	0.9646	0.9628	0.9609	0.9587
1.9	0.9818	0.9800	0.9769	0.9723	0.9694	0.9659	0.9643	0.9626	0.9608	0.9587	0.9565
2.0	0.9809	0.9790	0.9757	0.9709	0.9678	0.9641	0.9625	0.9607	0.9587	0.9566	0.9542
2.1	0.9799	0.9779	0.9745	0.9694	0.9662	0.9623	0.9606	0.9587	0.9566	0.9544	0.9519
2.2	0.9790	0.9768	0.9732	0.9680	0.9646	0.9605	0.9587	0.9567	0.9546	0.9522	0.9496
2.3	0.9780	0.9758	0.9720	0.9665	0.9630	0.9587	0.9568	0.9548	0.9525	0.9500	0.9473
2.4	0.9770	0.9747	0.9708	0.9650	0.9613	0.9570	0.9550	0.9528	0.9505	0.9479	0.9450
2.5	0.9761	0.9737	0.9696	0.9636	0.9597	0.9552	0.9531	0.9508	0.9484	0.9457	0.9427
2.6	0.9751	0.9726	0.9681	0.9621	0.9581	0.9534	0.9512	0.9489	0.9463	0.9435	0.9404
2.7	0.9742	0.9716	0.9672	0.9607	0.9565	0.9516	0.9493	0.9469	0.9443	0.9414	0.9381
2.8	0.9732	0.9705	0.9659	0.9592	0.9549	0.9498	0.9475	0.9449	0.9422	0.9392	0.9358
2.9	0.9723	0.9695	0.9647	0.9578	0.9533	0.9480	0.9456	0.9430	0.9401	0.9370	0.9335
3.0	0.9713	0.9684	0.9635	0.9563	0.9517	0.9462	0.9437	0.9410	0.9381	0.9348	0.9312
3.1	0.9704	0.9674	0.9623	0.9549	0.9501	0.9444	0.9418	0.9390	0.9360	0.9327	0.9290
3.2	0.9694	0.9663	0.9611	0.9534	0.9485	0.9426	0.9400	0.9371	0.9339	0.9305	0.9267
3.3	0.9684	0.9653	0.9599	0.9519	0.9469	0.9408	0.9381	0.9351	0.9319	0.9283	0.9244
3.4	0.9675	0.9642	0.9587	0.9505	0.9452	0.9390	0.9362	0.9331	0.9298	0.9261	0.9221
3.5	0.9665	0.9632	0.9574	0.9490	0.9436	0.9372	0.9343	0.9312	0.9277	0.9240	0.9198
3.6	0.9656	0.9621	0.9562	0.9476	0.9420	0.9354	0.9324	0.9292	0.9257	0.9218	0.9175
3.7	0.9646	0.9611	0.9550	0.9461	0.9404	0.9336	0.9306	0.9272	0.9236	0.9196	0.9152
3.8	0.9637	0.9600	0.9538	0.9447	0.9388	0.9318	0.9287	0.9253	0.9216	0.9175	0.9129
3.9	0.9627	0.9590	0.9526	0.9432	0.9372	0.9301	0.9263	0.9233	0.9195	0.9153	0.9106
4.0	0.9617	0.9579	0.9514	0.9417	0.9356	0.9283	0.9246	0.9213	0.9174	0.9131	0.9083

Table 3-D-5—Continued

	$\beta = d/D$									
h_w/P_{f_1}	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9976	0.9976	0.9975	0.9974	0.9973	0.9972	0.9971	0.9970	0.9969	0.9968
0.2	0.9953	0.9951	0.9950	0.9948	0.9947	0.9945	0.9943	0.9941	0.9938	0.9935
0.3	0.9929	0.9927	0.9925	0.9923	0.9920	0.9917	0.9914	0.9911	0.9907	0.9903
0.4	0.9906	0.9903	0.9900	0.9897	0.9893	0.9890	0.9986	0.9881	0.9876	0.9871
0.5	0.9882	0.9879	0.9875	0.9871	0.9867	0.9862	0.9857	0.9851	0.9845	0.9389
0.6	0.9859	0.9854	0.9850	0.9845	0.9840	0.9834	0.9828	0.9822	0.9814	0.9806
0.7	0.9835	0.9830	0.9825	0.9819	0.9813	0.9807	0.9800	0.9792	0.9784	0.9774
0.8	0.9811	0.9806	0.9800	0.9794	0.9787	0.9779	0.9771	0.9762	0.9753	0.9742
0.9	0.9788	0.9782	0.9775	0.9768	0.9760	0.9752	0.9742	0.9733	0.9722	0.9710
1.0	0.9764	0.9757	0.9750	0.9742	0.9733	0.9724	0.9714	0.9703	0.9691	0.9677
1.1	0.9741	0.9733	0.9725	0.9716	0.9707	0.9696	0.9685	0.9673	0.9660	0.9645
1.2	0.9717	0.9709	0.9700	0.9690	0.9680	0.9669	0.9657	0.9643	0.9629	0.9613
1.3	0.9694	0.9685	0.9675	0.9664	0.9653	0.9641	0.9628	0.9614	0.9598	0.9581
1.4	0.9670	0.9660	0.9650	0.9639	0.9627	0.9614	0.9599	0.9584	0.9567	0.9548
1.5	0.9646	0.9636	0.9625	0.9613	0.9600	0.9586	0.9571	0.9554	0.9536	0.9516
1.6	0.9623	0.9612	0.9600	0.9587	0.9573	0.9558	0.9542	0.9525	0.9505	0.9484
1.7	0.9599	0.9587	0.9575	0.9561	0.9547	0.9531	0.9514	0.9495	0.9474	0.9452
1.8	0.9576	0.9563	0.9550	0.9535	0.9520	0.9503	0.9485	0.9465	0.9443	0.9419
1.9	0.9552	0.9539	0.9525	0.9510	0.9493	0.9476	0.9456	0.9435	0.9412	0.9387
2.0	0.9529	0.9515	0.9500	0.9484	0.9467	0.9448	0.9428	0.9406	0.9381	0.9355
2.1	0.9505	0.9490	0.9475	0.9458	0.9440	0.9420	0.9399	0.9376	0.9351	0.9323
2.2	0.9481	0.9466	0.9450	0.9432	0.9413	0.9393	0.9371	0.9346	0.9320	0.9290
2.3	0.9458	0.9442	0.9425	0.9406	0.9387	0.9365	0.9342	0.9317	0.9289	0.9258
2.4	0.9434	0.9418	0.9400	0.9381	0.9360	0.9338	0.9313	0.9287	0.9258	0.9226
2.5	0.9411	0.9393	0.9375	0.9355	0.9333	0.9310	0.9285	0.9257	0.9227	0.9194
2.6	0.9387	0.9369	0.9350	0.9329	0.9307	0.9282	0.9256	0.9227	0.9196	0.9161
2.7	0.9364	0.9345	0.9325	0.9303	0.9280	0.9255	0.9227	0.9198	0.9165	0.9129
2.8	0.9340	0.9321	0.9300	0.9277	0.9253	0.9227	0.9199	0.9168	0.9134	0.9097
2.9	0.9316	0.9296	0.9275	0.9252	0.9227	0.9200	0.9170	0.9138	0.9103	0.9064
3.0	0.9293	0.9272	0.9250	0.9226	0.9200	0.9172	0.9142	0.9108	0.9072	0.9032
3.1	0.9269	0.9248	0.9225	0.9200	0.9173	0.9144	0.9113	0.9079	0.9041	0.9000
3.2	0.9246	0.9223	0.9200	0.9174	0.9147	0.9117	0.9084	0.9049	0.9010	0.8968
3.3	0.9222	0.9199	0.9175	0.9148	0.9120	0.9089	0.9056	0.9019	0.8979	0.8935
3.4	0.9199	0.9175	0.9150	0.9122	0.9093	0.9062	0.9027	0.8990	0.8948	0.8903
3.5	0.9175	0.9151	0.9125	0.9097	0.9067	0.9034	0.8999	0.8960	0.8918	0.8817
3.6	0.9151	0.9126	0.9100	0.9071	0.9040	0.9006	0.8970	0.8930	0.8887	0.8839
3.7	0.9128	0.9102	0.9075	0.9045	0.9013	0.8979	0.8941	0.8900	0.8856	0.8806
3.8	0.9104	0.9078	0.9050	0.9019	0.8987	0.8951	0.8913	0.8871	0.8825	0.8774
3.9	0.9081	0.9054	0.9025	0.8993	0.8960	0.8924	0.8884	0.8841	0.8794	0.8742
4.0	0.9057	0.9029	0.9000	0.8965	0.8933	0.8896	0.8856	0.8811	0.8763	0.8710

Reynolds number factor (F_r) = 1.0004
(from Equations 3-D-5, 3-D-8, 3-D-9, and 3-D-10; or Table 3-D-1 and Equation 3-D-11; or Table 3-D-3 and Equations 3-D-5, 3-D-11, and 3-D-12)
Expansion factor (Y_1) = 0.9983
(from Equations 3-D-13 and 3-D-14 or Table 3-D-4)
Base pressure factor (F_{pb}) = 1.0000
Base temperature factor (F_{tb}) = 1.0000
Flowing temperature factor (F_{tf}) = 0.9636
Relative density factor (F_{gr}) = 1.2910
Supercompressibility factor (F_{pv}) = 1.0299
Orifice flow constant (C') = 311.284
(from Equation 3-D-2)

Flow rate (Q_v) = 49.9367 MSCFH
= 1.19848 MMSCFD
(from Equation 3-D-1)

3–D.4.9.2 Example 2

Given the following physical parameters and flowing conditions, calculate the flow rate from a pipe tap orifice meter through one meter tube:

Tube diameter	10.020 in
Orifice diameter	4.5 in
Static pressure	350 psig (measured upstream)
Differential pressure	40 inches of water at 60°F
Base pressure	14.73 psia
Atmospheric pressure	14.7 psia (barometric)

Table 3-D-6—Expansion Factors for Pipe Taps (Y_2): Static Pressure Taken From Downstream Taps

	$\beta = d/D$										
h_w/P_{f_2}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	1.0008	1.0008	1.0006	1.0003	1.0002	1.0000	0.9999	0.9998	0.9997	0.9996	0.9995
0.2	1.0017	1.0015	1.0012	1.0007	1.0004	1.0000	0.9999	0.9997	0.9995	0.9993	0.9990
0.3	1.0025	1.0023	1.0018	1.0010	1.0006	1.0000	0.9998	0.9995	0.9992	0.9989	0.9986
0.4	1.0034	1.0030	1.0024	1.0014	1.0008	1.0001	0.9997	0.9994	0.9990	0.9986	0.9981
0.5	1.0042	1.0038	1.0030	1.0018	1.0010	1.0001	0.9997	0.9992	0.9988	0.9982	0.9976
0.6	1.0051	1.0045	1.0036	1.0021	1.0012	1.0001	0.9996	0.9991	0.9985	0.9979	0.9972
0.7	1.0059	1.0053	1.0041	1.0025	1.0014	1.0002	0.9996	0.9990	0.9983	0.9975	0.9967
0.8	1.0068	1.0060	1.0047	1.0028	1.0016	1.0002	0.9995	0.9988	0.9980	0.9972	0.9962
0.9	1.0076	1.0068	1.0053	1.0032	1.0018	1.0002	0.9995	0.9987	0.9978	0.9969	0.9958
1.0	1.0085	1.0075	1.0059	1.0036	1.0021	1.0003	0.9994	0.9986	0.9976	0.9965	0.9954
1.1	1.0093	1.0083	1.0065	1.0039	1.0023	1.0003	0.9994	0.9984	0.9974	0.9962	0.9949
1.2	1.0102	1.0091	1.0071	1.0043	1.0025	1.0004	0.9994	0.9983	0.9972	0.9959	0.9945
1.3	1.0110	1.0098	1.0077	1.0047	1.0027	1.0004	0.9994	0.9982	0.9970	0.9956	0.9941
1.4	1.0119	1.0106	1.0083	1.0051	1.0030	1.0004	0.9993	0.9981	0.9968	0.9953	0.9936
1.5	1.0127	1.0113	1.0089	1.0054	1.0032	1.0005	0.9993	0.9980	0.9966	0.9950	0.9932
1.6	1.0136	1.0121	1.0096	1.0058	1.0034	1.0006	0.9993	0.9979	0.9964	0.9947	0.9928
1.7	1.0144	1.0128	1.0102	1.0062	1.0036	1.0006	0.9992	0.9978	0.9962	0.9944	0.9924
1.8	1.0153	1.0136	1.0108	1.0066	1.0039	1.0007	0.9992	0.9977	0.9960	0.9941	0.9920
1.9	1.0161	1.0144	1.0114	1.0070	1.0041	1.0008	0.9992	0.9976	0.9958	0.9938	0.9916
2.0	1.0170	1.0151	1.0120	1.0073	1.0044	1.0008	0.9992	0.9975	0.9956	0.9935	0.9912
2.1	1.0178	1.0159	1.0126	1.0077	1.0046	1.0009	0.9992	0.9974	0.9954	0.9932	0.9908
2.2	1.0187	1.0167	1.0132	1.0081	1.0048	1.0010	0.9992	0.9973	0.9952	0.9929	0.9904
2.3	1.0195	1.0174	1.0138	1.0085	1.0051	1.0010	0.9992	0.9972	0.9950	0.9927	0.9900
2.4	1.0204	1.0182	1.0144	1.0089	1.0053	1.0011	0.9992	0.9971	0.9949	0.9924	0.9896
2.5	1.0212	1.0189	1.0150	1.0093	1.0056	1.0012	0.9992	0.9971	0.9947	0.9921	0.9893
2.6	1.0221	1.0197	1.0156	1.0097	1.0058	1.0013	0.9992	0.9970	0.9945	0.9919	0.9889
2.7	1.0229	1.0205	1.0162	1.0101	1.0061	1.0014	0.9992	0.9969	0.9944	0.9916	0.9885
2.8	1.0238	1.0212	1.0169	1.0104	1.0063	1.0014	0.9992	0.9968	0.9942	0.9914	0.9882
2.9	1.0246	1.0220	1.0175	1.0108	1.0066	1.0015	0.9992	0.9968	0.9941	0.9911	0.9878
3.0	1.0255	1.0228	1.0181	1.0112	1.0068	1.0016	0.9993	0.9967	0.9939	0.9908	0.9874
3.1	1.0264	1.0235	1.0187	1.0116	1.0071	1.0017	0.9993	0.9966	0.9938	0.9906	0.9871
3.2	1.0272	1.0243	1.0193	1.0120	1.0074	1.0018	0.9993	0.9966	0.9936	0.9904	0.9867
3.3	1.0280	1.0250	1.0199	1.0124	1.0076	1.0019	0.9993	0.9965	0.9935	0.9901	0.9864
3.4	1.0289	1.0258	1.0206	1.0128	1.0079	1.0020	0.9994	0.9965	0.9933	0.9899	0.9860
3.5	1.0298	1.0266	1.0212	1.0133	1.0082	1.0021	0.9994	0.9964	0.9932	0.9896	0.9857
3.6	1.0306	1.0273	1.0218	1.0137	1.0084	1.0022	0.9994	0.9964	0.9931	0.9894	0.9854
3.7	1.0314	1.0281	1.0224	1.0141	1.0087	1.0024	0.9994	0.9963	0.9929	0.9892	0.9850
3.8	1.0323	1.0289	1.0230	1.0145	1.0090	1.0025	0.9995	0.9963	0.9928	0.9890	0.9847
3.9	1.0332	1.0296	1.0237	1.0149	1.0093	1.0026	0.9995	0.9963	0.9927	0.9888	0.9844
4.0	1.0340	1.0304	1.0243	1.0153	1.0095	1.0027	0.9996	0.9962	0.9926	0.9885	0.9840

