BSR/ASHRAE Standard 41.10-2020R

Public Review Draft

Standard Methods for Refrigerant Volumetric or Mass Flow Measurement Using Flowmeters

First Public Review (September 2023)
(Complete Draft for Full Review)

This draft has been recommended for public review by the responsible project committee. To submit a comment on this proposed standard, go to the ASHRAE website at www.ashrae.org/standards-research--technology/public-review-drafts and access the online comment database. The draft is subject to modification until it is approved for publication by the Board of Directors and ANSI. Until this time, the current edition of the standard (as modified by any published addenda on the ASHRAE website) remains in effect. The current edition of any standard may be purchased from the ASHRAE Online Store at www.ashrae.org/bookstore or by calling 404-636-8400 or 1-800-727-4723 (for orders in the U.S. or Canada).

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(This foreword is not part of this standard. It is merely informative and does not contain requirements necessary for conformance to the standard. It has not been processed according to the ANSI requirements for a standard and may contain material that has not been subject to public review or a consensus process. Unresolved objectors on informative material are not offered the right to appeal at ASHRAE or ANSI.)

FOREWORD

Compared to the 2020 version, this version includes (a) supercritical phase refrigerant flow measurements in addition to gaseous phase and liquid phase refrigerant flow measurements, (b) volumetric refrigerant flow measurements in addition to refrigerant mass flow measurements, (c) updated methods for determining when steady-state operation has been achieved for data recording, (d) changes to make it easier for higher-tier standards to adopt this standard by reference, and (e) a new uncertainty example prepared in accordance with the latest uncertainty methods. This revision of Standard 41.10-2020 meets ASHRAE's mandatory language requirements.

Selecting an appropriate refrigerant flowmeter can be a daunting task given the wide variety of operating principles, measurement precision, and costs. Once a flowmeter has been selected, the user may need to consult with the source of the meter regarding installation specifics, operating range limits, calibration limits, and other similar performance specifics in order to obtain the expected measurement accuracy.

1. PURPOSE

This standard prescribes methods for refrigerant volumetric or mass flow rate measurement using flowmeters in laboratory and field applications. Each refrigerant mass flow rate is determined by subtracting the measured lubricant mass flow rate from the measured refrigerant/lubricant mixture mass flow rate.

2. SCOPE:

2.1 This standard applies to the following:

a. refrigerant volumetric or mass flow rate measurements using flowmeters in laboratory and field applications.
b. systems where the refrigerants are mixed with lubricant.
c. systems where the entire flow stream of the refrigerant in the refrigerant/lubricant mixture both enters and exits the flowmeter in a gaseous phase, in a liquid phase, or in a supercritical phase during data recording.

2.2 This standard does not apply to:

a. flow rate measurement of gaseous refrigerant not mixed with lubricant within the scope of ANSI/ASHRAE Standard 41.7.
b. flow rate measurement of liquid refrigerant not mixed with lubricant within the scope of ANSI/ASHRAE Standard 41.8.

3. DEFINITIONS

The following definitions apply to the terms used in this standard.

***accuracy*:** the degree of conformity of an indicated value to the corresponding true value.

error: the difference between the observed value of the measurand and its corresponding true value.
flowmeter: a device employing a detecting element that determines the flow rate of a refrigerant in the gaseous phase, liquid phase, or supercritical phase within a closed conduit by measuring the corresponding response of the detecting element.

lubricant circulation rate: the ratio of the mass of lubricant circulating through a refrigerant system to the total mass of refrigerant/lubricant mixture flowing through the system at a specified set of operating conditions.

measurement system: the instruments, signal conditioning systems if any, and data acquisition system if any.

operating tolerance limit: the upper or lower value of an operating tolerance that is associated with a test point or a targeted set point.

post-test uncertainty: an analysis to establish the uncertainty of a test result after conducting the test.

pretest uncertainty: an analysis to establish the expected uncertainty interval for a test result before conducting the test.

random error: the portion of the total error that varies randomly in repeated measurements of the true value throughout a test process.

refrigerant mass flow rate*:* the refrigerant plus lubricant mass flow rate minus the lubricant mass flow rate.

steady-state criteria: the criteria that establish negligible change of refrigerant/lubricant mixture volumetric or mass flow rate with time.

subcooling: the difference between the liquid temperature and the bubble-point temperature at a defined pressure for a refrigerant that operates at a subcritical pressure of the refrigerant.

superheat: the difference between the suction temperature and the dew-point temperature at a defined pressure for a refrigerant that operates at a subcritical pressure of the refrigerant.

systematic error: the portion of the total error that remains constant in repeated measurements of the true value throughout a test process.

targeted set points: a specific set of test conditions where the required refrigerant mass flow rates are unknown and has an associated operating tolerance.

test points: a specific set of test operating conditions for recording data where the measured required refrigerant mass flow rate is unknown and has an associated operating tolerance.

true value: the unknown, error-free value of a test result.

uncertainty: the limits of error within which the true value lies.

unit under test (UUT): equipment that is the subject of refrigerant volumetric or mass flow rate measurements.

4. CLASSIFICATIONS

4.1 Operating Phase During Data Recording

4.1.1 Gaseous Phase Flowmeters. In gaseous phase flowmeters, the refrigerant in the refrigerant/lubricant flow stream both enters and exits the flowmeter with the refrigerant in gaseous phase during data recording.

4.1.2 Liquid Phase Flowmeters. In liquid phase flowmeters, the refrigerant in the refrigerant/lubricant flow stream both enters and exits the flowmeter with the refrigerant in liquid phase during data recording.

4.1.3 Supercritical Phase Flowmeters. In supercritical phase flowmeters, the refrigerant in the refrigerant/lubricant flow stream both enters and exits the flowmeter with the refrigerant in supercritical phase during data recording.

4.2 Refrigerant Flow Measurement Conditions. Refrigerant flow measurement applications that are within the scope of this standard shall be classified as one of the following types:

4.2.1 Laboratory Conditions. Refrigerant volumetric or mass flow measurements under laboratory conditions are engineering development tests or tests to demonstrate product performance.

(***Informative Note:*** Laboratory refrigerant volumetric or mass flow measurements tend to use more accurate instruments than field measurements, and the installation of those instruments normally meet the instrument manufacturer's installation requirements.)

4.2.2 Field Conditions. Refrigerant volumetric or mass flow measurements under field conditions are tests to demonstrate installed system refrigerant volumetric or mass flow rates.

(Informative Note: Field refrigerant flow measurements tend to use less accurate instruments than laboratory measurements, and the installation of those instruments often do not meet the instrument manufacturer's installation requirements.)

4.3 Flowmeter Categories

4.3.1 Mass Flowmeters. Refrigerant flow meters in this category perform direct measurement of refrigerant mass flow rates.

4.3.2 Volumetric Flowmeters. Refrigerant flowmeters in this category perform direct measurement of volumetric flow rates. Where refrigerant mass flow rates are required, each volumetric refrigerant flow measurement shall be multiplied by the refrigerant density at the flow measurement location to obtain the corresponding refrigerant mass flow rate measurement.

4.4 Refrigerant Volumetric and Mass Flow Rate Measurement Methods. Refrigerant volumetric or mass flow measurement methods that are within the scope of this standard include the refrigerant volumetric or mass flow rate methods that are listed in Table 4-1. Each of these refrigerant volumetric or mass flow rate measurement methods is described in Section 7.

(***Informative Note:*** The presence of lubricant circulation in gaseous refrigerant flow streams may lead to flow measurement errors and flow instability. The flowmeter manufacturer or computational fluid dynamics analysis may be able to provide information regarding the magnitude of these errors.)

Table 4-1 Refrigerant Volumetric or Mass Flow Rate Measurement Methods

Refrigerant Flow Measurement Method	**Applies to Refrigerant Gas Phase Flow Measurement**	**Applies to Refrigerant Liquid Phase Flow Measurement**	**Applies to Refrigerant Supercritical Phase Flow Measurement**	**Section Number**
Coriolis Flowmeters	Yes	Yes	Yes	7.1
Thermal Flowmeters	Yes	Yes	Yes	7.2
Volume-Displacement Flowmeters	Yes	Yes	Yes	7.3
Orifice Meters, Flow Nozzles, and Venturi Flowmeters	Yes	Yes	Yes	7.4
Turbine Flowmeters	Yes	Yes	Yes	7.5
Variable-Area Flowmeters	Yes	Yes	Yes	7.6
Ultrasonic Flowmeters	Yes	Yes	Yes	7.7
Vortex-Shedding Flowmeters	Yes	Yes	Yes	7.8
Drag-Force Flowmeters	No	Yes	Yes	7.9
Magnetic Flowmeters	No	Yes	Yes	7.10
Positive-Displacement Flowmeters	No	Yes	Yes	7.11

(***Informative Note:*** The presence of lubricant circulation in gaseous phase refrigerant flow streams may lead to flow measurement errors and flow instability. The flowmeter manufacturer or computational fluid dynamics analysis may be able to provide information regarding the magnitude of these errors or instabilities.)