Table 3-D-6—Continued

	$\beta = d/D$									
h_w/P_{f_1}	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9994	0.9994	0.9993	0.9992	0.9991	0.9990	0.9989	0.9988	0.9987	0.9986
0.2	0.9989	0.9988	0.9986	0.9985	0.9983	0.9981	0.9979	0.9977	0.9974	0.9972
0.3	0.9984	0.9982	0.9979	0.9977	0.9974	0.9972	0.9969	0.9965	0.9962	0.9958
0.4	0.9978	0.9976	0.9972	0.9969	0.9966	0.9962	0.9958	0.9954	0.9949	0.9944
0.5	0.9973	0.9970	0.9966	0.9962	0.9958	0.9953	0.9948	0.9942	0.9936	0.9930
0.6	0.9968	0.9964	0.9959	0.9954	0.9949	0.9944	0.9938	0.9931	0.9924	0.9916
0.7	0.9962	0.9958	0.9953	0.9947	0.9941	0.9935	0.9928	0.9920	0.9912	0.9902
0.8	0.9957	0.9952	0.9946	0.9940	0.9933	0.9926	0.9918	0.9909	0.9899	0.9889
0.9	0.9952	0.9946	0.9940	0.9932	0.9925	0.9917	0.9908	0.9898	0.9887	0.9875
1.0	0.9947	0.9940	0.9933	0.9925	0.9917	0.9908	0.9898	0.9887	0.9875	0.9862
1.1	0.9942	0.9935	0.9927	0.9918	0.9909	0.9899	0.9888	0.9876	0.9863	0.9848
1.2	0.9937	0.9929	0.9920	0.9911	0.9901	0.9890	0.9878	0.9865	0.9851	0.9835
1.3	0.9932	0.9924	0.9914	0.9904	0.9893	0.9881	0.9868	0.9854	0.9839	0.9822
1.4	0.9928	0.9918	0.9908	0.9897	0.9885	0.9872	0.9859	0.9844	0.9827	0.9809
1.5	0.9923	0.9912	0.9902	0.9890	0.9877	0.9864	0.9849	0.9833	0.9815	0.9796
1.6	0.9918	0.9907	0.9896	0.9883	0.9870	0.9855	0.9840	0.9822	0.9804	0.9783
1.7	0.9913	0.9902	0.9889	0.9876	0.9862	0.9847	0.9830	0.9812	0.9792	0.9770
1.8	0.9908	0.9896	0.9883	0.9870	0.9854	0.9838	0.9821	0.9801	0.9780	0.9757
1.9	0.9904	0.9891	0.9877	0.9863	0.9847	0.9830	0.9811	0.9791	0.9769	0.9744
2.0	0.9899	0.9886	0.9872	0.9856	0.9840	0.9822	0.9802	0.9781	0.9757	0.9732
2.1	0.9895	0.9881	0.9866	0.9849	0.9832	0.9813	0.9793	0.9770	0.9746	0.9719
2.2	0.9890	0.9876	0.9860	0.9843	0.9825	0.9805	0.9784	0.9760	0.9734	0.9706
2.3	0.9886	0.9870	0.9854	0.9836	0.9817	0.9797	0.9774	0.9750	0.9723	0.9694
2.4	0.9881	0.9865	0.9948	0.9830	0.9810	0.9789	0.9765	0.9740	0.9712	0.9681
2.5	0.9877	0.9860	0.9842	0.9823	0.9803	0.9780	0.9756	0.9730	0.9701	0.9669
2.6	0.9873	0.9855	0.9837	0.9817	0.9796	0.9772	0.9747	0.9720	0.9690	0.9657
2.7	0.9868	0.9850	0.9831	0.9811	0.9788	0.9764	0.9738	0.9710	0.9679	0.9644
2.8	0.9864	0.9846	0.9826	0.9804	0.9781	0.9757	0.9730	0.9700	0.9668	0.9632
2.9	0.9860	0.9841	0.9820	0.9798	0.9774	0.9749	0.9721	0.9690	0.9657	0.9620
3.0	0.9856	0.9836	0.9815	0.9792	0.9767	0.9741	0.9712	0.9681	0.9646	0.9608
3.1	0.9852	0.9831	0.9809	0.9786	0.9760	0.9733	0.9703	0.9671	0.9635	0.9596
3.2	0.9848	0.9826	0.9804	0.9780	0.9754	0.9725	0.9695	0.9661	0.9625	0.9584
3.3	0.9843	0.9822	0.9798	0.9774	0.9747	0.9718	0.9686	0.9652	0.9614	0.9572
3.4	0.9839	0.9817	0.9793	0.9768	0.9740	0.9710	0.9678	0.9642	0.9603	0.9561
3.5	0.9835	0.9812	0.9788	0.9762	0.9733	0.9702	0.9669	0.9633	0.9593	0.9549
3.6	0.9832	0.9808	0.9783	0.9756	0.9727	0.9695	0.9661	0.9623	0.9582	0.9537
3.7	0.9828	0.9803	0.9778	0.9750	0.9720	0.9688	0.9652	0.9614	0.9572	0.9526
3.8	0.9824	0.9799	0.9772	0.9744	0.9713	0.9680	0.9644	0.9605	0.9562	0.9514
3.9	0.9820	0.9794	0.9767	0.9738	0.9707	0.9673	0.9636	0.9596	0.9551	0.9503
4.0	0.9816	0.9790	0.9762	0.9732	0.9700	0.9665	0.9628	0.9586	0.9541	0.9491

Flowing temperature	60°F
Base temperature	60°F
Relative density (specific gravity)	0.620
Carbon dioxide	2 mole percent
Nitrogen	3 mole percent
Differential pressure device	Bellows (recorder, dry)

The solution is calculated as follows:

Diameter ratio (β) = 0.449102

Extension = 120.781

Basic orifice factor (F_b) = 4776.30

Reynolds number factor (F_r) = 1.0002

Expansion factor (Y_1) = 0.9982

Base pressure factor (F_{pb}) = 1.0000

Base temperature factor (F_{tb}) = 1.0000
Flowing temperature factor (F_{tf}) = 1.0000
Relative density factor (F_{gr}) = 1.2700
Supercompressibility factor (F_{pv}) = 1.0273
Orifice flow constant (C') = 6221.53
Flow rate (Q_v) = 751.441 MSCFH
= 18.0346 MMSCFD

3–D.4.10 ADJUSTMENTS FOR INSTRUMENTATION CALIBRATION AND USE

Other multiplying factors may be applied to the orifice flow constant, C', as a function of the type of instrumentation applied, the method of calibration, the meter environment, or any combination of these. These factors are discussed in the body of the standard and in other appendixes to the standard. These factors are calculated and applied independently of tap type. With these factors, the orifice flow rate is calculated using the following equation:

$$Q_v = C' F_{hg} F_a F_{amt} F_{wl} F_{wt} F_{pwl} F_{hgm} F_{hgt} \sqrt{h_w P_f} \tag{3-D-17}$$

Where:

F_{hg} = mercury manometer factor (formerly F_m).
F_a = orifice thermal expansion factor.
F_{amt} = correction for air over water in a water manometer during differential instrument calibration
F_{wl} = local gravitational correction for water column calibration.
F_{wt} = water density correction (temperature or composition) for water column calibration.
F_{pwl} = local gravitational correction for deadweight tester static pressure calibration.
F_{hgm} = correction for gas column in a mercury manometer.
F_{hgt} = mercury manometer span correction for instrument temperature change after calibration.

APPENDIX 3-E—SI CONVERSIONS

This appendix contains tables of SI conversions that are pertinent to the information in this part of Chapter 14, Section 3. For additional information on SI units, refer to Chapter 15.

Table 3-E-1—Volume Reference Conditions for Custody Transfer Operations: Natural Gas Volume

Common Reference Conditions (ft³)		To Convert From	
Pressure (psia)	Temperature (°F)	ft³ to m³, Multiply by	m³ to ft³, Multiply by
14.4	60	0.02769321	36.10994
14.65	60	0.02817399	35.49373
14.696	60	0.02826245	35.38263
14.7	60	0.02827015	35.37300
14.73	60	0.02832784	35.30096
14.7347	60	0.02833688	35.28970
14.735	60	0.02833746	35.28898
14.9	60	0.02865478	34.89819
15.025	60	0.02889517	34.60786

Note: The following standard conditions were used for inch-pound units—a temperature of 60°F and a pressure of 14.73 pounds per square inch absolute. The following standard conditions were used for SI units—a temperature of 15°C and an absolute pressure of 101.325 kPa. The following values were assumed: 1 ft = 0.3048 m, 1 psi = 6.894757 kPa. The following methodology was used to obtain the conversion factors:

$$\left(\frac{ft^3}{m^3}\right)\left(\frac{T_{rep}}{T_{SI}}\right)\left(\frac{P_{SI}}{P_{rep}}\right) = \text{factor}$$

Table 3-E-2—Energy Reference Conditions

Unit	Used in	Definition	To Convert Btu to J, Multiply by
Btu_{IT}	International steam tables	1 Btu/lbm = 2326 J/kg	1055.056

Table 3-E-3—Heating Value Reference Conditions

Reference Conditions (ft³)		
Pressure (psia)	Temperature (°F)	To Convert From Btu_{IT}/ft³ to MJ/m³, Multiply by
14.4	60	0.03809801
14.65	60	0.03744787
14.696	60	0.03733066
14.7	60	0.03732050
14.73	60	0.03724449
14.7347	60	0.03723261
14.735	60	0.03723185
14.9	60	0.03681955
15.025	60	0.03651323

Note: The following standard conditions were used for inch-pound units—a temperature of 60°F and a pressure of 14.73 pounds per square inch absolute. The following standard conditions were used for SI units—a temperature of 15°C and an absolute pressure of 101.325 kPa. The following values were assumed: 1 ft = 0.3048 m; 1 psi = 6.894757 kPa; 1 Btu_{IT} = 1055.056 J. The following methodology was used to obtain the conversion factors:

$$\left(\frac{J}{Btu}\right)\left(\frac{MJ}{1 \times 10^6\ J}\right)\left(\frac{ft^3}{m^3}\right)\left(\frac{T_{rep}}{T_{SI}}\right)\left(\frac{P_{SI}}{P_{rep}}\right) = \text{factor}$$

APPENDIX F—HEATING VALUE CALCULATION

3–F.1 General

Heating value is a gas property evaluated on a per-unit mass basis (H_m). This property is technically termed an "ideal property" (H_m^{id}). From a practical standpoint, in mass measurement there is no difference between the "ideal" and the "real." The value is converted to a heating value per cubic foot (HV) using the following relationships. The more common convention has been applied in this appendix.

$$HV = H_m \frac{\rho_b^{id}}{Z_b} = H_m \rho_b \qquad \text{(3-F-1)}$$

The value of HV is used as a factor in calculating the energy flow rate, or the total energy passing through the flow meter. HV is also used for product specifications.

It is also convenient to define the following:

$$HV = \frac{H_v^{id}}{Z_b} \qquad \text{(3-F-2)}$$

3–F.2 Heating Value Symbols

Symbol	Description	Units
H_m	Heating value per pound mass	Btu/lbm
H_m^{id}	Ideal heating value per pound mass	Btu/lbm
H_v^{id}	Ideal heating value per cubic foot	Btu/ft^3
HV	Gross heating value	Btu/ft^3
Mr_i	Molar mass of component	lbm/lb-mol
P_b	Base pressure	lbf/in^2 (abs)
P_{f1}	Flowing pressure (upstream tap)	lbf/in^2 (abs)
P_v	Vapor pressure of water	lbf/in^2 (abs)
°R	Absolute temperature	—
T_b	Base temperature	°R
Z_b	Gas compressibility at base conditions (P_b, T_b)	—
ρ_b	Density at base conditions (P_b, T_b)	lbm/ft^3
ρ_b^{id}	Ideal density at base conditions	lbm/ft^3
ϕ	Mole fraction	%/100
ϕ_w	Mole fraction water	%/100

3–F.3 Heating Value

The gross heating value is an ideal gas property based on the ideal reaction:

$$\text{Fuel}^{id} + O_2^{id} \rightarrow CO_2^{id} + H_2O_l + SO_2^{id} \qquad \text{(3-F-3)}$$

Where:

Superscript id = ideal gas.
Subscript l = liquid.

(Each fuel requires different stoichiometric coefficients.) This gross ideal heating value includes the energy obtained from the condensation of the water vapor (formed by the ideal reaction expressed in the equation) to the liquid phase.

It should be noted that the gross heating value is expressed per unit (pound mass or cubic foot) of dry gas. Although water is a product of combustion, it is not indicated on the left-hand side of Equation 3-F-3 in either the fuel or the oxygen; water is a result, not a part, of the reaction.

Heating value may be determined directly by a calorimeter, either on line or from a sample cylinder. Heating value may also be calculated from gas analysis.

3-F.4 Physical Properties

Table 3-F-1 lists physical properties of many of the compounds present in natural gas in various hydrocarbon mixtures. The data in Table 3-F-1 have been adjusted to base or standard conditions, as defined in 3.2.3.4.

Table 3-F-1 provides the best currently available data on physical properties and is taken from GPA 2145-91. These data are subject to modification yearly as additional research is accomplished. Future revisions to GPA 2145 may include updated values. The values of the most recent edition of GPA 2145 should be used. The user of the GPA tables is cautioned that the information presented in them is calculated from different base conditions and that conversion is required when the information is used with Part 3 (see 3.5.2).