5. REQUIREMENTS

5.1 Test Plan. The test plan shall be one of the following documents:

a. A document provided by the person or the organization that authorized the tests and calculations to be performed.
b. A method of test standard.
c. A rating standard.
d. A regulation or code.
e. Any combination of a. through d.

The test plan shall specify:

a. The maximum allowable value for either the accuracy or the measurement uncertainty of the refrigerant flow measurement system.
b. The values to be determined and recorded are any items or combinations of items selected from this list: refrigerant volumetric flow measurement, refrigerant volumetric flow measurement pretest uncertainty, refrigerant volumetric flow measurement post-test uncertainty, refrigerant mass flow measurement, refrigerant mass flow measurement pretest uncertainty, refrigerant mass flow measurement post-test uncertainty, and the lubricant circulation rate.
c. Any combination of test points and targeted set points to be performed together with the

corresponding operating tolerances.

5.2 Values to be Determined and Reported

The test values to be determined and reported shall be as shown in Table 5-1 if required by the test plan in Section 5.1. Use the units of measure that are shown in Table 5-1 unless otherwise specified in the test plan.

Table 5-1 Measurement Values and Units of Measure

Quantity	**SI**	**I-P**
Refrigerant volumetric flow rate	cubic meter per second (m^3/s)	cubic foot per second (ft^3/s)
Refrigerant volumetric flow rate pretest uncertainty		
Refrigerant volumetric flow rate post-test uncertainty		
Refrigerant mass flow rate	kilogram per second (kg/s)	pound (avoirdupois) per hour (lb_m/h)
Refrigerant mass flow rate pretest uncertainty		
Refrigerant mass flow rate post-test uncertainty		

5.3 Test Requirements

5.3.1 Refrigerant Mass Flow Rate Determination. Each refrigerant volumetric or mass flow rate is obtained by subtracting the lubricant volumetric or mass flow rate from the refrigerant/lubricant mixture volumetric or mass flow rate.

5.3.2 Accuracy or Measurement Uncertainty. A selected refrigerant volumetric or mass flowmeter shall meet or exceed the required refrigerant volumetric or mass flow measurement system accuracy or measurement uncertainty specified in the test plan in Section 5.1 over the full range of operating conditions.

5.3.3 Pretest Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the expected uncertainty for each refrigerant volumetric or mass flow test point prior to the conduct of that test in accordance with the pretest uncertainty analysis procedures in ANSI/ASME PTC 19.1[1].

5.3.4 Post-test Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the expected refrigerant volumetric or mass flow measurement uncertainty for each refrigerant mass flow test point in accordance with the post-test uncertainty analysis procedures in ANSI/ASME PTC 19.1[1]. Alternatively, if specified in the test plan, the worst-case uncertainty for all test points shall be estimated and reported for each test point.

5.3.5 Lubricant Circulation Rate. The lubricant circulation rate through the flowmeter (a) shall not be greater than 2% for a liquid phase or supercritical phase refrigerant flowmeter, and (b) shall not be greater than 1% for a gaseous phase refrigerant flowmeter unless otherwise specified in the test plan in Section 5.1.

5.3.5.1 Lubricant circulation rate measurements are not required if the UUT is equipped with a lubricant separator that limits the lubricant circulation rate through the refrigerant flowmeter to not more than 2% for a liquid phase or supercritical phase refrigerant flowmeter, or not more than 1% for a gaseous phase refrigerant flowmeter.

5.3.5.2 The lubricant circulation rate shall be measured and recorded at each test point in accordance with Section 8 for UUTs that do not include a lubricant separator that limits the lubricant circulation rate through the refrigerant flowmeter to not greater than 2% for a liquid phase or supercritical phase refrigerant flowmeter, or not more than 1% for a gaseous phase refrigerant flowmeter unless otherwise specified in the test plan in Section 5.1.

5.3.5.2.1 Incorporate an auxiliary lubricant separator ahead of the refrigerant flowmeter if the lubricant circulation rate is greater than 2% for a liquid phase or supercritical phase refrigerant flowmeter, or greater than 1% for a gaseous phase refrigerant flowmeter.

5.3.5.2.2 All lubricant removed from the refrigerant/lubricant mixture by an auxiliary lubricant separator shall be returned to the refrigerant downstream of the flowmeter.

5.3.6 Lubricant Sampling Port. A lubricant sampling port in accordance with ANSI/ASHRAE 41.4[2] shall be provided for extracting samples of liquid refrigerant and circulating lubricant for use in determining lubricant circulation rates if required by Section 5.3.5.2

5.3.7 Single-Phase Flow

5.3.7.1 Gaseous Phase Flowmeters. Gaseous phase refrigerant volumetric and mass flowmeters are restricted to applications where the refrigerant in the refrigerant/lubricant mixture flow stream both enters and exits the flowmeter in gaseous phase during data recording. The refrigerant superheat at the volumetric or mass flowmeter inlet shall be not less than 2ºC (3.6ºF). Trace amounts of liquid shall be less than 1% by mass unless otherwise specified by the flowmeter manufacturer or by the test plan in Section 5.1.

5.3.7.2 Liquid Phase Flowmeters. Liquid phase refrigerant volumetric and mass flowmeters are restricted to applications where the refrigerant in the refrigerant/lubricant mixture flow stream both enters and exits the flowmeter in liquid phase during data recording. The subcooling at the flowmeter inlet shall be not less than 2ºC (3.6ºF).

5.3.7.3 Supercritical Phase Flowmeters. Supercritical refrigerant volumetric and mass flowmeters are restricted to applications where the refrigerant in the refrigerant/lubricant mixture flow stream both enters and exits the flowmeter in supercritical phase during data recording.

5.3.8 Steady-State Test Criteria for Refrigerant Volumetric and Mass Flow Rate Measurements. Refrigerant volumetric and mass flow rate test data shall be recorded at steady-state conditions if specified in the test plan in Section 5.1.

5.3.8.1 Steady-State Test Criteria for Refrigerant Volumetric Flow Rate Measurements for Compressors that do not Incorporate Pulse-Width Modulation

5.3.8.1.1 Steady-State Test Criteria for Refrigerant Volumetric Flow Rate Measurements Under Laboratory Test Conditions. If the test plan in Section 5.1 requires refrigerant volumetric flow rate test data points to be recorded at steady-state test conditions under laboratory test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, then determine that steady-state test conditions have been achieved using one of the following methods:

a. Apply the steady-state criteria in Section 5.3.8.1.3 if the test plan provides test point operating conditions for refrigerant volumetric flow rate measurement.

b. Apply the steady-state criteria in Section 5.3.8.1.4 if the test plan provides set point operating conditions for refrigerant volumetric flow rate measurement.

5.3.8.1.2 Steady-State Test Criteria for Refrigerant Volumetric Flow Rate Measurements Under Field Test Conditions. If the test plan in Section 5.1 requires refrigerant volumetric flow rate test data points to be recorded at steady-state test conditions under field test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, the methods in Section 5.3.8.1.1 are optional.

(Informative Note: The steady-state methods in Section 5.3.8.1.1 are likely to be impractical under field test conditions. Section 5.3.10 provides instructions for making measurements that are not at steady state conditions.)

5.3.8.1.3 Steady-State Refrigerant Volumetric Flow Rate Criteria for Test Points

Starting with the time set to zero, sample not less than 30 refrigerant volumetric flow rate measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-1 states the relationship of the test duration to the number of refrigerant volumetric flow rate samples and the equal time intervals.

$$\Delta t = (N-1)\delta t \tag{5-1}$$

(Informative Note: Circumstances for measurement vary, so the user should select a duration of test and the equal time intervals based upon the longest period of the observed refrigerant volumetric flow rate fluctuations during operation near the steady-state conditions.)

Record each sampled refrigerant volumetric flow rate measurement Q_i and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the refrigerant volumetric flow rate data trend line using Equation 5-2.

$$b = \left\{ \frac{\left[N\left(\sum_{i=1}^{N} t_i Q_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} Q_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} {t_i}^2\right) - \left(\sum_{i=1}^{N} t_i\right)^2\right]} \right\} \tag{5-2}$$

(Informative Note: It should be noted that the units for the slope in Equation 5-2 are refrigerant volumetric flow rate, $\mathrm{m^3/s}$ ($\mathrm{ft^3/s}$), divided by the units that the user has selected for time.)

The mean of the sampled refrigerant volumetric flow rate $\bar{Q}$ is defined by Equation 5-3.

$$\bar{Q} = \frac{1}{N}\left[\sum_{i=1}^{N}(Q_i)\right], \mathrm{m^3/s\ (ft^3/s)} \tag{5-3}$$

The difference between the maximum and minimum sampled values shall be less than or equal to the specified operating tolerance limit as defined in Equation 5-4 where Q_L is the operating tolerance limit.

$$Q_{max} - Q_{imin} \le \mathrm{Q}_L \ \ \mathrm{m^3/s\ (ft^3/s)} \tag{5-4}$$

The restriction on the slope of the trend line b is defined in Equation 5-5 where Δt is the sample time interval.

$$|b \times \Delta t| \le 0.5 \times \ \mathrm{Q}_L \ \ \mathrm{m^3/s\ (ft^3/s)} \tag{5-5}$$

$\bar{Q}$, as determined by Equation 5-3, represents the steady-state mean refrigerant volumetric flow rate where Equations 5-4 and 5-5 are both satisfied.