3-F.5 Heating Value Determined on a Volume Basis

A calculation of a mixture's gross ideal heating value, using H_v values from Table 3-F-1 and using mole fractions of the gas composition, involves determining the heating value per unit volume of real gas. *HV* can be determined by using Equation 3-F-2 and the following relationship:

Table 3-F-1—Physical Properties of Gases at Exactly 14.73 Pounds Force per Square Inch Absolute and 60°F (See Note 1)

								Thermal Energy	
Compound	Formula	*Mr* (Note 2)	P_c (psia) (Note 3)	T_c (°R) (Note 3)	G_i (Note 4)	Ideal Density (lbm/ft³) (Note 5)	Viscosity (cp) (Note 6)	H_m^{id} (Btu/lbm) (Note 7)	H_v^{id} (Btu/ft³) (Note 7)
Hydrogen	H_2	2.0159	167.5	59.36	0.06960	0.00532	0.00871	61,025	324.9
Helium	He	4.0026	32.9	9.34	0.13820	0.01057	0.01927	0	0
Water	H_2O	18.0153	3,200.1	1,164.85	0.62202	0.04758		1,059.8	50.4
Carbon monoxide	CO	28.010	507.5	239.26	0.96711	0.07398	0.01725	4,342.4	321.3
Nitrogen	N_2	28.0134	493.1	227.16	0.96723	0.07399	0.01735	0	0
Oxygen	O_2	31.9988	731.4	278.24	1.10484	0.08452	0.02006	0	0
Hydrogen sulfide	H_2S	34.08	1306	672.12	1.17669	0.09001	0.01240	7,094.2	638.6
Argon	Ar	39.948	710.4	271.55	1.37930	0.10551	0.02201	0	0
Carbon dioxide	CO_2	44.010	1,071.0	547.42	1.51955	0.11624	0.01439	0	0
Air (Note 8)		28.9625	546.9	238.36	1.00000	0.07650	0.01790	0	0
Methane	CH_4	16.043	667.0	343.00	0.55392	0.04237	0.01078	23,891	1,012.3
Ethane	C_2H_6	30.070	707.8	549.76	1.03824	0.07942	0.00901	22,333	1,773.7
Propane	C_3H_8	44.097	615.0	665.64	1.52256	0.11647	0.00788	21,653	2,521.9
iso-Butane	C_4H_{10}	58.123	527.9	734.13	2.00684	0.15351	0.00732	21,232	3,259.4
n-Butane	C_4H_{10}	58.123	548.8	765.25	2.00684	0.15351	0.00724	21,300	3,269.8
iso-Pentane	C_5H_{12}	72.150	490.4	828.70	2.49115	0.19057		21,043	4,010.2
n-Pentane	C_5H_{12}	72.150	488.1	845.44	2.49115	0.19057		21,085	4,018.2
n-Hexane	C_6H_{14}	86.177	439.5	911.47	2.97547	0.22762		20,943	4,766.9
n-Heptane	C_7H_{16}	100.204	397.4	970.57	3.45978	0.26466		20,839	5,515.2
n-Octane	C_8H_{18}	114.231	361.1	1,017.67	3.94410	0.30172		20,759	6,263.4
n-Nonane	C_9H_{20}	128.258	330.7	1,070.57	4.42842	0.33876		20,701	7,012.7
n-Decane	$C_{10}H_{22}$	142.285	304.6	1,111.87	4.91273	0.37581		20,651	7,760.8

Notes:

1. The source for the data in this table is Gas Processors Association 2145-91. The accuracy of the experimental numbers is estimated to be 1 in 1000; the additional figures are for calculation consistency.
2. The following molecular weights were used: C = 12.011; H = 1.00794; O = 15.9994; N = 14.0067; and S = 32.06 (1979).
3. The data in these columns come from the Thermodynamics Research Center, Texas A&M University, IUPAC and National Bureau of Standards selections.
4. The ideal relative density is the ratio of the molecular weight of the gas to that of air (Mr/Mr_a).
5. Ideal density = 0.0026413*Mr* at 60°F and 14.73 pounds force per square inch absolute.
6. The data in this column are from N. B. Vargaftik, *Tables on Thermodynamic Properties of Liquids and Gases* (2nd ed.), New York, Wiley, 1975.
7. See Equation 3-F-3. Depending on the fuel, the reaction has various stoichiometric coefficients. The H_m^{id} column comes from data, whereas the H_v^{id} comes from multiplying H_m^{id} by the ideal gas density. The ideal energy released as heat is H_m^{id} multiplied by the real gas flow rate (in cubic feet per hour) divided by Z. Water has gross values for H_m^{id} and H_v^{id} (the ideal enthalpy of condensation).
8. The data in this row are from F. E. Jones, *National Bureau of Standards Journal of Research*, 1978, Volume 83, p. 491.

$$H_v^{id} = \phi_1 (H_{vi}^{id})_1 + \phi_2 (H_{vi}^{id})_2 + \dots + \phi_n (H_{vi}^{id})_n \qquad (3\text{-F-4})$$

Or

$$H_v^{id} = \sum_{i=1}^{n} \phi_i (H_{vi}^{id})_i \qquad (3\text{-F-5})$$

When

$$HV = \frac{H_v^{id}}{Z_b} \qquad (3\text{-F-2})$$

Where:

ϕ = mole fraction (percent/100).

3–F.6 Heating Value Determined on a Mass Basis

The question of compressibility factor disappears when the ideal heating value per pound mass is used with the mass flow rate. The following equation is applicable for using H_m and Mr values from Table 3-F-1 to calculate the heating value:

$$H_m^{id} = \frac{\phi_1 Mr_1 (H_m^{id})_1 + \phi_2 Mr_2 (H_m^{id})_2 + \dots + \phi_n Mr_n (H_m^{id})_n}{\phi_1 Mr_1 + \phi_2 Mr_2 + \dots + \phi_n Mr_n} \qquad (3\text{-F-6})$$

Or

$$H_m^{id} = \frac{\sum_{i=1}^{n} \phi_i Mr_i (H_m^{id})_i}{\sum_{i=1}^{n} \phi_i Mr_i} \qquad (3\text{-F-7})$$

The result from Equation 3-F-7 can be converted to the gross heating value per cubic foot of real gas at base conditions by using Equation 3-F-1:

$$HV = H_m^{id} \frac{\rho_b^{id}}{Z_b} = H_m^{id} \rho_b$$

3–F.7 Heating Value of a Natural Gas Mixture Containing Water

To define heating value on a dry basis for gas containing water, the relationships in Equations 3-F-1 and 3-F-2 are valid if the mole fractions of the components are corrected for water content by using Equation 3-F-8 and the compressibility (Z) reflects the water content:

$$\phi_{i,wet} = \phi_i (1 - \phi_w) \qquad (3\text{-F-8})$$

Where the gas is water saturated under flowing conditions, Raoult's law may be used to estimate the mole fraction of water:

$$\phi_w = \frac{P_v}{P_f} \qquad (3\text{-F-9})$$

Where:

P_v = absolute vapor pressure of water at flowing conditions or T_f.

Therefore,

$$\phi_{i,wet} = \phi_i \left(1 - \frac{P_v}{P_f}\right) \qquad (3\text{-F-10})$$

APPENDIX G—DEVELOPMENT OF CONSTANTS FOR FLOW EQUATIONS

3–G.1 General

The practical orifice flow equation used in Part 3 is given in Part 1 of this standard as Equation 1-2:

$$q_m = N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P} \qquad (1\text{-}2)$$

Where:

$C_d(FT)$ = coefficient of discharge at a specific pipe Reynolds number for a flange-tapped orifice meter.
d = orifice plate bore diameter calculated at flowing temperature.
ΔP = orifice differential pressure.
E_v = velocity of approach factor.
q_m = mass flow rate.
$\rho_{t,p}$ = density of fluid at flowing conditions (P_f, T_f).

And

N_1 = factor that incorporates the "constants" from Equation 1-1 and the required numeric conversions, including the following:

$\dfrac{3.14159}{4}$ = constant in Equation 1-1.
$\sqrt{2(32.1740)}$ = constant in Equation 1-1.
$\sqrt{\dfrac{62.3663}{12}}$ = converts differential pressure (ΔP) from pounds force per square foot to inches of water at 60°F.
$\dfrac{1}{12^2}$ = converts the diameter of the orifice bore (d) from feet to inches.

Therefore,

$$N_1 = \left(\frac{3.14159}{4}\right)\sqrt{2(32.1740)}\sqrt{\frac{62.3663}{12}}\left(\frac{1}{12^2}\right)$$
$$= 0.0997424$$

(This is shown as the factor for U.S. units in Part 1, Table 1-2.)

Note: Some numeric constants do not have absolute values (for example, π and e). To express six significant digits accurately, the values were computed using double precision (16 significant digits). The results were then rounded to the values shown. In this appendix, for ease of understanding, the computations are shown to only six significant digits.

Mass flow can be modified to provide volume units by dividing the mass by the density at base conditions

$$q_v = \frac{q_m}{\rho_b}$$

Where:

q_m = mass flow rate, in pounds mass per second.
q_v = volume flow rate at base conditions, in cubic feet per second.
ρ_b = density at base conditions, in pounds mass per cubic foot.

3–G.2 Symbols and Units

3–G.2.1 GENERAL

Some of the symbols and units listed below are specific to Appendix 3-B and were developed based on the customary inch-pound system of units. Regular conversion factors can

be used where applicable; however, if SI units are used, the more generic equations in Part 1 should be used for consistent results.

3–G.2.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
$C_d(FT)$	Coefficient of discharge at a specified pipe Reynolds number for flanged-tapped orifice meter	—
d	Orifice plate bore diameter calculated at flowing temperature, T_f	in
D	Meter tube internal diameter calculated at flowing temperature, T_f	in
E_v	Velocity of approach factor	—
°F	Temperature, in degrees Fahrenheit	—
°R	Temperature, in degrees Rankine	459.67 + °F
F_n	Numeric conversion factor (see Appendix 3-B)	—
g_c	Gravitational constant	32.1740 (lbm-ft)/(lbf-sec^2)
G_i	Ideal gas relative density (specific gravity)	—
G_r	Real gas relative density (specific gravity)	—
h_w	Orifice differential pressure	inches of water column at 60°F
N_1	Numeric conversion factor (see Part 1)	—
P	Pressure	lbf/in^2 (abs)
P_b	Base pressure	lbf/in^2 (abs)
P_{f_1}	Flowing pressure (upstream tap)	lbf/in^2 (abs)
P_s	Standard pressure	14.73 lbf/in^2 (abs)
Q_m	Mass flow rate per hour	lbm/hr
Q_v	Volume flow rate per hour at standard (base) conditions	ft^3/hr
R	Universal gas constant	1545.35 (lbf-ft)/(lb-mol-°R)
T	Temperature	°R
T_b	Base temperature	°R
T_f	Flowing temperature	°R
T_s	Standard temperature	519.67°R
Y_1	Expansion factor (upstream tap)	—
Z_b	Compressibility at base conditions	—
$Z_{b_{air}}$	Compressibility of air at 14.73 psia and 60°F	0.999590
Z_{f_1}	Compressibility at upstream flowing conditions	—
Z_s	Compressibility at standard conditions (P_s, T_s)	—
β	Ratio of orifice plate bore diameter to meter tube internal diameter (d/D) calculated at flowing temperature, T_f	—
π	Universal constant	3.14159
ρ_b	Gas density at base conditions (P_b, T_b, and Z_b)	lbm/ft^3
$\rho_{b_{air}}$	Density of air at base conditions (P_b, T_b, and Z_b)	lbm/ft^3
$\rho_{t,p}$	Density at flowing conditions (P_f, T_f, and Z_f)	lbm/ft^3
ρ_{t,p_1}	Density at flowing conditions (P_{f_1}, T_f, and Z_{f_1})	lbm/ft^3

3–G.3 General Numeric Constant for Mass Flow

Equation 3-1 expresses flow in pounds mass per hour (Q_m) rather than pounds mass per second (q_m) and requires an additional factor, 3600, to convert from seconds to hours.

Therefore, in Equation 3-1,

$$N_1 = 0.0997424(3600)$$
$$= 359.072$$

And

$$Q_m = 359.072 C_d (\mathrm{FT}) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w} \qquad (3\text{-}1)$$

Equation 3-4a is Equation 3-1 divided by ρ_b, as described above. The numeric constant is the same.

$$Q_b = \frac{359.072 C_d (\mathrm{FT}) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_b} \qquad (3\text{-}4a)$$

3–G.4 Numeric Constant for Mass Flow Developed From Ideal Gas Relative Density

Equation 3-2 substitutes Equation 3-55 for ρ_{t,p_1} in Equation 3-1.

$$Q_m = 359.072 C_d (\mathrm{FT}) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} G_i (28.9625)(144) h_w}{Z_{f_1} \mathrm{R} T_f}}$$

Where:

28.9625 = molecular weight of dry air.
1545.35 = universal gas constant (R).
144 = factor to convert pressure from pounds force per square foot to pounds force per square inch.

In Equation 3-2, therefore,

$$N_1 = 359.072 \sqrt{28.9625 \left(\frac{144}{1545.35} \right)}$$
$$= 589.885$$

And

$$Q_m = 589.885 C_d (\mathrm{FT}) E_v Y_1 d^2 \sqrt{\frac{G_i P_{f_1} h_w}{Z_{f_1} T_f}} \qquad (3\text{-}2)$$

3–G.5 Numeric Constant for Mass Flow Developed From Real Gas Relative Density

Equation 3-3 substitutes G_r for G_i in Equation 3-2 through the use of Equation 3-48:

$$Q_m = 589.885 C_d (\mathrm{FT}) E_v Y_1 d^2 \sqrt{\frac{Z_b G_r P_{f_1} h_w}{Z_{b_{air}} Z_{f_1} T_f}}$$

And for standard conditions,

$$Z_{b} = Z_{b_{air}} = 0.999590 \text{ at } 14.73 \text{ psia and } 519.67°\mathrm{R}\ (60°\mathrm{F})$$

In Equation 3-3, therefore,

$$N_1 = \frac{589.885}{\sqrt{0.999590}}$$
$$= 590.006$$

And

$$Q_m = 590.006 C_d (\mathrm{FT}) E_v Y_1 d^2 \sqrt{\frac{Z_b G_r P_{f_1} h_w}{Z_{f_1} T_f}} \qquad (3\text{-}3)$$

3–G.6 Numeric Constant for Base Volume Developed From Ideal Gas Relative Density

The constant 359.072 in Equation 3-4a was developed in 3-G.3. Equation 3-5a substitutes Equation 3-55 for ρ_{t,p_1} and Equation 3-56 for ρ_b in Equation 3-4a.

$$Q_b = \frac{359.072C_d(FT)E_vY_1d^2\sqrt{\rho_{t,p_1}h_w}}{\rho_b} \qquad (3\text{-}4a)$$

$$Q_b = 359.072C_d(FT)E_vY_1d^2\sqrt{\frac{P_{f_1}G_i(28.9625)(144)h_w}{Z_{f_1}RT_f}}\sqrt{\frac{Z_bRT_b}{P_bG_i(28.9625)(144)}}$$

Where:

1545.35 = universal gas constant (R).

28.9625 = molecular weight of dry air.

144 = factor to convert flowing pressure (P_{f_1}) from pounds force per square foot to pounds force per square inch.

144 = factor to convert base pressure (P_b) from pounds force per square foot to pounds force per square inch.

In Equation 3-5a, therefore,

$$N_1 = \frac{359.072\sqrt{1545.35\left(\frac{144}{28.9625}\right)}}{144}$$

$$= 218.573$$

And

$$Q_b = 218.573C_d(FT)E_vY_1d^2\,\frac{T_bZ_b}{P_b}\sqrt{\frac{P_{f_1}h_w}{G_iZ_{f_1}T_f}} \qquad (3\text{-}5a)$$

For the following standard conditions:

$P_b = P_s$

$= 14.73$ lbf/in^2 (abs)

$T_b = T_s$

$= 519.67$°R (60°F)

$Z_b = Z_s$

= compressibility of the gas at P_s and T_s

In Equation 3-5b,

$$N_1 = 218.573\left(\frac{519.67}{14.73}\right)$$

$$= 7711.19$$

Therefore,

$$Q_b = 7711.19C_d(FT)E_vY_1d^2Z_s\sqrt{\frac{P_fh_w}{G_iZ_{f_1}T_f}} \qquad (3\text{-}5b)$$

3–G.7 Numeric Constant for Base Volume Developed From Real Gas Relative Density

Equation 3-6a substitutes G_r for G_i in Equation 3-5a through the use of Equation 3-48. The inclusion of ρ_b moves this correction to the numerator:

$$Q_b = 218.573C_d(FT)E_vY_1d^2\frac{T_b}{P_b}\sqrt{\frac{Z_bZ_{b_{air}}P_{f_1}h_w}{G_rZ_{f_1}T_f}}$$

In Equation 3-6a, therefore,

$$N_1 = 218.573$$

For the following standard conditions:

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ lbf/in}^2 \text{ (abs)} \\ T_b &= T_s \\ &= 519.67^\circ\text{R } (60^\circ\text{F}) \\ Z_{b_{air}} &= Z_{s_{air}} \\ &= 0.999590 \end{aligned}$$

In Equation 3-6b,

$$\begin{aligned} N_1 &= 218.573\left(\frac{519.67}{14.73}\right)\sqrt{0.999590} \\ &= 7709.61 \end{aligned}$$

$$Q_v = 7709.61C_d(FT)E_vY_1d^2\sqrt{\frac{P_{f_1}Z_sh_w}{G_rZ_{f_1}T_f}} \qquad (3\text{-}6b)$$

3–G.8 Numeric Constant for Standard Volume Developed From Real Gas Relative Density

In Appendix 3-B, F_n, as expressed in Equation 3-B-5, includes additional numeric ratios, as stated in Equation 3-B-1, including the following:

519.67 = base temperature at 60°F, expressed in degrees Rankine.

$\frac{1}{14.73}$ = base pressure of 14.73 pounds force per square inch absolute.

$\sqrt{\frac{1}{519.67}}$ = flowing temperature at 60°F, expressed in degrees Rankine.

$\sqrt{0.999590}$ = compressibility of air at the base pressure of 14.73 pounds force per square inch absolute and the base temperature of 519.57°R.

In Equation 3-B-5, therefore,

$$\begin{aligned} N_1 &= 218.573\left(\frac{519.67}{14.73}\right)\sqrt{\frac{1}{519.67}} \\ &= 338.196 \end{aligned}$$

And

$$F_n = 338.196E_vd^2 \qquad (3\text{-}B\text{-}5a)$$

Or

$$F_n = 338.196E_vD^2\beta^2 \qquad (3\text{-}B\text{-}5b)$$

Manual of Petroleum Measurement Standards Chapter 14—Natural Gas Fluids Measurement

Section 8—Liquefied Petroleum Gas Measurement

Measurement Coordination Department

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Chapter 14—Natural Gas Fluids Measurement

SECTION 8—LIQUEFIED PETROLEUM GAS MEASUREMENT

14.8.0 Scope and Purpose

This publication describes dynamic and static metering systems used to measure liquefied petroleum gas in the density range of 0.30 to 0.70 grams per cubic centimetre. The physical properties of the components to be measured and the mixture composition of liquefied petroleum gas should be reviewed to determine the measurement system to be used Various systems and methods can be used in metering the product, and mutual agreement on the system and method between the contracting parties is required.

This publication does not endorse or advocate the preferential use of any specific type of meter or metering system. Further, this publication is not intended to restrict the future development of meters or measuring devices nor to in any way affect metering equipment already installed and in operation.

This publication serves as a guide in the selection, installation, operation, and maintenance of measuring systems applicable to liquefied petroleum gases and includes functional descriptions for individual systems.

14.8.1 Application

This publication does not set tolerances or accuracy limits. The application of the information here should be adequate to achieve acceptable measurement performance using good measurement practices, while in addition considering user requirements and applicable codes and regulations.

Systems for measuring liquefied petroleum gases use either volumetric or mass determination methods, and both methods apply to either static or dynamic conditions.

Volumetric methods of measurement are generally used where physical property changes in temperature and pressure are known and correction factors can be applied to correct the measurement to standard conditions.[1] Volumetric measurement is applicable to most pure components and many commercial product grades.

Mass determination methods of measurement are most commonly used where conditions in addition to temperature and pressure will affect the measurement. Such conditions include compositional changes, intermolecular adhesion, and volumetric changes caused by solution mixing. Mass measurement is applicable to liquefied petroleum gas mixtures where accurate physical correction factors have not been determined and in some manufacturing processes for a mass balance.

Many of the measurement procedures pertaining to the measurement of other products are applicable to the measurement of liquefied petroleum gases. However, certain characteristics of liquefied petroleum gas require extra precautions to improve measurement accuracy

Liquefied petroleum gas will remain in the liquid state only if a pressure sufficiently greater than the equilibrium vapor pressure is maintained (see Chapters 5.3 and 6.6). In liquid meter systems, adequate pressure must be maintained to prevent vaporization caused by pressure drops attributed to piping, valves, and meter tubes. When liquefied

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[1] Standard temperature is 60°F in the English (or customary) system and 15°C in the International System of Units (SI) Standard pressure is the vapor pressure at 60°F (15°C) or 14 696 pounds per square inch absolute (101.325 kilopascals), whichever is higher This is not the same pressure base standard as that used for gas.

petroleum gas is stored in tanks or containers, a portion of the liquid will vaporize and fill the space above the liquid. The amount vaporized will be related to the temperature and the equilibrium constant for the mixture of components.

Liquefied petroleum gas is more compressible and has a greater coefficient of thermal expansion than the heavier hydrocarbons. The application of appropriate compressibility and temperature correction factors is required to correct measurements to standard conditions, except when measurement for mass determination is from density and volume at metering temperatures and pressures.

Meters should be proven on each product at or near the normal operating temperature and pressure. Should the product or operating conditions change so that a significant change in the meter factor occurs, the meter should be proven again according to Chapters 4 and 5.

14.8.2 Referenced Publications

To the extent specified in the text, the latest edition or revision of the following standards and publications form a part of this publication.

API

Manual of Petroleum Measurement Standards

Chapter 2, "Tank Calibration" (in preparation)
Chapter 4, "Proving Systems"
Chapter 5.2, "Measurement of Liquid Hydrocarbons by Positive Displacement Meter"
Chapter 5.3, "Turbine Meters"
Chapter 5.4, "Instrumentation or Accessory Equipment for Liquid Hydrocarbon Metering Systems"
Chapter 6.6, "Pipeline Metering Systems"
Chapter 9.1, "Hydrometer Test Method for Density, Relative Density, or API Gravity of Crude Petroleum and Liquid Petroleum Products"
Chapter 11.1, "Volume Correction Factors"
Chapter 12.2, "Calculation of Liquid Petroleum Quantities Measured by Turbine or Displacement Meters"
Chapter 14.1, "Measuring, Sampling, Testing, and Base Conditions for Natural Gas Fluids"
Chapter 14.3, "Orifice Metering of Natural Gas"
Chapter 14.4, (in preparation)
Chapter 14.6, "Installing and Proving Density Meters"
Chapter 14.7, (in preparation)

ASTM[2]

DS 4A *Physical Constants of Hydrocarbons* C_1 *to* C_{10}

GPA[3]

2140 *Liquefied Petroleum Gas Specifications and Test Methods* (ASTM D 1265; ANSI Z11.91)
2145 *Physical Constants for the Paraffin Hydrocarbons and Other Components of Natural Gas*
2165 *Method for Analysis of Natural Gas Liquid Mixtures by Gas Chromatography*
2174 *Method for Obtaining Hydrocarbon Fluid Samples Using a Floating Piston Cylinder*

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[2] American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103

[3] Gas Processors Association, 1812 First Place, Tulsa, Oklahoma 74103

2177	*Tentative Method for the Analysis of Demethanized Hydrocarbon Liquid Mixtures Containing Nitrogen and Carbon Dioxide by Gas Chromatography*
2261	*Method of Analysis for Natural Gas and Similar Gaseous Mixtures by Gas Chromatography*
8173	*A Standard for Converting Natural Gas Liquids and Vapors to Equivalent Liquid Volumes*

GPSA[4]
Engineering Data Book

14.8.3 Requirements for All Measurement Methods

The following general requirements apply to dynamic measurement systems using either volumetric or mass determination methods of measuring liquefied petroleum gases.

14.8.3.1 PROVISIONS TO ENSURE THAT FLUIDS ARE IN THE LIQUID PHASE

Provisions shall be made to ensure that liquefied petroleum gas measurement conditions of temperature and pressure will be adequate to keep the fluid totally in the liquid phase. Measurement in the liquid phase must occur at a pressure at least 1.25 times the equilibrium vapor pressure at measurement temperature, plus twice the pressure drop across the meter at maximum operating flow rate, or at a pressure 125 pounds per square inch higher than the vapor pressure at a maximum operating temperature, whichever is lower (see Chapters 5.3 and 6.6)

14.8.3.2 ELIMINATION OF SWIRL

To prevent swirl through the measuring device when using turbine or orifice meters, straightening vanes or adequate unrestricted straight lengths of piping should be used in the upstream and downstream metering tube.

14.8.3.3 TEMPERATURE MEASUREMENT

Temperature measurements, where required, should be made at a point that indicates conditions in the measuring device. The accuracy of instruments and the type of measurement used are specified in Chapters 5.2, 5.3, 5.4, and 14.6.

14.8.3.4 PRESSURE MEASUREMENT

Pressure measurements, where required, should be made at a point that will be responsive to varying pressure conditions in the measuring device. The accuracy of instruments and the type of measurement used should be as described in Chapters 5.2 and 14.6.

14.8.3.5 DENSITY OR RELATIVE DENSITY MEASUREMENT

The point for measurement of density or relative density (specific gravity) of the liquid should be sensitive to varying conditions in the measuring device. Densities to be used for mass measurement determination must be obtained at the same flowing conditions that exist at the meter. The accuracy of instruments and the type of measurement used should be as described in Chapters 9 and 14.6.

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[4] Gas Processors Suppliers Association. Order from Gas Processors Association, 1812 First Place, Tulsa, Oklahoma 74103

14.8.3.6 LOCATION OF MEASURING AND SAMPLING EQUIPMENT

Measuring and sampling equipment must be located to minimize or eliminate the influence of pulsation or mechanical vibration caused by pump or control valve generated noise. Special precautions should be taken to minimize or eliminate the effects of electrical interference that may be induced in the flow meter pick-up coil circuit.

14.8.4 Volumetric Determination in Dynamic Systems

Measurement of liquefied petroleum gas (liquid phase) in a dynamic condition can be performed using several measurement devices. The use of a specific type of measuring device is dependent upon mutual agreement between the contracting parties.

14.8.4.1 MEASUREMENT BY ORIFICE METER

Measurement of liquefied petroleum gases by orifice meter shall conform to Chapter 14.3, using orifice and line internal diameter ratios and appropriate coefficients for flow as agreed upon between the parties. Location factors, F_l, and orifice thermal expansion factor, F_a, should be used where applicable according to the procedure in Chapter 14.3, Appendix B.14 and B.15 respectively. Manometer factors, F_m, must be calculated according to the procedure in this section for recorders utilizing mercury manometers. (F_m = 1.000 for bellows type differential pressure instruments.)

Measurement of liquefied petroleum gas having a high vapor pressure is simplified where deliveries are obtained in mass units, by multiplying the volume at flowing conditions times the density or relative density (measured within prescribed limits at the same flowing temperature and pressure that exists at the meter) times an appropriate constant. Calculation of the volume at standard conditions can then be made using 14.8.6 or GPA Standard 8173.

The following equations can be used to determine flow rate:

1. Flow rate in cubic feet per hour at flowing conditions.

$$Q_f = 0.134452\, F_b F_r Y\, F_m F_a F_l \sqrt{\frac{h_w}{G_f}}$$

$$Q_f = 1.0618\, F_b F_r Y\, F_m F_a F_l \sqrt{\frac{h_w}{\rho_f}}$$

2. Flow rate in pounds mass per hour

$$Q_m = 8.3853\ F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, G_f}$$

$$Q_m = 1.0618\ F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, \rho_f}$$

3. Flow rate in cubic feet per hour at base conditions.

$$Q_b = \frac{0.134452}{G_b} F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, G_f}$$

$$Q_b = \frac{1.0618}{\rho_b} F_b F_r Y\, F_m F_a F_l \sqrt{h_w\, \rho_f}$$

Where

F_b = basic orifice factor from Chapter 14.3 (F_b = 338.17 d^2K_o).

F_m = manometer factor for mercury manometers only.
Y = expansion factor, calculated using a specific heat ratio for flowing conditions as determined from data or an equation of state.
F_r = Reynolds number factor.