(***Informative Note:*** For further reading about this method of determining steady-state conditions, refer to Informative Appendix A, References A1 and A2.)

5.3.8.1.4 Steady-State Refrigerant Volumetric Flow Rate Criteria for Targeted Set Points
Starting with the time set to zero, sample not less than 30 refrigerant volumetric flow rate measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-6 states the relationship of the test duration to the number of samples and the equal time intervals.

$$\Delta t = (N - 1)\delta t \tag{5-6}$$

(Informative Note: Circumstances for measurement vary, so the user should select a duration of test and the equal time intervals based upon the longest period of the observed refrigerant volumetric flow rate fluctuations during operation near the steady-state conditions.)

Record each sampled refrigerant volumetric flow rate measurement Q_i and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the refrigerant volumetric flow rate data trend line using Equation 5-7

$$b = \left\{ \frac{\left[N\left(\sum_{i=1}^{N} t_i Q_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} Q_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} t_i^{2}\right) - \left(\sum_{i=1}^{N} t_i\right)^{2}\right]} \right\} \tag{5-7}$$

(***Informative Note:*** It should be noted that the units for the slope in Equation 5-7 are refrigerant volumetric flow rate, m^3/s (ft^3/s), divided by the units that the user has selected for time.)

The mean of the sampled refrigerant volumetric flow rate $\bar{Q}$ is defined by Equation 5-8.

$$\bar{Q} = \frac{1}{N}\left[\sum_{i=1}^{N}(Q_i)\right] \ \text{m}^3/\text{s (ft}^3/\text{s)} \tag{5-8}$$

The difference between the maximum and minimum sampled values shall be less than or equal to the specified operating tolerance limit as defined in Equation 5-9 where Q_L is the operating tolerance limit.

$$Q_{max} - Q_{min} \le \mathrm{Q}_L \ \text{m}^3/\text{s (ft}^3/\text{s)} \tag{5-9}$$

The restriction on the slope of the trend line *b* is defined in Equation 5-10 where Δt is the sample time interval.

$$|b \times \Delta t| \le 0.5 \times Q_L \ \text{m}^3/\text{s (ft}^3/\text{s)} \tag{5-10}$$

The difference between the test condition and mean of the sampled values shall be less than or equal to half of the specified operating tolerance limit as defined in Equation 5-11 where Q_{SP} is the set point volumetric flow rate and Q_L is the operating tolerance limit.

$$|Q_{SP} - \bar{Q}| \le 0.5 \times \mathrm{Q}_L \ \text{m}^3/\text{s (ft}^3/\text{s)} \tag{5-11}$$

$\bar{Q}$, as determined by Equation 5-8, represents the steady-state mean refrigerant volumetric flow rate where

Equations 5-9, 5-10, and Equation 5-11 are all satisfied.

(***Informative Note:*** For further reading about this method of determining steady-state conditions, refer to Informative Appendix A, References A1 and A2.)

5.3.8.2 Steady-State Test Criteria for Refrigerant Mass Flow Rate Measurements for Compressors that do not Incorporate Pulse-Width Modulation

5.3.8.2.1 Steady-State Test Criteria for Refrigerant Mass Flow Rate Measurements Under Laboratory Test Conditions. If the test plan in Section 5.1 requires refrigerant mass flow rate test data points to be recorded at steady-state test conditions under laboratory test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, then determine that steady-state test conditions have been achieved using one of the following methods:

a. Apply the steady-state criteria in Section 5.3.8.2.3 if the test plan provides test point operating conditions for refrigerant mass flow rate measurement.
b. Apply the steady-state criteria in Section 5.3.8.2.4 if the test plan provides targeted set point operating conditions for refrigerant mass flow rate measurement.

5.3.8.2.2 Steady-State Test Criteria for Refrigerant Mass Flow Rate Measurements Under Field Test Conditions. If the test plan in Section 5.1 requires refrigerant mass flow rate test data points to be recorded at steady-state test conditions under field test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, the methods in Section 5.3.8.2.1 are optional.

(Informative Note: The steady-state methods in Section 5.3.8.2.1 are likely to be impractical under field test conditions. Section 5.3.10 provides instructions for making measurements that are not at steady state conditions.)

5.3.8.2.3 Steady-State Refrigerant Mass Flow Rate Criteria for Test Points
Starting with the time set to zero, sample not less than 30 refrigerant mass flow rate measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-12 states the relationship of the test duration to the number of samples and the equal time intervals.

$$\Delta t = (N - 1)\delta t \tag{5-12}$$

(Informative Note: Circumstances for measurement vary, so the user should select a duration of test and the equal time intervals based upon the longest period of the observed refrigerant mass flow rate fluctuations during operation near the steady-state conditions.)

Record each sampled refrigerant mass flow rate measurement, $\dot{m}_i$, and the corresponding time, t_i. Apply the least squares line method to determine the slope *b* of the refrigerant mass flow rate data trend line using Equation 5-13.

$$b = \left\{ \frac{\left[N\left(\sum_{i=1}^{N} t_i \dot{m}_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} \dot{m}_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} t_i^2\right) - \left(\sum_{i=1}^{N} t_i\right)^2\right]} \right\} \tag{5-13}$$

(***Informative Note:*** It should be noted that the units for the slope in Equation 5-13 are refrigerant mass flow rate, kg/s (lb_m/h), divided by the units that the user has selected for time.)

The mean of the sampled refrigerant mass flow rates $\bar{\dot{m}}$ is defined by Equation 5-14

$$\bar{\dot{m}} = \frac{1}{N}\left[\sum_{i=1}^{N}(\dot{m}_i)\right] \quad \text{kg/s (lb}_\text{m}\text{/h)} \qquad (5\text{-}14)$$

The difference between the maximum and minimum sampled values must be less than or equal to the specified test operating tolerance as defined in Equation 5-15 where $\dot{m}_L$ is the operating tolerance limit.

$$\dot{m}_{max} - \dot{m}_{imin} \leq \dot{m}_L \quad \text{kg/s (lb}_\text{m}\text{/h)} \qquad (5\text{-}15)$$

The restriction on the slope of the trend line b is defined in Equation 5-16 where Δt is the sample time interval.

$$|b \times \Delta t| \leq 0.5\ \times\ \dot{m}_L \quad \text{kg/s (lb}_\text{m}\text{/h)} \qquad (5\text{-}16)$$

$\bar{\dot{m}}$, as determined by Equation 5-14, represents the steady-state mean refrigerant mass flow rate where Equations 5-15 and 5-16 are both satisfied.

(***Informative Note:*** For further reading about this method of determining steady-state conditions, refer to Informative Appendix A, References A1 and A2.)

5.3.8.2.4 Steady-State Refrigerant Mass Flow Rate Criteria for Targeted Set Points
Starting with the time set to zero, sample not less than 30 refrigerant mass flow rate measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-17 states the relationship of the test duration to the number of refrigerant mass flow rate samples and the equal time intervals.

$$\Delta t = (N - 1)\delta t \qquad (5\text{-}17)$$

> ***(Informative Note:*** Circumstances for measurement vary, so the user should select a duration of test and the equal time intervals based upon the longest period of the observed refrigerant mass flow rate fluctuations during operation near the steady-state conditions.)

Record each sampled refrigerant mass flow rate measurement $\dot{m}_i$ and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the refrigerant mass flow rate data trend line using Equation 5-18.

$$b = \left\{\frac{\left[N\left(\sum_{i=1}^{N} t_i\dot{m}_i\right)-\left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N}\dot{m}_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} {t_i}^2\right)-\left(\sum_{i=1}^{N} t_i\right)^2\right]}\right\} \qquad (5\text{-}18)$$

> ***(Informative Note:*** It should be noted that the units for the slope in Equation 5-16 are refrigerant mass flow rate, kg/s (lb$_\text{m}$/h), divided by the units that the user has selected for time.)