The Reynolds number factor may be calculated using b values from Table 5 or Table 9 of Chapter 14.3. CAUTION: Do not use the equations for F_r in Tables 5 or 9, but use the b values only in the following equations to obtain the Reynolds number factor

$$F_r = 1 + \frac{b\ 8{,}423\mu_{pfs}}{\sqrt{h_w \rho_f}} = 1 + \frac{b\ 1{,}067\mu_{pfs}}{\sqrt{h_w G_f}}$$

$$F_r = 1 + \frac{b\ 271{,}000\mu_e}{\sqrt{h_w \rho_f}} = 1 + \frac{b\ 34{,}316\mu_e}{\sqrt{h_w G_f}}$$

$$F_r = 1 + \frac{b\ 5.66\mu_{cp}}{\sqrt{h_w \rho_f}} = 1 + \frac{b\ 0.7167\mu_{cp}}{\sqrt{h_w G_f}}$$

$$b = \frac{E}{12{,}835dK}$$

The Reynolds number factor also may be calculated from the following:

$$F_r = 1 + E/R_d$$

Where:

$$R_d = \frac{V_f d\rho}{12\mu_{pfs}}$$

d = diameter of orifice, in inches.
ρ = density, in pounds per cubic foot.
V_f = velocity of jet in orifice, in feet per second.
μ_{pfs} = absolute viscosity, in pounds per foot per second.

$$R_d = \frac{2{,}267.8\ dK\sqrt{h_w \rho_f}}{\mu_{cp}} = \frac{17{,}909\ dK\sqrt{h_w G_f}}{\mu_{cp}}$$

$$R_d = \frac{0.04736\ dK\sqrt{h_w \rho_f}}{\mu_e} = \frac{0.37405\ dK\sqrt{h_w G_f}}{\mu_e}$$

$$R_d = \frac{1\ 5238\ dK\sqrt{h_w \rho_f}}{\mu_{pfs}} = \frac{12.034\ dK\sqrt{h_w G_f}}{\mu_{pfs}}$$

R_d can also be determined by trial and error as follows: Set F_r = 1.000 in the flow equation to get an approximate Q_m or Q_b, and use this result to calculate F_r. With this calculated value of F_r, obtain a new value of F_r and of Q_m or Q_b. Repeat this process until the value of Q_m or Q_b is within the limits desired.

$$R_d = R_D/\beta$$

$$R_D = \frac{6.30\ Q_m}{D\mu_{cp}} = \frac{294\ 30\ Q_b G_b}{D\mu_{cp}}$$

$$R_D = \frac{0.0001319\ Q_m}{D\mu_e} = \frac{0.004244\ Q_m}{D\mu_{pfs}}$$

$$F_r = 1 + \frac{0.1582\beta\, E\, D\mu_{cp}}{Q_m} = 1 + \frac{0.002539\beta\, E\, D\mu_{cp}}{Q_b G_b}$$

$$F_r = 1 + \frac{7581.5\beta\, E\, D\mu_{e}}{Q_m} = 1 + \frac{235.63\beta\, E\, D\mu_{pfs}}{Q_m}$$

Where:

μ_{pfs} = absolute viscosity, in pounds per foot per second. = $g\mu_e$
μ_e = absolute viscosity, in pounds per square foot per second.
μ_{cp} = absolute viscosity, in centipoises.
μ_e = $0.03108\mu_{pfs} = 0.00002089\mu_{cp}$.
ρ_b = density of liquid, in pounds per cubic foot at base conditions.
ρ_f = density of liquid, in pounds per cubic foot at flowing temperature and pressure.
D = diameter (inside) of meter tube, in inches.
d = diameter of orifice bore, in inches.
β = d/D (commonly called the beta ratio).
G_f = relative density at flowing conditions. Ratio of the density of the liquid at flowing conditions to the density of water at 60°F. (The U.S. National Bureau of Standards has established 0.999012 gram per cubic centimetre as the density of air-free pure water in a vacuum at a temperature of 60°F and a pressure of 14.696 pounds per square inch and standard gravitational acceleration of 980.665 centimetres per second per second.)
G_b = relative density of liquid at base conditions.
K = coefficient of discharge for a sharp edge orifice.
K = $K_o\,(1 + E/R_d)$

$$K_o = \frac{K_e}{1 + \dfrac{15E}{1{,}000{,}000d}}$$

Where:

K_o = coefficient of discharge for infinite Reynolds number.
K_e = coefficient of discharge when the Reynolds number is equal to $\dfrac{1{,}000{,}000d}{15}$.

$$E = d\left(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + \frac{520}{\sqrt{D}}\right), \quad \text{for flange taps}$$

$$E = d\left(905 - 5000\beta + 9000\beta^2 - 4200\beta^3 + \frac{875}{D}\right), \quad \text{for pipe taps.}$$

For flange taps

$$K_e = 0.5993 + \left[0.364 - \frac{0.076}{\sqrt{D}}\right]\beta^4 + 0.4\left[1.6 - \frac{1}{D}\right]^5\left[\left(0.07 + \frac{0.5}{D}\right) - \beta\right]^{2.5}$$
$$- \left[0.009 + \frac{0.034}{D}\right]\left[0.5 - \beta\right]^{1.5} + \left[\frac{65}{D^2} + 3\right]\left[\beta - 0.7\right]^{2.5} + \frac{0.007}{D}$$

For pipe taps

$$K_e = 0.5925 + \frac{0.0182}{D} + \left[0.440 - \frac{0.06}{D}\right]\beta^2 + \left[0.935 + \frac{0.225}{D}\right]\beta^5$$

$$+ 1.35\ \beta^{14} + \frac{1.43}{\sqrt{D}}\ (0.25 - \beta)^{2.5}$$

NOTE: When any of the terms in K_e is negative, that term is set equal to zero.

F_l = location factor.

The location factor is used to correct for the change in specific weight of (a) the mercury in mercury manometer type differential gages, (b) the calibrating liquid in the test manometer, and (c) the weights for a deadweight gage used in calibrating the instruments. See Chapter 14.3, Appendix B, B. 34 for equations.

F_m = manometer factor

The manometer factor is required only in mercury manometer type gages to correct for the error in differential pressure indication caused by the weight of the liquid column above the mercury and the change in the density of the mercury at temperatures other than the base temperature of 60°F.

$$F_m = 0.034374\ \sqrt{\rho_m - \rho_l}$$

Where.

ρ_m = density of mercury at ambient temperature, in pounds per cubic foot.

ρ_m = 846.324 [1 − 0.000101(T_a − 60)]

T_a = ambient temperature, in degrees Fahrenheit.

ρ_l = density of liquid on mercury at ambient temperature, in pounds per cubic foot. See Chapter 11.1, Tables 6, for density correction.

F_a = orifice thermal expansion factor.

This factor is used to correct for the error resulting from the expansion or contraction of the orifice bore at operating temperatures different from the temperature of the plate when bored, usually assumed to be 68°F.

F_a = 1 + 0.0000185 (°F − 68) for Type 304 and 316 stainless steels.

F_a = 1 + 0.0000159 (°F − 68) for Monel.

14.8.4.2 MEASUREMENT BY POSITIVE DISPLACEMENT METER

The manufacturer's recommendations should be carefully considered in sizing turbine and positive displacement meters (see Chapters 5.2 and 5.3).

Air eliminators should be used with caution, particularly where the line in which they are installed could be shut-in occasionally, and where complete vaporization could occur.

Vapor formation, resulting from the effects of ambient temperature or heat tracing on the line ahead of the meter, could cause inaccuracies and damage, which are most likely to be encountered during startup. Caution must be exercised.

14.8.4.2.1 Volume at Standard or Base Conditions

Liquid measurement by positive displacement meters should conform to the procedures in Chapter 5.2. Appropriate correction factors should be used to adjust the measured volume to standard conditions by correcting for temperature, pressure, and meter factor. Factors to be applied will be found in Chapters 11 and 12.

The positive displacement measurement equation is:

$$V_b = V_f \times \text{M.F.} \times C_{tl} \times C_{pl}$$

Where:

V_b = volume at base or standard conditions.
V_f = volume at flowing conditions, indicated by a measuring device.
M.F. = meter factor, obtained by proving the meter according to Chapters 4 and 12.2.
C_{tl} = correction factor for temperature to correct the volume at flowing temperature to standard temperature. See Chapter 11.1, Tables 24, or other agreed-upon tables.
C_{pl} = correction factor for pressure to correct the volume at flowing pressure to standard conditions. See Chapter 11.1, Tables 24, or other agreed-upon tables.

14.8.4.2.2 Volume at Flowing Conditions for Mass Determination

The volume measured at flowing conditions (V_m) times the meter factor equals the volume at flowing conditions. Displacement meters used for volumetric measurement in deriving total mass shall conform to the standards described in Chapter 5.2 for the service intended. Temperature or pressure compensation devices are not to be used on these meters and the accessories used shall conform to Chapter 5.4.

14.8.4.3 MEASUREMENT BY TURBINE METER

See 14.8.4.2 for cautions about air eliminators and vapor formation in lines. Also carefully consider the manufacturer's recommendations about sizing of meters.

Liquid measurement by turbine meter should conform to the procedures described in Chapter 5.3. Appropriate correction factors should be used that will adjust the measured volume to standard conditions by correcting for temperature, pressure, and meter factor. Factors to be applied will be found in Chapters 4, 11, and 12.

The following equation is used when measuring by turbine meter.

$$V_b = V_f \times \text{M.F.} \times C_{tl} \times C_{pl}$$

Where:

V_b = volume at base or standard conditions
V_f = volume at flowing conditions, indicated by a measuring device.
M.F. = meter factor, obtained by proving the meter according to Chapters 4 and 12.2.
C_{tl} = correction factor for temperature to correct the volume at flowing temperature to standard temperature. See Chapter 11.1, Tables 24, or other agreed-upon tables
C_{pl} = correction factor for pressure to correct the volume at flowing pressure to standard conditions. See Chapter 11.1, Tables 24, or other agreed-upon tables

Turbine meters used for volumetric measurement in deriving total mass shall conform to Chapter 5.3 for the service intended. Temperature or pressure compensating devices shall not be used on these meters and accessories shall conform to Chapter 5.4. The mass delivered and the volume of each component at standard conditions may be determined according to Chapter 14.7.

14.8.4.4 MEASUREMENT BY OTHER DEVICES

Dynamic measurement of liquefied petroleum gas can be accomplished using other types of equipment by mutual agreement of the contracting parties.

14.8.4.5 METER PROVING

The primary measuring device must be compared to a known standard. Comparison to a standard is accomplished by proving displacement and turbine meters using a pipe prover calibrated in accordance with Chapter 4. Tank-type provers are not recommended because liquefied petroleum gas may vaporize in the tank, making accountability for these vapors difficult. When a meter is used to measure more than one product, the meter shall be proved at the operating rates of flow, pressure, and temperature and the specification of the liquid that it will measure in routine operation. Several meter factors may be required where normal operations change significantly. The proving device should be installed so that the temperature and pressure within the prover and meter coincide as closely as possible. Should meter and prover temperatures or pressures vary, the prover volume shall be corrected to meter operating conditions according to Chapters 4, 11, and 12 or as agreed to by the contracting parties. Factors shall be adjusted as required between proving dates as a result of significant changes in metering pressure and/or temperature since the last proving.

14.8.4.6 SAMPLING

Sampling shall be accomplished to yield a sample that is proportional to, and representative of, the flowing stream during the measuring interval. Proportional samplers take small samples of the flowing stream proportional to the flow rate. Time incremental sampling may be used only when the flow rate is constant.

The sample collecting system shall be designed to contain the collected sample in the liquid state. This may be done using a piston cylinder or a cylinder with a bladder. Both the piston cylinder and bladder cylinder normally use inert gas vapor, hydraulic oil, or pipeline fluid to oppose the liquid injection and maintain a pressure level above the vapor pressure of the sample. A typical proportional sampler is described in the appendix to this publication.

Precautions shall be taken to avoid vaporization in sample loop lines when operating near the product vapor pressure. In some instances, insulating sample lines and sample containers or controlling the pressure or temperature of sample containers containing volatile materials may be necessary.

Sample loops should be short and of small diameter, sampling from the center of the stream. Adequate sample loop flow rates should be maintained to keep fresh product at the sample valve and to reduce the time lag between the meter and the sampler to a minimum.

All sample lines, pumps, and related equipment should be purged or bled down when sample collection cylinders are emptied to avoid contamination or distortion of the flowing sample. Sampler systems should be designed to minimize dead product areas, which could distort samples.

Obtaining a representative sample for transport to the laboratory shall be in accordance with GPA 2174, Appendix B of Chapter 14.1, or other recognized safety procedures. Sample containers must be adequately sized. If samples are to be shipped by common carrier, containers must comply with the latest hazardous materials regulations of the United States Department of Transportation.

Products or mixtures that have equilibrium vapor pressures above atmospheric pressure shall be maintained at a pressure where vaporization cannot occur within the on-line sample system or transfer containers.

Use of sample collection and transportation containers equipped with floating pistons or bladders (and equipped to maintain sample storage pressures above vapor pressure) is one effective way to avoid liquid-vapor separation. When using this type of equipment, adequate precautions must be observed to allow for thermal expansion of the product so that excessive pressure or release of product does not occur. Procedures described in the appendix of this publication may be used.

Sample handling procedures outlined in API Chapter 14.1, Appendix B, using immiscible fluid outage cylinders, may also be used. Water used with this method may result in removal of carbon dioxide or other water-soluble components from the sample.

Sample injection pumps or devices that inject the sample into containers shall be designed to deliver a constant volume per stroke over their normal operating pressure range. Procedures as outlined in Chapter 14.1, the appendix to this publication, and GPA Publication 2174 shall be followed, as applicable.

Samples taken over a period of time using a proportional sampler must be mixed to be truly representative before they are transferred to portable sample containers. Product mixing should not be attempted until the sampler has been isolated from the source. Procedures for thorough mixing of samples shall be provided to ensure that samples transferred to transportation cylinders and the analysis obtained are representative of the flowing stream during the measured interval.

After mixing, the sampled product is transferred to a portable piston cylinder or a double valved sample cylinder, using the immiscible fluid displacement method. Transfer the sampler to the portable cylinder using the same procedure used to take spot samples. When the required number of portable cylinders has been filled, the remaining product in the sampler must be vented back into the pipeline or disposed of before the sampler is returned to service.

Obtaining a representative sample of the stream liquid for transport to the laboratory shall be in accordance with GPA Publication 2174 or Appendix B of Chapter 14.1. Provisions shall be made for thermal expansion. Department of Transportation approved containers shall be used.

14.8.4.7 SAMPLE ANALYSIS

Depending upon the composition of the stream, liquid sample analysis shall follow the chromatographic procedures described in GPA Publications 2165, 2177, and 2261, or other methods agreed upon by the contracting parties.

Where applicable, such as with liquefied petroleum gas mixtures, special efforts shall be made to accurately determine the molecular weight and the density of the heptanes plus fraction (or of the last significant fraction determined by agreement).

14.8.5 Mass Determination in Dynamic Systems (Density Range 0.30 to 0.70 g/cm^3)

Mass measurement is applicable to liquefied petroleum gas mixtures and to components that are affected by compositional changes, intermolecular adhesions, solution mixing, or extreme pressure and temperature conditions where accurate physical correction factors have not been determined.

Mass measurement in a dynamic state normally utilizes (1) a volumetric measuring device at flowing conditions, (2) a density or relative density (specific gravity) measuring device for determining density or relative density at the same flowing conditions as the measuring device, and (3) a representative sample of the fluid flowing through the measuring system, collected proportional to flow, as presented in Chapter 14.7.

Mass measurement is accomplished by multiplying the measured volume at flowing conditions times flowing density measured at the same conditions, using consistent units. The equivalent volume at standard conditions of each component in the mixture may be

obtained by using a compositional analysis of the representative sample and the density of each component at 60°F and the equilibrium pressure at 60°F.

Liquids with densities below 0.3 and above 0.7 grams per cubic centimetre and cryogenic fluids are excluded from the scope of this document. However, the principles can apply to these fluids with modified application techniques.

Equipment exists which uses diverse principles for measuring volume, sampling the product, and determining the composition and density of the product. This publication does not advocate the preferential use of any particular type of equipment. It is not the intention of this publication to restrict future development or improvement of equipment.

14.8.5.1 BASE CONDITIONS

Density is defined as mass per unit volume:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

Mass is an absolute measure of the quantity of matter. Weight is the force resulting from an acceleration due to gravity acting upon a mass. Changes of gravity acceleration from one locality to another will affect the resulting weight force observed. Therefore, quantities determined in accordance with Chapter 14.7 shall be *mass* rather than weight. This may be accomplished through procedures in Chapter 14.6 by referral to weighing devices used to calibrate density meters to test weights of known mass. This referral or calibration is done at or near the densitometer location, eliminating the need for further correction for local gravitational force variances.

Weight observations to determine fluid density shall be corrected for air bouyancy (commonly called "weighed in vacuum") and for local gravity, as necessary. Such observations can be used in conjunction with the calibration of density meters or for checking the performance of equation of state correlations. Procedures are outlined in Chapter 14.6.

Volumes and densities for mass measurement shall be determined at operating temperature and pressure to eliminate temperature and compressibility corrections. However, equivalent volumes of components are often computed for the determined mass flow. These volumes will be stated as follows: temperature, 15°C (or 60°F); pressure, 101.325 kilopascals (14.696 pounds per square inch absolute), or the product equilibrium vapor pressure at 15°C (or 60°F), whichever is higher.

14.8.5.2 MASS MEASUREMENT USING DISPLACEMENT TYPE OR TURBINE METERS

The equation for determining mass using displacement-type or turbine meters is:

$$\text{Mass} = \begin{bmatrix} \text{Metered volume} \\ \text{at meter} \\ \text{operating} \\ \text{conditions} \end{bmatrix} \times \begin{bmatrix} \text{Meter factor} \\ \text{at meter} \\ \text{operating} \\ \text{conditions} \end{bmatrix} \times \begin{bmatrix} \text{Density per} \\ \text{unit volume at} \\ \text{meter operating} \\ \text{conditions} \end{bmatrix} \times \begin{bmatrix} \text{Densitometer} \\ \text{correction} \\ \text{factor (if} \\ \text{applicable)} \end{bmatrix}$$

14.8.5.3 MASS MEASUREMENT USING ORIFICE METERS

The equation for determining mass using orifice meters is:

$$Q_m = C' \sqrt{h_w \rho_f} = \text{flow rate expressed in units of mass/units of time.}$$

The terms for this equation are defined and discussed in 14.8.5.1.

14.8.5.4 DENSITY DETERMINATION

14.8.5.4.1 Empirical Density

Liquid density may be calculated as a function of composition, temperature, and pressure. It is preferred that the calculated or measured density be applied in real time to the flow meter. This provides for the maximum mass measurement precision, that is, the incremental volume of measured liquid is always in direct time relation to the density measured or calculated. However, it is common practice to use the composition of a sample taken continuously during the delivery period proportional to the volume delivered, and to use the average temperature and pressure for the delivery period.

Calculations may be made by means of empirical correlations or by generalized equations of state. The empirical correlations are derived from fitting experimental data covering specific ranges of compositions, temperatures, and pressures and can be inaccurate outside these ranges. Gas Processors Association procedure TP-1 for ethane/propane mix and TP-2 for high ethane raw make streams are examples. TP-3 is a more theoretical procedure for application to liquefied natural gas.

Generalized equations of state do not have strict limitations on ranges of compositions and conditions and can be applied to a wide variety of systems; however, empirical correlations are much more accurate when applied to the specific systems for which they were derived. The Rackett equation, the Starling-Han modification of the BWR equation of state, and several modified Redlich-Kwong equations of state (Soave, Mark V, Peng-Robinson) are examples.

It is the responsibility of the contracting parties to verify the validity and limits of the accuracy of methods considered for empirical density determination on the particular fluids to be measured.

Significant errors can occur from inaccuracies in temperature and pressure measurement, recording, or integration. Products with a density of less than 0.6 grams per cubic metre are particularly susceptible to errors and require a higher level of precision. See Chapter 14.6 for recommended precision levels of temperature and pressure.

14.8.5.4.2 Measured Density

Measured density of products between 0.3 and 0.7 grams per cubic centimetre shall be determined using density meters installed and calibrated in accordance with Chapter 14.6 or as otherwise agreed between the contracting parties.

Density instruments or probes shall be installed as follows:

1. No interaction that would adversely affect the flow or density measurement shall exist between the flow meter and the density transducer or probe.
2. Temperature and pressure differences among the fluid in the flow meter, the density measuring device, and the calibrating devices must be minimized and must be within specified limits for the fluid being measured and the mass measurement accuracy expected or required.
3. Density meters may be installed either upstream or downstream of primary flow devices in accordance with Chapter 14.6 but should not be located between flow straightening devices and meters and must not bypass the primary flow measurement device.

Densitometer accuracy will be seriously affected by the accumulation of foreign material from the flowing stream. The possibility of accumulation should be considered in selecting density measurement equipment and in determining the frequency of density equipment calibration and maintenance. Accuracy of the data recording, transmission, and computation equipment and methods should also be considered in system selection. See Chapter 14.6 for further comments.

14.8.5.5 CONVERSION OF MEASURED MASS TO VOLUME

Conversion from mass determined into equivalent volumes of components shall be in accordance with the latest revision of GPA Publication 8173, as described below. In this procedure, a chromatographic analysis representative of the delivered product is used to determine the mass of each individual component that comprised the total mass. The individual component masses are then converted to their respective equivalent liquid volumes at 15°C (or 60°F) and equilibrium vapor pressure at 15°C (or 60°F), using component density values from GPA Publication 2145.

The calculation of total mass flowing must be performed continuously on-line by a suitable device or by off-line integration of charts on which metered volume and density are continuously recorded so that at all times the density corresponds to the volume measured.

Conversion of the determined mass into an equivalent volume of each component at base or standard conditions at equilibrium vapor pressure at 15°C (60°F) or 101.325 kilopascals (14.696 pounds per square inch absolute), whichever is higher, shall be in accordance with Chapter 14.4. In this procedure a chromatographic analysis, representative of the delivered product, is used to determine the mass of each individual component comprising the total mass. The individual component masses are then converted to their respective equivalent liquid volumes at 15°C (or 60°F) and the equilibrium vapor pressure at 15°C (or 60°F) using component density values in vacuum from Chapter 11 or GPA Publication 2145. Example calculations, repeated from Chapter 14.4, are provided in 14.8.5.6.

14.8.5.6 CALCULATIONS FOR LIQUID-VAPOR CONVERSION

The density of pure hydrocarbons in pounds mass per gallon (weight in vacuum) shall be as stated in GPA Standard 2145. Should constants be required for a hydrocarbon component that is not presented in GPA Standard 2145, the constants contained in the GPSA *Engineering Data Book*, Section 16, "Physical Properties," shall be used. If the required constants are not contained in the GPSA *Engineering Data Book*, the ASTM Data Series Publication, DS 4A, constants shall be used. The steps described in Figure 1 are required

14.8.5.7 SPECIAL PRECAUTIONS FOR MASS MEASUREMENT

Volume measurement must be made at flowing conditions. The measuring device must be proven at flowing conditions.

Density or relative density (specific gravity) measurements must be made at the same flowing conditions as the volume measurements.

Temperature compensated metering devices shall not be used in the mass measurement method

14.8.6 Volumetric Measurement in Static Systems

The liquid volume of liquefied petroleum gas consists of the sum of the liquid volume and the volume of the vapor above the liquid converted to its liquid equivalent

Volumetric measurement is accomplished by using calibrated vessels or tanks with gaging devices that can be read at the vessel operating pressures to determine the liquid level. The volume of vapor above the liquid is determined by using the ideal gas law ($PV = NRT$) corrected by the gas compressibility factor. The liquid and vapor are corrected for temperature and pressure to standard or base conditions of temperature and the vapor pressure of the product at standard or base temperature. The vapor volume can be converted to equivalent liquid volume by using the appropriate factors.

Step 1—Convert to mass analysis. Given: 825,300 = Total pounds mass.

Component	Mole Percent	Mole Weight	Mole Percent × Mole Weight	Weight of Fraction of Component
CO_2	0.11	44.01	4.84	0.001107
C_1	2.14	16.043	34.33	0.007852
C_2	38.97	30.069	1171.79	0.268010
C_3	36.48	44.096	1608.62	0.367921
IC_4	2.94	58.123	170.88	0.039083
nC_4	8.77	58.123	509.74	0.116587
iC_5	1.71	72.15	123.38	0.028219
nC_5	1.82	72.15	131.31	0.030033
C_6+	7.06	87.436	617.30	0.141188
	100.00		4372.19	1.000000

Step 2—Calculate the mass of each component as follows: Weight fraction times total pounds mass equals pounds mass each component:

Component	Weight Fraction of Component	Total Pounds Mass	Pounds Mass of Component
CO_2	0.001107	825,300	914
C_1	0.007852	825,300	6,480
C_2	0.268010	825,300	221,189
C_3	0.367921	825,300	303,645
IC_4	0.0339083	825,300	32,255
nC_4	0.116587	825,300	96,219
iC_5	0.028219	825,300	23,289
nC_5	0.030033	825,300	24,786
C_6+	0.141188	825,300	116,523
			825,300

Step 3—Calculate the volume of each component at equilibrium pressure and 60°F as follows.

Component	Component Pounds Mass	Density Pounds/Gallon (in vacuum)	U.S. Gallons
CO_2	914	6.817	134
C_1	6,480	2.50	2,592
C_2	221,189	2.97	74,474
C_3	303,645	4.231	71,767
IC_4	32,255	4.694	6,872
nC_4	96,219	4.871	19,765
IC_5	23,289	5.206	4,473
nC_5	24,786	5.262	4,710
C_6+	116,523	5.951*	19,580
			204,355

*From analysis

Figure 1—Calculations for Liquid Vapor Conversion

A pressure vessel or container must be able to safely withstand the vapor pressures of the contained product at the maximum operating temperature.

14.8.6.1 TANK CALIBRATION

Procedures for calibrating tanks and vessels are presented in Chapter 2.

14.8.6.2 TANK GAGING OF LIQUEFIED PETROLEUM GAS

Procedures for gaging liquefied petroleum gas in storage tanks are presented in Chapter 3. Special precautions are necessary to accurately account for the vapors above the liquid.

The composition and volume of the vapors are dependent upon the temperature and pressure conditions of the liquid.

14.8.6.3 TEMPERATURE MEASUREMENT

Chapter 5.4 contains general requirements for temperature measurement. Procedures for measuring the temperature of liquefied petroleum gas in storage vessels under static conditions are presented in Chapter 7.

14.8.6.4 RELATIVE DENSITY MEASUREMENT

Procedures for determining relative density of liquefied petroleum gas are presented in Chapters 9, 11, 12, 14.6, and 14.7. Observed relative densities (specific gravities) are corrected to standard or base conditions by using tables in Chapter 11.1.

14.8.6.5 WATER AND FOREIGN MATERIAL

Water and sediment content is not as serious a problem with liquefied petroleum gases as with crude oil. Product specifications in contracts for custody transfer should contain a section on product quality to provide for testing propane by the freeze valve method (ANSI/ASTM D 2713-76), the cobal bromide method, or the Bureau of Mines method. Other mutually acceptable methods for determining dryness may be used for other liquefied petroleum gases having a high vapor pressure.

14.8.6.6 SAMPLING

The scope of Chapter 8 does not include sampling of liquefied petroleum gases; however, GPA Publication 2140 contains a section on sampling this type of product. GPA Publication 2140 is also designated as ASTM D 1265. Its scope covers the procedure for obtaining representative samples of liquefied petroleum gases, such as propane, butane, or mixtures thereof, in containers other than those used in laboratory testing apparatus. A liquid sample is transferred from the source into a sample container by purging the container and filling it with liquid to 80 percent of capacity.

Considerable effort may be required to obtain a representative sample, especially if the material being sampled is a mixture of liquefied petroleum gases. The following factors must be considered.

1. Samples must be obtained in the liquid phase.
2. When it is definitely known that the material being sampled is composed predominantly of only one liquefied petroleum gas, a liquid sample may be taken from any part of the vessel.
3. When the material being sampled has been agitated until uniformity is assured, a liquid sample may be taken from any part of the vessel.
4. Because of wide variations in the construction details of containers for liquefied petroleum gases, it is difficult to specify a uniform method for obtaining representative samples of heterogeneous mixtures. If it is not practicable to agitate a mixture for homogeneity, obtain liquid samples by a procedure that has been agreed upon by the contracting parties.

Directions for sampling cannot be explicit enough to cover all cases. They must be supplemented by judgment, skill, and sampling experience. Extreme care and good judgment are necessary to ensure that samples represent the general character and average condition of the material. Because of the hazards involved, liquefied petroleum gases should be sampled by, or under the supervision of, persons familiar with the necessary safety precautions.

14.8.6.7 VOLUMETRIC CALCULATION

When product is removed from or added to a tank, the beginning and ending liquid levels are obtained along with corresponding temperatures and pressures. The volumes of liquid and vapor are calculated for the beginning and ending conditions, and the difference between the beginning and ending calculations of the total volume of the vapor and liquid is the volume change in the vessel.

$$\begin{bmatrix}\text{Total volume}\\ \text{at standard}\\ \text{conditions}\end{bmatrix} = \begin{bmatrix}\text{Volume of liquid}\\ \text{at standard}\\ \text{conditions}\end{bmatrix} + \begin{bmatrix}\text{Volume of vapor}\\ \text{above the liquid}\\ \text{in equivalent}\\ \text{liquid units at}\\ \text{standard conditions}\end{bmatrix}$$

$$\begin{bmatrix}\text{Volume of}\\ \text{liquid at}\\ \text{standard}\\ \text{conditions}\end{bmatrix} = \begin{bmatrix}\text{Liquid volume}\\ \text{at tank}\\ \text{conditions}\end{bmatrix} \times \begin{bmatrix}\text{Volume correction}\\ \text{factor for}\\ \text{temperature and}\\ \text{gravity}\end{bmatrix}$$

$$\begin{bmatrix}\text{Volume of vapor}\\ \text{above liquid in}\\ \text{equivalent liquid}\\ \text{units at base}\\ \text{conditions}\end{bmatrix} = \begin{bmatrix}\text{Volume of}\\ \text{vapor above}\\ \text{the liquid}\end{bmatrix} \times \frac{P_o}{P_s} \times \frac{T_s}{T_o} \times \begin{bmatrix}\text{Factor for liquid}\\ \text{volume per vapor}\\ \text{volume}\end{bmatrix}$$

Where:

Total volume = (volume of product in the vessel as a liquid) + (vapor above the liquid converted to its liquid volume equivalent) Volume measured at standard conditions.

Volume of liquid at standard conditions = volume measured at standard temperature and vapor pressure of the liquid at standard temperature.

Volume of liquid at tank conditions = volume of vessel at liquid level determined by tank calibration and gaging device.

Volume of vapor above the liquid = volume of vessel above the liquid level determined by tank calibration and gaging device.

Volume correction factor = factor used to correct the liquid volume to standard temperature. Refer to tables in Chapters 11 and 12.

P_o = observed pressure, in absolute units.

P_s = standard pressure, in absolute units.

T_o = observed temperature, in kelvins (K) or degrees Rankine (°R).

T_s = standard temperature in kelvins (K) or degrees Rankine (°R).