The mean of the sampled refrigerant mass flow rates $\bar{\dot{m}}$ is defined by Equation 5-19.

$$\bar{\dot{m}} = \frac{1}{N}\left[\sum_{i=1}^{N}(\dot{m}_i)\right] \quad \text{kg/s (lb}_\text{m}\text{/h)} \qquad (5\text{-}19)$$

The difference between the maximum and minimum sampled values must be less than or equal to the specified test operating tolerance as defined in Equation 5-20 where $\dot{m}_L$ is the operating tolerance limit.

$$\dot{m}_{max} - \dot{m}_{min} \le \dot{m}_L \text{ kg/s (lb}_\text{m}\text{/h)} \tag{5-20}$$

The restriction on the slope of the trend line b is defined in Equation 5-21 where Δt is the sample time interval.

$$|b \times \Delta t| \le 0.5 \times \dot{m}_L \text{ kg/s (lb}_\text{m}\text{/h)} \tag{5-21}$$

The difference between the test condition and mean of the sampled values shall be less than or equal to half of the specified operating tolerance limit as defined in Equation 5-22 where $\dot{m}_{SP}$ is the set point mass flow rate and $\dot{m}_L$ is the operating tolerance limit.

$$|\dot{m}_{SP} - \bar{\dot{m}}| \le 0.5 \times \dot{m}_L \text{ kg/s (lb}_\text{m}\text{/h)} \tag{5-22}$$

$\bar{\dot{m}}$, as determined by Equation 5-19, represents the steady-state mean refrigerant mass flow rate where Equations 5-20, 5-21, and 5-22 are all satisfied.

(***Informative Note:*** For further reading about this method of determining steady-state conditions, refer to Informative Appendix A, References A1 and A2.)

5.3.9 Steady-State Criteria for Refrigerant Mass Flow Rate Measurements for Compressors that Incorporate Pulse-Width Modulation. Compressors that operate using pulse-width modulation vary the refrigerant flow rate by alternatively switching the refrigerant flow on-and-off for variable time intervals at a specific frequency. To illustrate the principles, Figure 5-1 shows the theoretical cycle, modeled as a square-wave, for the refrigerant flow in a pulse-width modulated compressor that is switched on to deliver 50% load.

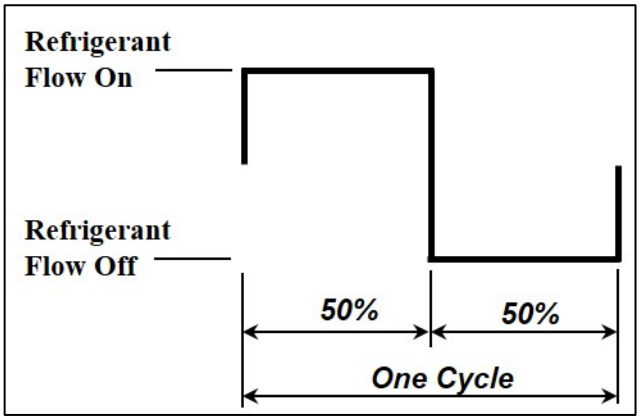


FIGURE 5-1 Theoretical cycle of refrigerant flow rate for a pulse-width modulated compressor that delivers 50% load

The off-and-on changes in the refrigerant flow illustrated in Figure 5-1 cause comparable changes in (a) suction and discharge temperatures, (b) suction and discharge pressures, and (c) compressor power input if measurement of the compressor power input is required by the test plan in Section 5.1. Each data sample shall consist of the following recorded measurements:

1. Refrigerant mass flow rate, kg/s (lb$_\text{m}$/h)
2. Compressor suction temperature, ºC (ºF)
3. Compressor discharge temperature, ºC (ºF)

4. Compressor suction pressure, kPa (psia)
5. Compressor discharge pressure, kPa (psia)
6. Compressor power input, W (W), if required by the test plan in Section 5.1.

The time interval for recording test samples shall be determined from Equation 5-23 if the load is less than 50%, or from Equation 5-24 if the load is 50% or greater.

$$t_{ts} = \frac{t_{on}}{n} \tag{5-23}$$

$$t_{ts} = \frac{t_{off}}{n} \tag{5-24}$$

where

t_{ts} = time interval between sequential test samples
t_{on} = time interval in each cycle that the refrigerant flow is on
t_{off} = time interval in each cycle that the refrigerant flow is off
n = an integer not less than 5

Each data set is comprised of not less than 30 consecutive cycles of test samples. Not less than 3 sequential data sets shall be recorded for each test data point.

Steady-state operation for a pulse-width modulated compressor shall be established where both of the following requirements have been achieved unless otherwise stated in the test plan in Section 5.1:

a. The recording time interval for each data set shall be within ±5% of the average recording time interval for the combined data sets.
b. The refrigerant mass flow rate recorded for each data set shall be within ±2% of the average refrigerant mass flow rate for the combined data sets.

5.3.10 Unsteady Refrigerant Volumetric or Mass Flow Rate Measurements. If required by the test plan in Section 5.1, refrigerant mass flow rate test data shall be recorded:

a. at operating conditions that are not steady state,
b. at the time intervals specified in the test plan,
c. within the test condition limits specified in the test plan,
d. using instrument response times specified in the test plan.

5.3.11 Refrigerant Properties. Refrigerant properties shall be obtained from *NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP)*[3] or from the refrigerant supplier if a constituent of the refrigerant being tested is not included in REFPROP.

(***Informative Note:*** The composition of refrigerant blends may change between the flowmeter entrance and exit.)

5.3.12 Leak Testing. The refrigerant system shall be leak tested. Use a vacuum pump to evacuate the refrigerant system to a pressure less than 26.7 Pa (200 microns). After achieving this vacuum, close valves to isolate the refrigerant system from the vacuum pump for not less than 15 minutes. During that time, the pressure shall not be greater than 28.7 Pa (215 microns) unless otherwise specified in the test plan.

5.3.13 Refrigerant and Lubricant Charging. If the refrigerant system is not pre-charged with lubricant, install the lubricant charge as prescribed by the UUT manufacturer, and then evacuate the system to less than 26.7 Pa (200 microns) unless otherwise specified in the test plan. Then charge the system with the specified refrigerant type and the quantity of refrigerant required for flowmeter testing.

5.3.14 Gaseous Phase Flowmeter Installation. A selected gaseous phase flow measurement plane shall exceed 7.5 inside pipe diameters downstream of an obstruction or any change in the gaseous phase flow direction and shall exceed 3 inside pipe diameters upstream of an obstruction or change in the gaseous phase flow direction unless otherwise specified by the gaseous phase flowmeter instrument manufacturer or the source of the flowmeter.

5.3.15 Liquid Phase Flowmeter Installation. A selected liquid phase flow measurement plane shall exceed 10 inside pipe diameters downstream of an obstruction or any change in the liquid phase flow direction and shall exceed 5 inside pipe diameters upstream of an obstruction or change in the liquid phase flow direction unless otherwise specified by the liquid phase flowmeter instrument manufacturer or the source of the flowmeter.

5.3.16 Supercritical Phase Flowmeter Installation. A selected supercritical phase flow measurement plane shall exceed 10 inside pipe diameters downstream of an obstruction or any change in the supercritical phase flow direction and shall exceed 5 inside pipe diameters upstream of an obstruction or change in the supercritical phase flow direction unless otherwise specified by the supercritical phase flowmeter instrument manufacturer or the source of the flowmeter.

5.3.17 Operating Limits. Operating conditions during refrigerant/lubricant volumetric or mass flow rate data measurements shall not exceed limits for pressure, pressure differential, temperature, fluid velocity, or pressure pulsation specified by the flowmeter manufacturer to achieve the measurement accuracy or measurement uncertainty required by the test plan in Section 5.1.

5.3.18 Input Power. If required by the test plan in Section 5.1, input power shall be measured in accordance with ANSI/ASHRAE 41.11.[4]

6. INSTRUMENTS

6.1. Instrumentation Requirements for All Measurements

6.1.1 Instruments and data acquisition systems shall be selected to meet the measurement system accuracy specified in the test plan in Section 5.1.

6.1.2 Measurements from the instruments shall be traceable to primary or secondary standards calibrated by the National Institute of Standards and Technology (NIST) or to the Bureau International des Poids et Mesures (BIPM) if a National Metrology Institute (NMI) other than NIST is used. In either case, the indicated corrections shall be applied to meet the uncertainty stated in subsequent sections. Instruments shall be recalibrated on regular intervals that do not exceed the intervals prescribed by the instrument manufacturer and calibration records shall be maintained. Instruments shall be installed in accordance with the instrument manufacturer's requirements or the manufacturer's accuracy does not apply.

6.1.3 Instruments shall be applied and used in accordance with the following standards:

a. Temperature – ANSI/ASHRAE Standard 41.1[5] if temperature measurements are required.
b. Pressure – ANSI/ASHRAE Standard 41.3[6] if pressure measurements are required.
c. Lubricant circulation rate: ANSI/ASHRAE 41.4.[2]

6.2 Temperature Measurements

If temperature measurements are required by the test plan in Section 5.1, the temperature measurement system accuracy shall be within the following limits unless otherwise specified in the test plan

a. Temperature measurement system accuracy shall be within ±0.28°C (±0.5°F) for both laboratory and field applications.
b. Temperature difference measurement system accuracy for both laboratory and field applications shall be within ±l.0% of the measured temperature difference but not more accurate than ±0.1°C (±0.2°F).

(***Informative Notes:***

1. Requiring the differential temperature measurement accuracy to be within ±1% of the measured differential temperature for small differential temperatures would be impractical where the required accuracy would be less than commercial temperature sensor accuracies.
2. Informative Appendix D lists several sources of temperature measurement errors.

6.3 Pressure Measurements

6.3.1 Laboratory Pressure Measurements

6.3.1.1 If pressure measurements are required by the test plan in Section 5.1, the pressure measurement system accuracy shall be within ±7 kPa (±1 psi) unless otherwise specified in the test plan. If absolute pressure sensors are not used, the barometric pressure shall be added to the gage pressure readings to obtain absolute pressure values prior to performing uncertainty calculations.

6.3.1.2 If differential pressure measurements are required by the test plan, the pressure measurement system accuracy shall be within ±1% of the measured pressure difference but not more accurate than ±7 kPa (±1 psid) unless otherwise specified in the test plan. Pressure shall be measured in close proximity to the flow meter in accordance with the flow meter manufacturer's specifications.

(***Informative Note:*** Requiring the differential pressure measurement accuracy to be within ±1% of the measured differential pressure for small differential pressures would be impractical where the required accuracy would be less than commercial pressure sensor accuracies.)

6.3.2 Field Pressure Measurements

6.3.2.1 If pressure measurements are required by the test plan in Section 5.1, the pressure measurement system accuracy shall be within ±20 kPa (±3 psi) unless otherwise specified in the test plan. If absolute pressure sensors are not used, the barometric pressure shall be added to the gage pressure readings to obtain absolute pressure values prior to performing uncertainty calculations.

6.3.2.2 If differential pressure measurements are required by the test plan, the pressure measurement system accuracy shall be within ±3% of the measured pressure difference but not more accurate than ±20 kPa (±3 psid) unless otherwise specified in the test plan. Pressure shall be measured at the flowmeter in accordance with the flowmeter manufacturer's specifications.

(***Informative Note:*** Requiring the differential pressure measurement accuracy to be within ±3% of the measured differential pressure for small differential pressures would be impractical where the required accuracy would be less than commercial pressure sensor accuracies.)

6.4 Time Measurements

Time measurement system accuracy shall be within ±0.5% of the elapsed time measured, including any uncertainty associated with starting and stopping the time measurement unless (a) otherwise specified in the test plan in Section 5.1, or (b) a different value for time measurement system accuracy is required to be consistent with the measurement system accuracy specified in the test plan.

7. REFRIGERANT FLOWMETER TEST METHODS

Refrigerant flowmeter test methods that are within the scope of this standard include, but are not limited to, the methods listed in Sections 7.1 through 7.9.

7.1 Coriolis Flowmeters. Coriolis flowmeters provide direct measurement of gaseous phase, liquid phase, or supercritical phase refrigerant mass flow rates. In a Coriolis flowmeter, the gaseous phase, liquid phase, or supercritical phase of the refrigerant flows through a vibrating sensor tube within the meter. An electromagnetic coil located on the sensor tube vibrates the tube at a known frequency. Gaseous phase, liquid phase, or supercritical phase refrigerant enters a vibrating tube and is given the momentum of the tube. Combined, these effects create a twist angle. According to Newton's Second Law of Motion, the amount of sensor tube twist angle is directly proportional to the mass flow rate of gaseous phase, liquid phase, or supercritical phase refrigerant flowing through the tube. Electromagnetic velocity sensors, located on opposing sides of the sensor tube, measure the velocity of the vibrating tube. Mass flow rate is determined by measuring the time difference in the velocity measurements – the greater the time difference, the greater the mass flow rate.

Because a Coriolis flowmeter measures mass flow rates, the lubricant mass flow rates, if any, shall be subtracted from the measured mass flow rates to determine the net refrigerant mass flow rates.

(***Informative Note***: See Informative Appendix A Section A3 for additional information.)

7.2 Thermal Flowmeter. Thermal flowmeters provide direct measurement of gaseous phase. liquid phase, or supercritical phase mass flow rates. The basic elements of the thermal mass flowmeters are two temperature sensors on opposite sides of an electric heater positioned that supplies a constant heat input to the gaseous, liquid phase, or supercritical phase of the refrigerant. The gaseous phase, liquid phase, or supercritical phase mass flow rate shall be obtained from Equation 7-1.

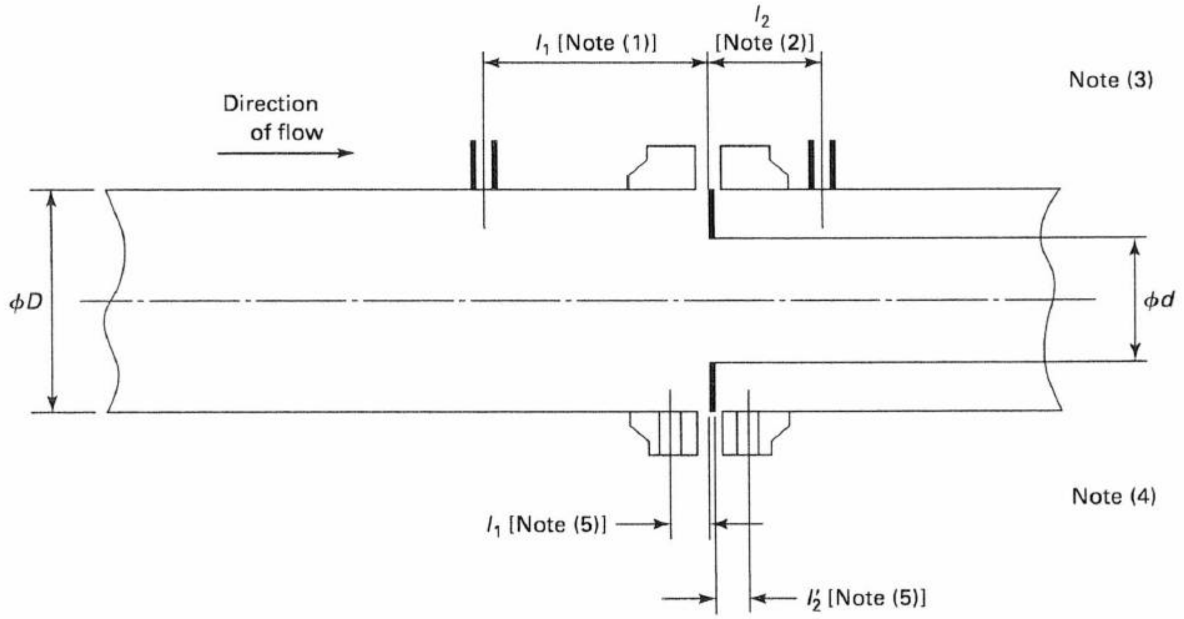
$$\dot{m} = \frac{Kq}{C_p(T_2 - T_1)} \tag{7-1}$$

where

$\dot{m}$ = gaseous phase, liquid phase, or supercritical phase mass flow rate, kg/s (lb_m/s)
K = meter coefficient, dimensionless
q = constant electric heat flux rate, kJ/s (Btu/s)
C_p = constant pressure specific heat of the gaseous phase, liquid phase, or supercritical phase of the refrigerant, kJ/(kg-°C) (Btu/(lb_m-°F))
T_1 = entering refrigerant temperature, °C (°F)
T_2 = exiting refrigerant temperature, °C (°F)

7.3 Orifices, Flow Nozzles, and Venturi Tube Flow Meters. ANSI/ASME PTC 19.5[7] and ANSI/ASME MFC-3M[8] describe measurement of gaseous phase, liquid phase, and supercritical phase flow in pipes using orifices, flow nozzles, and venturi tubes, including construction proportions and port locations.

7.3.1 Orifices, Flow Nozzles, and Venturi Tube Flowmeter Geometric Profiles. Figure 7-1 illustrates the geometric profile of an orifice metering section. Figure 7-2 illustrates the geometric profile of a long radius nozzle, and Figure 7-3 shows the geometric profile of a venturi tube.



NOTES:
(1) $l_1 = D \pm 0.1D$.
(2) $l_2 = 0.5D \pm 0.02D$ for $\beta \leq 0.6$.
$= 0.5D \pm 0.01D$ for $\beta > 0.6$.
(3) D and $D/2$ pressure tap arrangement.
(4) Flange tap arrangement.
(5) $l_1 = l'_2 =$ 25.4 mm ± 0.5 mm (1.00 in. ± 0.02 in.) for $\beta > 0.6$ and $D <$ 150 mm (6 in.)
= 25.4 mm ± 1 mm (1.00 in. ± 0.04 in.) for $\beta \leq 0.6$
= 25.4 mm ± 1 mm (1.00 in. ± 0.04 in.) for $\beta > 0.6$ and 150 mm $\leq D \leq$ 1000 mm (6 in. $\leq D \leq$ 40 in.)