Factor for liquid volume per vapor volume = standard conversion unit for product being measured

14.8.6.8 MIXTURE CALCULATION

When mixtures are measured, the composition of the liquid and vapor will be different for varying conditions of temperature and pressure. The composition of each phase can be determined by sampling and analysis of each. Refer to Chapter 14.4 for the procedure for calculating liquid equivalent of the vapor volume above stored natural gas liquid mixtures.

14.8.7 Mass Measurement in Static Systems

Mass is determined by weighing the container or vessel before and after product has been added to, or removed from, the vessel. The difference in weight provides the basis

for total mass of the product contained in the vessel.

To calculate the volume using mass units:

$$V_b = \frac{\text{Mass}}{\text{Density}}$$

Where:

V_b = volume at standard temperature and vapor pressure of the product at standard temperature.

Mass = difference between before and after mass determination.

Density = density in vacuum of liquid product at standard conditions in same units as mass.

Refer to Chapter 11 to determine relative density at standard conditions.

APPENDIX—INSTALLATION AND OPERATION OF FLOATING PISTON SAMPLERS

The procedures included here are presented to supplement other existing procedures, specifications, and standards in sampling higher than atmospheric vapor pressure products where flashing of lighter components within the container may cause distortion of the sample composition.

All samples should be obtained using some type of probe from the center of the flowing stream. A bypass around a device that causes a differential pressure, such as an orifice plate or small pump, is used to supply fresh product to bypass-type sample injection valves. See Figures A-1 and A-2. Bypass lines must not bypass primary volume measurement devices.

Figure A-3 provides an example of a typical proportional sampler.

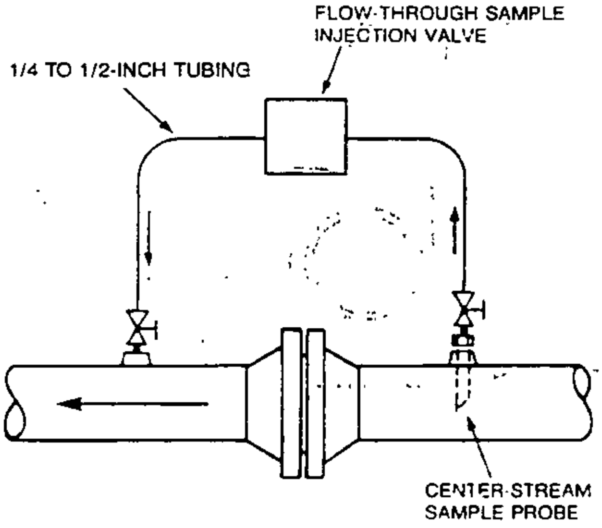

Figure A-1—Typical Sample Probe Installation on an Orifice Flange

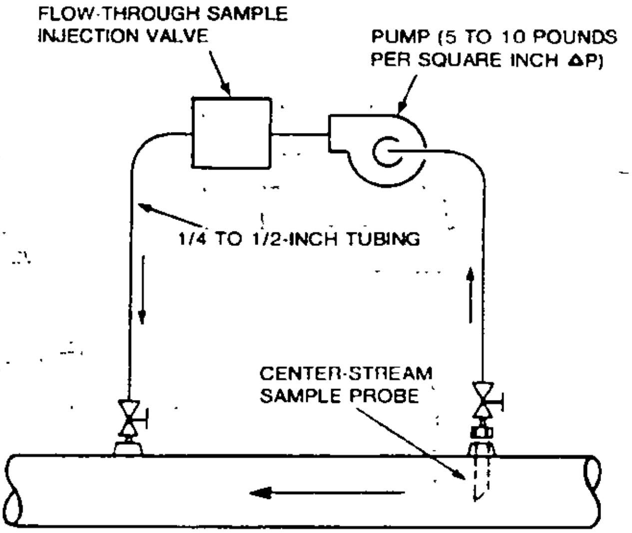

Figure A-2—Typical Sample Probe Installation for a Pump

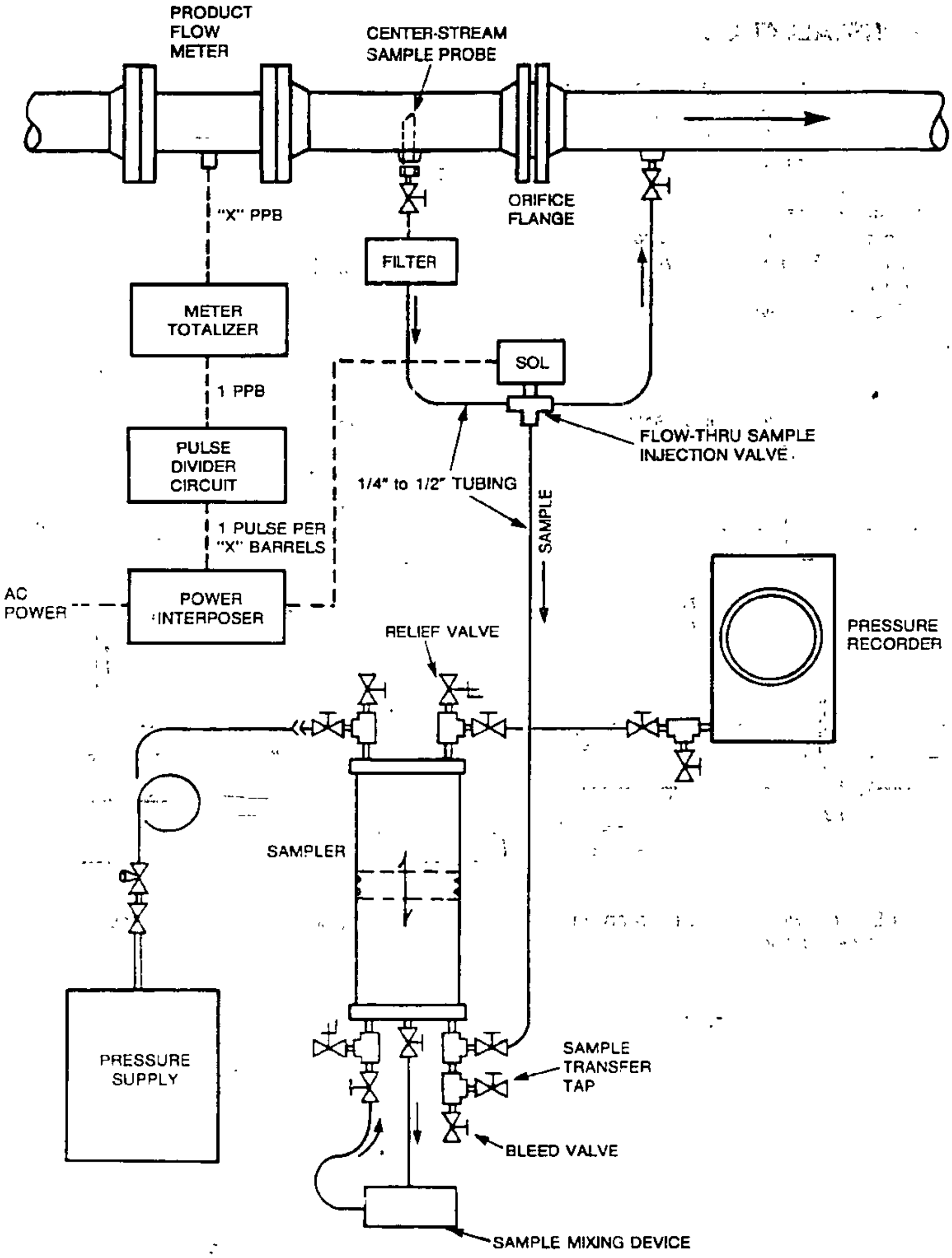

Figure A-3—Typical Proportional Sampler

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- Water 15
- Weight 11

Para los gases reales se han desarrollado muchas ecuaciones de estado, pero en general son complicadas y difíciles de aplicar. La ecuación de estado más simple hace uso del factor de compresibilidad:

$$PV = nZRT$$

Z = factor de compresibilidad

Z(=) adimensional

Esta ecuación se usa para determinar la densidad de los gases en cualquier condición de temperatura y presión. El valor de Z se puede obtener de las gráficas del factor de compresibilidad contra la presión y temperatura reducidas. Una de las ecuaciones más famosas para predecir el comportamiento de los gases reales es la llamada ecuación de Van der Waals:

$$\left(P + \frac{an^2}{V^2}\right)(V - nb) = nRT$$

en donde a y b son constantes para cada gas (apéndice X).

Densidad de una mezcla de gases reales

Para la mezcla de gases reales se puede usar también la gráfica del factor de compresibilidad, si se usan en vez de las presiones y temperaturas críticas las presiones y temperaturas seudocríticas, definidas por:

$$P'c = \Sigma Pci \cdot \bar{y}i$$
$$T'c = \Sigma Tci \cdot \bar{y}i$$

$P'c$ = presión seudocrítica (=) $ML^{-1}\theta^{-2} = FL^{-2}$
Pci = presión crítica del compuesto i (=) $ML^{-1}\theta^{-2} = FL^{-2}$
$T'c$ = temperatura seudocrítica (=) T
Tci = temperatura crítica del componente i (=) T
$\bar{y}$ = fracción mol

de manera que la presión y temperatura seudocrítica son las que se usarán en la gráfica del factor de compresibilidad

$$P'r = \frac{P}{P'c} \qquad T'r = \frac{T}{T'c}$$

(Ver apéndice VIII.)

Problema 1.6

El gas natural saliente de un pozo petrolero está a 100 atm de presión y 80°C y tiene la siguiente composición:

metano	40%	en mol
etano	2%	en mol
nitrógeno	58%	en mol

Calcule el volumen ocupado por 1000 kg de ese gas. ¿Cuál será su densidad absoluta?

3. CÁLCULOS

3.1 Datos de los gases (apéndice VIII)

	PM	*Tc* °C	*Pc* atm	$\bar{y}$
Metano	16	-82.5	45.8	0.4
Etano	30	32.1	48.8	0.02
Nitrógeno	28	-147.1	33.5	0.58

3.2 Condiciones seudocríticas

$PM = 0.4(16) + 0.02(30) + 0.58(28) = 23.24$ g/gmol
$P'c = 0.4(45.8) + 0.02(48.8) + 0.58(33.5) = 38.726$ atm.
$T'c = 0.4(190.5) + 0.02(305.1) + 0.58(125.9) = 155.28\,^{0}K$

3.3 Valor del factor de compresibilidad

$$P'r = \frac{100 \text{ atm}}{38.726 \text{ atm}} = 2.582$$

$$T'r = \frac{80 + 273}{155.28} = 2.27$$

Del diagrama $Z = 0.96$

3.4 Volumen

$$\text{Moles de gas} = \frac{1000 \text{ kg}}{23.24 \text{ kg/kgmol}} = 43.02 \text{ kgmol}$$

$$G = 0.96\,(43.02)\,(0.082)\,(273 + 80) = 11.954 \text{ m}^3$$

3.5 Densidad

$$\rho = \frac{1000 \text{ kg}}{11.954 \text{ m}^3} = 83.65 \text{ kg/m}^3$$

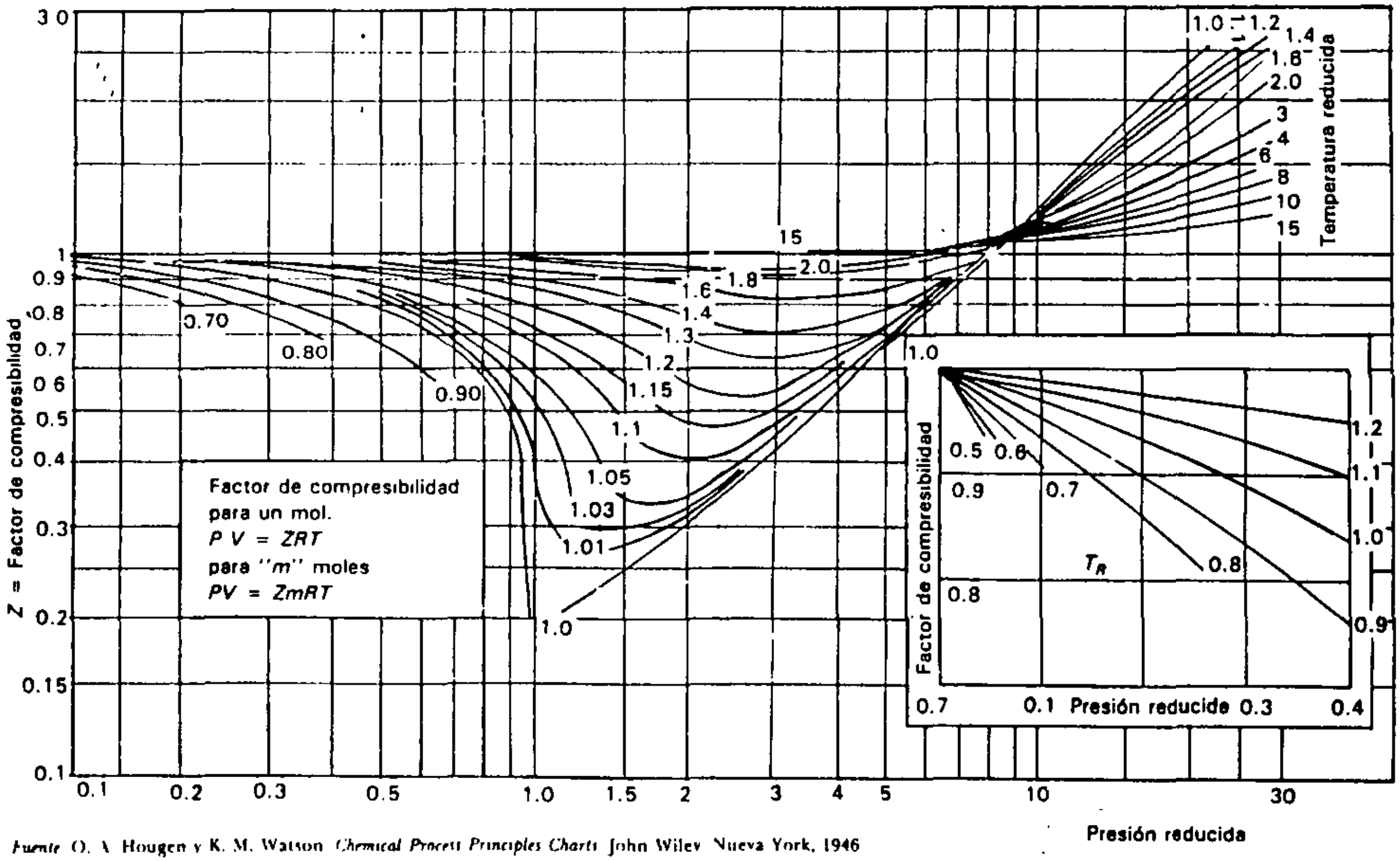
4. RESULTADOS

El volumen es de 11.954 m^3 y la densidad de 83.65 kg/m^3.

Apéndice VIII. Valores críticos.