Figure 7-1 Orifice Flowmeter Geometric Profile
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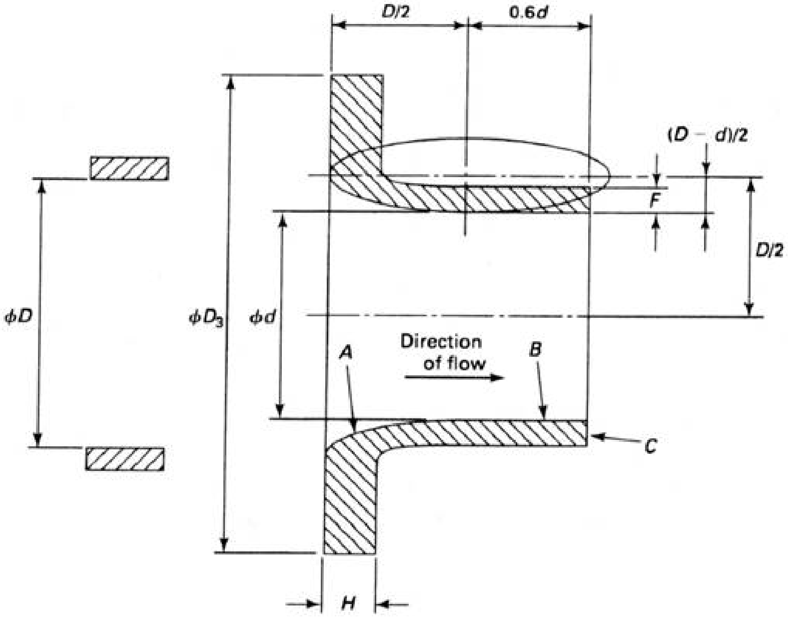
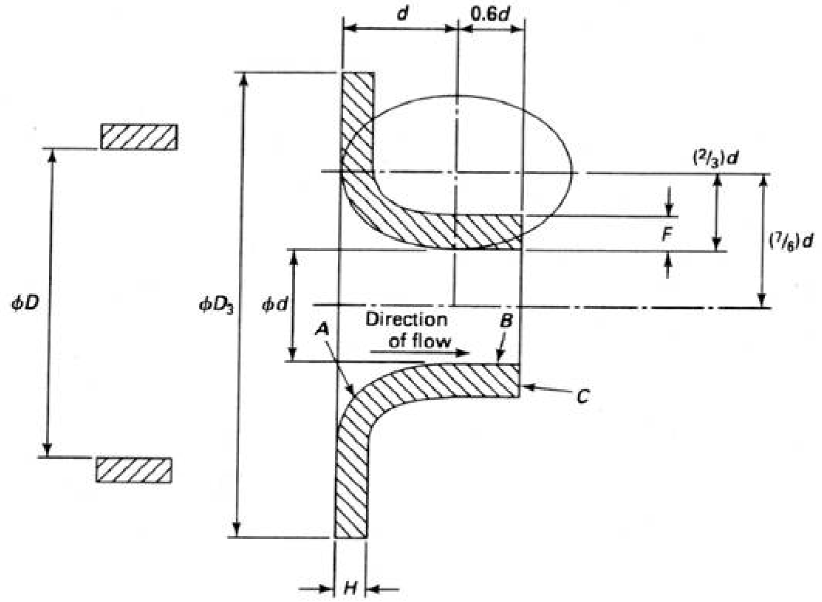


(a) High Ratio 0.25 $\leq \beta \leq$ 0.8



(b) Low Ratio 0.2 $\leq \beta \leq$ 0.5

Figure 7-2 Long Radius Nozzle Geometric Profile
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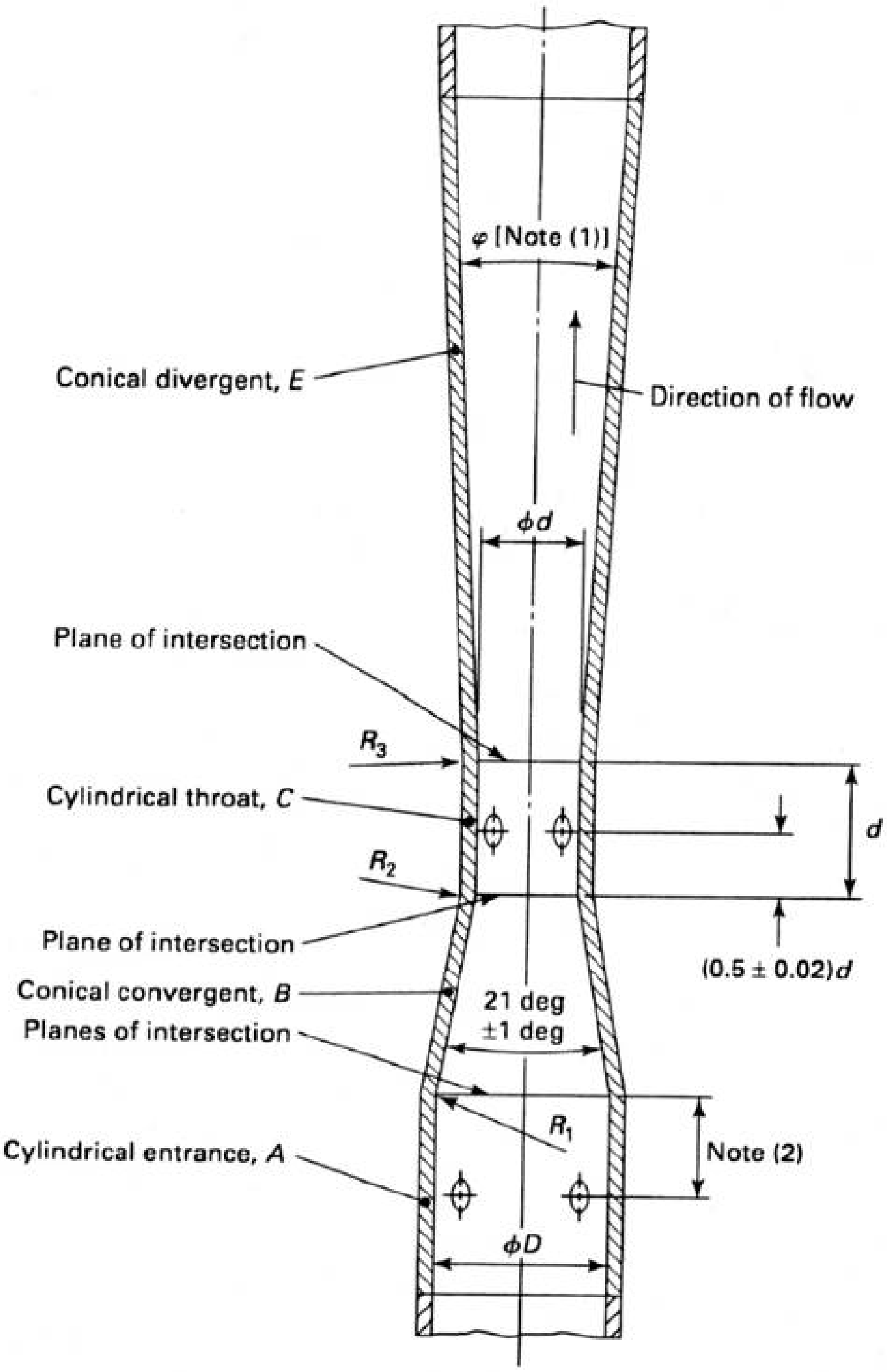

NOTES:
(1) 7 deg ≤ φ ≤ 15 deg.
(2) See para. 4-4.4.7.

Figure 7-3 Venturi Tube Flowmeter Geometric Profile
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7.3.2 Nozzle Mass Flow Rate Equations and Procedures for Liquid Phase and Supercritical Phase Flowmeters.

This section provides the equations and procedures for calculating liquid phase and supercritical phase refrigerant mass flow rates using long radius nozzles. This section provides reference information for calculating refrigerant flow rates using orifices, ISA 1932 nozzles, venturi nozzles, and venturi tube flowmeters.

Calculating a liquid phase or supercritical phase refrigerant mass flow rate using these methods requires iteration because the discharge coefficient *C* is a function of the Reynolds number, the Reynolds number is a function of the average refrigerant flow velocity, and the average refrigerant flow velocity is not known until the refrigerant mass flow rate has been determined. ANSI/ASME PTC 19.5[5] includes an example of this iterative procedure on page 25, and ANSI/ASME MFC-3M[6] provides the limits of use, discharge coefficient equations, and expansibility factor equations for orifices, long radius nozzles, ISA 1932 nozzles, venturi nozzles, and venturi tube flowmeters.

7.3.2.1 Required Straight Lengths for Nozzle Flowmeters. Unless flow straighteners are used, the required straight length from a 90-degree bend upstream of a nozzle flowmeter shall be ≥ 10 nozzle inlet pipe inside diameters. The required straight length downstream from the nozzle flowmeter discharge shall be ≥ 5 nozzle inlet pipe inside diameters.[6]

7.3.2.2 Measurements: Measurements required for liquid phase or supercritical phase nozzle refrigerant flow are:

a. inlet pipe inside diameter D, m (ft)
b. nozzle throat diameter d, m (ft)
c. nozzle inlet absolute pressure p_1, Pa (psia)
d. nozzle throat absolute pressure p_2, Pa (psia)
e. nozzle differential pressure $\Delta p = (p_1 - p_2)$, Pa (psid)
f. nozzle inlet temperature t_1, °C (°F)

7.3.2.3 Nozzle Limits for Use and Reynolds Number. Limits for the use for long radius nozzle are:

a. 50 mm (2 in.) $\leq D \leq$ 630 mm (25 in.)
b. $R_a/D \leq 3.2\ (10^{-4})$ where R_a is the mean of the surface roughness in the upstream duct
c. $1\ (10^4) \leq Re_D \leq 1000\ (10^7)$ where Re_D is defined in Equation 7-2.

$$Re_D = \frac{\rho V D}{\mu} \tag{7-2}$$

where

ρ = nozzle inlet refrigerant density, kg/m^3 (lb$_m$/ft^3)
V = nozzle throat average refrigerant velocity, m/s (ft/s)
D = nozzle inlet hydraulic diameter, m (ft)
μ = nozzle inlet dynamic viscosity, kg/(m-s) (lb$_m$/s-ft)

7.3.2.4 Nozzle Beta Ratio. The nozzle beta ratio shall be obtained from Equation 7-3. If refrigerant flow operating temperatures are not within ±6ºC (±10ºF) of the of the ambient temperature during the dimensional measurements, parameters *d*, *D*, and *β* shall be corrected to account for thermal expansion in compliance with ANSI/ASME PTC 19.5[6] Section 3-10.

$$\beta = \left(\frac{d}{D}\right), \text{ dimensionless} \tag{7-3}$$

7.3.2.5 Nozzle Liquid Phase or Supercritical Phase Refrigerant Inlet Density. The nozzle liquid phase or supercritical phase refrigerant inlet density ρ shall be obtained from the refrigerant property data prescribed in Section 5.3.11 as a function of the nozzle inlet temperature t_1 and pressure p_1 at each data point.

7.3.2.6 Nozzle Liquid Phase or Supercritical Phase Volumetric Flow Rates. Nozzle liquid phase or supercritical phase volumetric flow rates shall be calculated from Equation 7-4 in SI units or Equation 7-5 in I-P units.

In SI units:

$$Q = CAK_1\sqrt{\frac{2(\Delta p)}{\rho(1-\beta^4)}} \tag{7-4}$$

where

Q = nozzle liquid phase or supercritical phase volumetric flow rate, m^3/s
C = nozzle discharge coefficient, dimensionless
A = nozzle throat area, m^2
K_1 = nozzle calibration coefficient, dimensionless
ρ = nozzle inlet liquid phase or supercritical phase density, kg/m^3
Δp = nozzle differential pressure, Pa
β = d/D, dimensionless

In I-P units:

$$Q = 0.47268 \times CAK_1\sqrt{\frac{2(\Delta p)}{\rho(1-\beta^4)}} \tag{7-5}$$

where

Q = nozzle liquid phase or supercritical phase volumetric flow rate, ft^3/s
C = nozzle discharge coefficient, dimensionless
A = nozzle throat area, ft
K_1 = nozzle calibration coefficient, dimensionless
ρ = nozzle inlet liquid phase or supercritical phase density, lb_m/ft^3
Δp = nozzle differential pressure, psid
β = d/D_h, dimensionless
0.47268 = unit conversion coefficient, $\sqrt{\frac{(lb_m-ft^3)}{(psid-in^4-s^2)}}$

If the refrigerant flow operating temperatures are not the same as the refrigerant flow operating temperatures during calibration, parameters d, D, and β shall be corrected to account for thermal expansion in accordance with ANSI/ASME PTC 19.5[5] Sections 3-10.

7.3.2.7 Nozzle Discharge Coefficient. The dimensionless nozzle discharge coefficient C is a function of β and the Reynolds number based upon the nozzle inlet diameter. The discharge coefficient C for long radius nozzles shall be obtained from Equation 7-6.

$$C = 0.9965 - \left(0.00653\beta^{0.5}\right)\left(\frac{10^6}{Re_D}\right)^{0.5} \qquad (7\text{-}6)$$

The Reynolds number shall be calculated from Equation 20, but the average velocity is not known until the liquid phase or supercritical phase refrigerant mass flow rate has been determined. Iteration is required to determine the liquid phase or supercritical phase refrigerant mass flow rate. Choose $C = 1.0$ to begin the iterative calculation procedure for long radius nozzles, ISA 1932 nozzles, venturi nozzles and for venturi tube flowmeters, or choose $C = 0.6$ for orifice flowmeters. Iteration shall continue until the calculated discharge coefficient C matches the previous discharge coefficient within ±0.005.

To calculate liquid phase or supercritical phase refrigerant mass flow rates for orifices, ISA 1932 nozzles, venturi nozzles, or venturi tubes, refer to the paragraphs in ANSI/ASME MFC-3M[8] that are listed in Table 7-1 and use the same procedures that have been described for the long radius nozzles.

Table 7-1 References in ANSI/ASME MFC-3M[8] for ISA 1932 Nozzles, Venturi Nozzles, and Venturi Tubes

Flowmeter Type	Limit of Use Section Number	Discharge Coefficient Equation
Orifices	2-4.3.1	2-4
ISA 1932 Nozzles	3-4.1.6.1	3-6
Venturi Nozzles	3-4.3.4.1	3-16
Venturi Tubes	4-4.5.1	4-4.5.1, 4-5.4.2, or 4-4.5.3

7.3.2.8 Nozzle Liquid Phase or Supercritical Phase Refrigerant Mass Flow Rates. The nozzle liquid phase or supercritical phase refrigerant mass flow rate shall be obtained from Equation 7-7, where ρ is the nozzle liquid phase or supercritical phase inlet refrigerant density, kg/m^3 (lb$_m$/ft^3) and Q is the liquid phase or supercritical phase refrigerant volumetric flow rate, m^3/s (ft^3/s) using Equation 7-4 in SI units or Equation 7-5 in I-P units.

$$\dot{m} = \rho Q, \text{ kg/s (lb}_m\text{/s)} \qquad (7\text{-}7)$$

7.4 Nozzle Mass Flow Rate Equations and Procedures for Gaseous Phase Flowmeters

This section provides the equations procedures for calculating gaseous phase mass flow rates using long radius nozzles and provides reference information for calculating gaseous phase mass flow rates for orifices, ISA 1932 nozzles, venturi nozzles, or venturi tubes.

Calculating a gaseous phase mass flow rate using these methods requires iteration because (a) the discharge coefficient C is a function of the Reynolds number and the Reynolds number is a function of the average gaseous phase flow velocity, and (b) the average gaseous phase flow velocity is not known until the gaseous phase mass flow rate has been determined. ANSI/ASME PTC 19.5[7] includes an example of this iterative procedure on page 25, and ANSI/ASME MFC-3M[8] provides the limits of use, discharge coefficient equations, and expansibility factor equations for orifices, long radius nozzles, ISA 1932 nozzles, venturi nozzles, and venturi tube flowmeters.

7.4.1 Required Straight Lengths for Gaseous Phase Flowmeters. Unless flow straighteners are used, the required straight length from a 90-degree bend upstream of a nozzle flowmeter shall be ≥ 7.5 nozzle inlet pipe inside diameters. The required straight length downstream from the nozzle flowmeter discharge shall be ≥ 3 nozzle inlet pipe inside diameters.[6]

7.4.2 Measurements: Measurements required for gaseous phase nozzle flow are:

a. inlet pipe inside diameter D, m (ft)
b. nozzle throat diameter d, m (ft)
c. nozzle inlet absolute pressure p_1, Pa (psia)
d. nozzle throat absolute pressure p_2, Pa (psia)
e. nozzle differential pressure $\Delta p = (p_1 - p_2)$, Pa (psid)
f. nozzle inlet temperature t_1, °C (°F)

7.4.3 Nozzle Limits for Use and Reynolds Number. Limits for the use for long radius nozzle are:

a. 50 mm (2 in.) $\le D \le$ 630 mm (25 in.)
b. $R_a/D \le 3.2\ (10^{-4})$ where R_a is the mean of the surface roughness in the upstream duct
c. $1\ (10^4) \le Re_D \le 1000\ (10^7)$ where Re_D is defined in Equation 7-8.

$$Re_D = \frac{\rho V D}{\mu} \qquad (7\text{-}8)$$

where

ρ = nozzle inlet gaseous phase density, kg/m^3 (lb$_m$/ft^3)
V = nozzle throat average gaseous phase velocity, m/s (ft/s)
D = nozzle inlet inside diameter, m (ft)
μ = nozzle inlet dynamic viscosity, kg/(s-m) [lb$_m$/(s-ft)]

7.4.4 Nozzle Beta Ratio. The nozzle beta ratio shall be obtained from Equation 7-9. If gas flow operating temperatures are not within ±6ºC (±10ºF) of the ambient temperature during the dimensional measurements, parameters d, D, and β shall be corrected to account for thermal expansion in compliance with ANSI/ASME PTC 19.5[7] Section 3-10.

$$\beta = \left(\frac{d}{D}\right), \text{ dimensionless} \qquad (7\text{-}9)$$

7.4.5 Nozzle Gaseous Phase Refrigerant Inlet Density. The nozzle gaseous phase refrigerant inlet density ρ shall be obtained from the refrigerant property data prescribed in Section 5.3.11 as a function of the nozzle inlet temperature t_1 and pressure p_1 at each data point.