		Tc °C	*Pc atm*
Ácido acético	$C_2H_4O_2$	321.6	57.2
Ácido bromhídrico	HBr	90	84
Ácido clorhídrico	HCl	51.4	81.6
Ácido sulfhídrico	H_2S	100.4	88.4
Acetona	C_3H_6O	235	47
Acetonitrilo	C_2H_3N	274.7	47.7
Aire	—	—140.7	37.2
Agua	H_2O	374.15	218.4
Alcohol metílico	CH_3OH	240	78.7
Amoniaco	NH_3	132.4	111.5
Benceno	C_6H_6	288.5	47.7
Bromo	Br_2	311	102
n-butano	C_4H_{10}	153	36
i-butano	C_4H_{10}	134	37
Ciclohexano	C_6H_{12}	281	40.4
Cloro	Cl_2	144	76.1
Cloruro de metilo	CH_3Cl	143.1	65.8
Dióxido de carbono	CO_2	31.1	73
Etano	C_2H_6	32.1	48.8
Etileno	C_2H_4	9.7	50.5
Flúor	F	—155	25
Helio	He	—267.9	2.26
Heptano	C_7H_{16}	266.8	26.8
Hexano	C_6H_{14}	234.8	29.5
Hidrógeno	H_2	239.9	12.8
Metano	CH_4	— 82.5	45.8
Monóxido de carbono	CO	—139	35
Nitrógeno	N_2	—174.1	33.5
Mercurio	Hg	1550	200
Octano	C_8H_{18}	296	24.6
Oxígeno	O_2	—118.8	49.7
n-pentano	C_5H_{12}	197.2	33
i-pentano	C_5H_{12}	187.8	32.8
Propano	C_3H_8	96.8	42
Propileno	C_3H_6	92.3	45
Tetracloruro de carbono	CCl_4	283.1	45
Tolueno	$C_6H_5CH_3$	320.6	41.6
Vapor de agua	H_2O	374	217.7

Apéndice IX. Factores de compresibilidad.



Fuente O. A. Hougen y K. M. Watson *Chemical Process Principles Charts* John Wiley Nueva York, 1946

Apéndice VII. Valores de la constante de los gases (*R*).

1.9872 cal/gmol°K

8.3144 joules (abs)/gmol°K

82.057 cm^3 at/mol°K

0.082 lt atm/gmol°K

0.082 m^3 atm/kgmol°K

62.361 lt mmHg/gmol°K

1.314 ft^3 atm/lbmol°R

1.9872 BTU/lbmol°R

0.7302 ft^3 atm/lbmol°R

21.85 ft^3 inHg/lbmol°R

555.0 ft^3 mmHg/lbmol°R

1545.0 ft^3 (lb/ft^2)/lbmol°R

10.73 ft^3 (lb/in^2)/lbmol°R

847.3 m^3 $(\overline{kg}/m^2)$/kg mol°R

Metric Conversion Tables

Multiply	By	To Obtain
LENGTH		
millimeters	0.10	centimeters
millimeters	0.001	meters
millimeters	0.039	inches
millimeters	0.00328	feet
centimeters	10.0	millimeters
centimeters	0.010	meters
centimeters	0.394	inches
centimeters	0.0328	feet
inches	25.40	millimeters
inches	2.54	centimeters
inches	0.0254	meters
inches	0.0833	feet
feet	304.8	millimeters
feet	30.48	centimeters
feet	0.304	meters
feet	12.0	inches
AREA		
sq millimeter	0.010	sq centimeter
sq millimeter	10^{-6}	sq meter
sq millimeter	0.00155	sq inches
sq millimeter	1.076×10^{-5}	sq feet
sq centimeters	100	sq. millimeters
sq centimeters	0.0001	sq meters
sq centimeters	0.155	sq inches
sq centimeters	0.001076	sq feet
sq inches	645.2	sq millimeters
sq inches	6.452	sq centimeters
sq inches	0.000645	sq meters
sq inches	0.00694	sq feet
sq feet	9.29×10^{4}	sq millimeters
sq feet	929	sq centimeters
sq feet	0.0929	sq meters
sq feet	144	sq inches
FLOW RATES		
gallons US/minute GPM	3.785	liters
gallons US/minute	0.133	ft^3/min
gallons US/minute	8.021	ft^3/hr
gallons US/minute	0.227	m^3/hr
gallons US/minute	34.29	Barrels/day, (42 US gals)
cubic feet/minute	7.481	GPM
cubic feet/minute	28.32	liters/minute
cubic feet/minute	60.0	ft^3/hr
cubic feet/minute	1.699	m^3/hr
cubic feet/minute	256.5	Barrels/day
cubic feet/hr	0.1247	GPM
cubic feet/hr	0.472	liters/min
cubic feet/hr	0.01667	ft^3/min
cubic feet/hr	0.0283	m^3/hr
cubic meters/hr	4.403	GPM
cubic meters/hr	16.67	liters/minute
cubic meters/hr	0.5886	ft^3/min
cubic meters/hr	35.31	ft^3/hr
cubic meters/hr	150.9	Barrels/day
VELOCITY		
feet per second	60	ft/min
feet per second	0.3048	meters/second
feet per second	1.097	km/hr
feet per second	0.6818	miles/hr
meters per second	3.280	ft/sec
meters per second	196.9	ft/min
meters per second	3.600	km/hr
meters per second	2.237	miles/hr
VOLUME & CAPACITY		
cubic cm	0.06102	cubic inches
cubic cm	3.531×10^{-6}	cubic feet
cubic cm	10^{-6}	cubic meters
cubic cm	0.001	liters
cubic cm	2.642×10^{-4}	gallons (US)
cubic meters	10^{6}	cubic cm
cubic meters	61,023.0	cubic inches
cubic meters	35.31	cubic feet
cubic meters	1000.0	liters
cubic meters	264.2	gallons
cubic feet	28,320.0	cubic cm
cubic feet	1728.0	cubic inches
cubic feet	0.0283	cubic meters

Multiply	By	To Obtain
VOLUME & CAPACITY		
cubic feet	28.32	liters
cubic feet	7.4805	gallons
liters	1,000.0	cubic cm
liters	61.02	cubic inches
liters	0.03531	cubic feet
liters	0.001	cubic meters
liters	0.264	gallons
gallons	3785.0	cubic cm
gallons	231.0	cubic inches
gallons	0.1337	cubic feet
gallons	3.785×10^{-3}	cubic meters
gallons	3.785	liters
WEIGHT		
pounds	0.0005	short ton
pounds	0.000446	long ton
pounds	0.453	kilogram
pounds	0.000453	metric ton
short ton	2000.0	pounds
short ton	0.8929	long ton
short ton	907.2	kilogram
short ton	0.9072	metric ton
long ton	2240	pounds
long ton	1.120	short ton
long ton	1016	kilogram
long ton	1.016	metric ton
kilogram	2.205	pounds
kilogram	0.0011	short ton
kilogram	0.00098	long ton
kilogram	0.001	metric ton
metric ton	2205	pounds
metric ton	1.102	short ton
metric ton	0.984	long ton
metric ton	1000.0	kilogram
PRESSURE & HEAD		
pounds/sq inch	0.06895	bar
pounds/sq inch	0.06804	atmosphere
pounds/sq inch	0.0703	kg/cm^2
pounds/sq inch	6.895	kPa
pounds/sq inch	2.307	ft of H_2O (4 DEG C)
pounds/sq inch	0.703	m of H_2O (4 DEG C)
pounds/sq inch	5.171	cm of Hg (0 DEG C)
pounds/sq inch	51.71	torr (mm of Hg) (0 DEG C)
pounds/sq inch	2.036	in of Hg (0 DEG C)
atmosphere	14.69	psi
atmosphere	1.013	bar
atmosphere	1.033	Kg/cm^2
atmosphere	101.3	kPa
atmosphere	33.9	ft of H_2O
atmosphere	10.33	m of H_2O
atmosphere	76.00	cm of Hg
atmosphere	760.0	torr (mm of Hg)
atmosphere	29.92	in of Hg
bar	14.50	psi
bar	0.9869	atmosphere
bar	1.020	Kg/cm^2
bar	100.0	kPa
bar	33.45	ft of H_2O
bar	10.20	m of H_2O
bar	75.01	cm of Hg
bar	750.1	torr (mm of Hg)
bar	29.53	in of Hg
kilogram/sq cm	14.22	psi
kilogram/sq cm	0.9807	bar
kilogram/sq cm	0.9678	atmosphere
kilogram/sq cm	98.07	kPa
kilogram/sq cm	32.81	ft of H_2O
kilogram/sq cm	10.00	m of H_2O
kilogram/sq cm	73.56	cm of Hg
kilogram/sq cm	735.6	torr (mm of Hg)
kilogram/sq cm	28.96	in of Hg
kiloPascal	0.145	psi
kiloPascal	0.01	bar
kiloPascal	0.00986	atmosphere
kiloPascal	0.00102	kg/cm^2
kiloPascal	0.334	ft of H_2O
kiloPascal	0.102	m of H_2O
kiloPascal	0.7501	cm of Hg
kiloPascal	7.501	torr (mm of Hg)
kiloPascal	0.295	in of Hg

CAPÍTULO 3

Balance de masa y energía en flujo de fluidos

CAUDAL

Se denomina caudal al volumen del líquido o gas que atraviesa una sección en la unidad de tiempo. En México suele recibir también el nombre de gasto volumétrico.

$$Ca = uA$$

Ca = caudal (=) $L^3\,\theta^{-1}$
u = Velocidad promedio del fluido (=) $L\,\theta^{-1}$
A = Sección transversal de flujo (=) L^2

Gasto másico

Con mucha frecuencia se utiliza el término de gasto o flujo másico o gasto o flujo molar, el cual indica la cantidad de masa o moles que pasan por un punto dado.

$$\dot{M} = u\tilde{A}\rho = Ca.\rho$$

$$\tilde{M} = \frac{M}{PM}$$

M = Gasto másico del fluido (=) $M\,\theta^{-1}$
ρ = Densidad del fluido (=) ML^{-3}
$\tilde{M}$ = Gasto molar del fluido (=) moles θ^{-1}
PM = Peso molecular del fluido

Ecuación de Bernoulli y ecuación de continuidad

En la mecánica de los fluidos se conocen dos expresiones matemáticas fundamentales, a) la ecuación de continuidad, que es una expresión simplificada de la ley de conservación de la materia (ecuación 10) y b) la ecuación de Bernoulli, que es una expresión simplificada de la ecuación de conservación de la energía.

El principio de continuidad establece que el flujo másico es el mismo en todas las secciones transversales de una tubería. Esto es, la cantidad de materia que ingresa a la tubería por un extremo es la misma que sale por la tubería en el extremo de salida. Por supuesto, esa afirmación asume que las paredes de la tubería son suficientemente rígidas, y no existe acumulación de materia en el sistema. Si el fluido es incompresible, entonces el flujo volumétrico también es constante a lo largo del sistema. Este principio es de gran importancia al estudiar el funcionamiento de los medidores de flujo puesto que significa que cuando la sección transversal disminuye, entonces la velocidad del fluido se incrementa y viceversa.

$$\sum \dot{m}_e = \sum \dot{m}_s \tag{10}$$

$$\sum (\rho \bar{v} A)_e = \sum (\rho \bar{v} A)_s \tag{11}$$

La ecuación de Bernoulli expresa, en términos matemáticos, que la energía que posee el fluido permanece constante en cualquier sección tranversal a lo largo una línea de corriente. Esta expresión es sumamente útil porque relaciona los cambios de presión con los cambios de velocidad y de nivel a lo largo de una línea de corriente. Sin embargo, mediante ella se consiguen resultados correctos sólo cuando se aplica a aquellos casos donde las restricciones siguientes se satisfacen razonablemente,

- ✓ Flujo estacionario
- ✓ Flujo incompresible
- ✓ Flujo sin rozamiento
- ✓ Flujo a lo largo de una línea de corriente

$$\frac{P_1}{\rho} + g Z_1 + \frac{\bar{V}_1^2}{2} = \frac{P_2}{\rho} + g Z_2 + \frac{\bar{V}_2^2}{2} \tag{12}$$

$$\frac{P_1}{g\rho} + Z_1 + \frac{\bar{V}_1^2}{2g} = \frac{P_2}{g\rho} + Z_2 + \frac{\bar{V}_2^2}{2g} = \text{Constante de Bernoulli} \tag{13}$$

donde

P: presión del fluido, [Pa]
ρ: densidad del fluido, [kg/m^3]

g: aceleración local de la gravedad, [m/s^2]
$\bar{v}$: velocidad del fluido, [m/s]
z: altura respecto de un nivel de referencia, [m]

en la ecuación 12, cada uno de los términos representa energía por unidad de masa. El término P/ρ representa la energía de presión, el término gZ representa la energía potencial; mientras que el término $\bar{v}^2$ representa la energía cinética.

La ecuación 12 indica que la energía total a lo largo de una línea de corriente es constante. Lo que significa que para sistemas en los cuales la energía potencial es constante, entonces cualquier disminución en la energía de velocidad se verá compensada por un incremento en la energía de presión, y vice versa.

La combinación de la ecuación de continuidad y de Bernoulli son usadas para obtener los modelos matemáticos de funcionamiento de diferentes equipos de medición de flujo de fluidos.

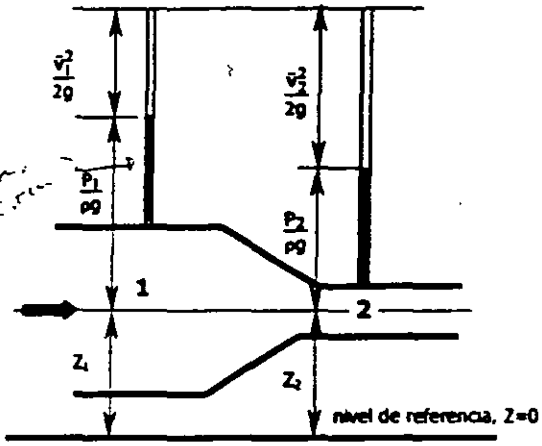


Fig. 9 Formas de energía en un fluido a través de una tubería recta.

Cavitación

De la ecuación de Bernoulli se sabe que al incrementarse la velocidad del fluido, debido a una reducción en la sección transversal, entonces la presión que el fluido ejerce sobre las paredes de la tubería disminuirá.

Si la caída de presión es suficientemente grande entonces se presentará el fenómeno de cavitación. Este evento puede presentarse en dos formas básicas. En agua y en gases licuados, cuando la presión del fluido se aproxima al valor de la presión de vapor correspondiente a la temperatura actual, entonces se inicia la formación de pequeñas burbujas o bolsas de vapor. Dichas burbujas se colapsarán en cuanto se aproximen a una región de mayor presión. El colapso de las burbujas es conocido como implosión, y los efectos de este fenómeno son muy dañinos para cualquier componente hidráulico. En la Fig. 10 se ilustran los daños por cavitación en un material de acero inoxidable con dureza de 50 HRc.