7.4.6 Nozzle Gaseous Phase Volumetric Flow Rates. Nozzle gaseous phase volumetric flow rates shall be calculated from Equation 7-10 in SI units or Equation 7-11 in I-P units.

In SI units:

$$Q = C\varepsilon A K_2 \sqrt{\frac{2(\Delta p)}{\rho(1-E\beta^4)}} \tag{7-10}$$

where

Q = nozzle gaseous phase volumetric flow rate, m^3/s
C = nozzle discharge coefficient, dimensionless
ε = nozzle expansibility factor, dimensionless
A = nozzle throat area, m^2
K_2 = nozzle calibration coefficient, dimensionless
ρ = nozzle inlet gaseous phase density, kg/m^3
E = flow kinetic energy coefficient = 1.043[9], dimensionless
Δp = nozzle differential pressure, Pa
β = d/D, dimensionless

(***Informative Note:*** The superscript "9" in "1.043[9]" above is reference number, not an exponent.)

In I-P units:

$$Q = 0.47268 \times C\varepsilon A K_2 \sqrt{\frac{2(\Delta p)}{\rho(1-E\beta^4)}} \tag{7-11}$$

where

Q = nozzle gaseous phase volumetric flow rate, ft^3/s
C = nozzle discharge coefficient, dimensionless
ε = nozzle expansibility factor, dimensionless
A = nozzle throat area, ft^2
K_2 = nozzle calibration coefficient, dimensionless
ρ = nozzle inlet gaseous phase density, lb$_m$/ft^3
E = flow kinetic energy coefficient = 1.043[9], dimensionless
Δp = nozzle differential pressure, psid
β = d/D, dimensionless
0.47268= unit conversion coefficient, $\sqrt{\frac{(lb_m - ft^3)}{(psid - in^4 - s^2)}}$

(***Informative Note:*** The superscript "9" in "1.043[9]" above is reference number, not an exponent.)

7.4.7 Nozzle Expansibility Factor. The dimensionless nozzle expansibility factor ε for a long radius nozzle shall be obtained from Equation 7-12. This equation assumes that the gas is an ideal gas and the gas flow is an isentropic process.

$$\varepsilon = \left[r^{\frac{2}{\gamma}} \left(\frac{\gamma}{\gamma-1}\right) \left(\frac{1-r^{\frac{\gamma-1}{\gamma}}}{1-r}\right) \left(\frac{1-\beta^4}{1-\beta^4 r^{\frac{2}{\gamma}}}\right) \right]^{1/2} \tag{7-12}$$

where

r = absolute pressure ratio $\left[\frac{p_2}{p_1}\right]$, dimensionless

γ = ratio of specific heats $\left[\frac{C_p}{C_v}\right]$, dimensionless
$\beta = d/D$, dimensionless

7.4.8 Nozzle Discharge Coefficient. The dimensionless nozzle discharge coefficient *C* is a function of β and the Reynolds number based upon the nozzle inlet diameter. The discharge coefficient *C* for long radius nozzles shall be obtained from Equation 7-13.

$$C = 0.9965 - \left(0.00653\beta^{0.5}\right)\left(\frac{10^6}{Re_D}\right)^{0.5} \quad (7\text{-}13)$$

The Reynolds number shall be calculated from Equation 41, but the average velocity is not known until the gaseous phase mass flow rate has been determined. Iteration is required to determine the gas mass flow rate. Choose *C* = 1.0 to begin the iterative calculation procedure for long radius nozzles, ISA 1932 nozzles, venturi nozzles and for venturi tube flowmeters, or choose *C* = 0.6 for orifice flowmeters. Iteration shall continue until the calculated discharge coefficient *C* matches the previous discharge coefficient within ±0.005. To calculate gaseous phase mass flow rates for orifices, ISA 1932 nozzles, venturi nozzles, or venturi tubes, refer to the paragraphs in ANSI/ASME MFC-3M[8] that are listed in Table 7-2 and use the same procedures that have been described for the long radius nozzles.

Table 7-2 References in ANSI/ASME MFC-3M[8] for ISA 1932 Nozzles, Venturi Nozzles, and Venturi Tubes

Flowmeter Type	Limit of Use Section Number	Discharge Coefficient Equation	Expansibility Factor Equation
Orifices	2-4.3.1	2-4	2-6
ISA 1932 Nozzles	3-4.1.6.1	3-6	3-7
Venturi Nozzles	3-4.3.4.1	3-16	3-7
Venturi Tubes	4-4.5.1	4-4.5.1, 4-5.4.2, or 4-4.5.3	4-3

7.4.9 Nozzle Gaseous Phase Mass Flow Rate. The nozzle gas mass flow rate shall be obtained from Equation 7-14, where ρ is the nozzle inlet gaseous phase density, kg/m^3 (lb$_m$/ft^3) and Q is the gaseous phase volumetric flow rate, m^3/s (cfm), using Equation 7-10 in SI units or Equation 7-11 in I-P units.

$$\dot{m} = \rho Q, \text{ kg/s (lb}_m\text{/min)} \quad (7\text{-}14)$$

7.5 Turbine Flow Meters for Gaseous Phase, Liquid Phase, or Supercritical Phase Refrigerant Volumetric Flow Measurements. Turbine flowmeters are volumetric flow meters that have a turbine rotor suspended on low-friction bearings in the gaseous phase, liquid phase, or supercritical phase refrigerant stream. The rotational speed of the turbine is a linear function of the average gaseous phase, liquid phase, or supercritical phase refrigerant velocity and is therefore a linear function of the volumetric flow rate. Turbine rotation rates are sensed using one of these methods: (a) reluctance sensors, (b) inductance sensors, (c) capacitance sensors, (d) Hall-effect sensors, or (e) mechanical sensors.

(***Informative Note:*** See Informative Appendix A, Bibliography item A4 for additional information.)

7.6 Variable-Area Flowmeters for Gaseous Phase, Liquid Phase, or Supercritical Phase Refrigerant Volumetric Flow Measurements. Variable-area flowmeters are volumetric flowmeters that consist of a float that is free to move vertically inside a tapered transparent tube that has a graduated scale as illustrated in Figure 7-4. The gaseous phase, liquid phase, or supercritical refrigerant volumetric flow to be metered enters at the narrow bottom end of the tube and flows upward, passing through the annulus formed between the float and the inside wall of the tube. The position of the float is a balance between the gaseous phase, liquid phase, or supercritical phase refrigerant pressure forces across the annulus acting upward and gravity acting downward on the float.

(***Informative Note:*** See Informative Appendix A, Bibliography item A5 for additional information.)

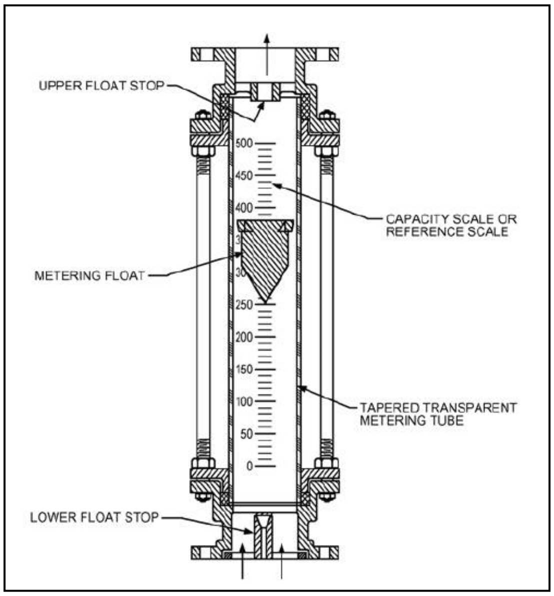

Figure 7-4 Variable-Area Flowmeter
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7.7 Ultrasonic Flowmeters for Gaseous Phase, Liquid Phase, or Supercritical Phase Velocity Measurements. Ultrasonic flowmeters measure gaseous phase, liquid phase, or supercritical phase flow velocity by measuring the change in sound frequency of the moving refrigerant. Use of a clamp-on or immersion type of ultrasonic flowmeter is capable of measuring refrigerant or gaseous phase, liquid phase, or supercritical phase refrigerant without intrusion into the flow stream.

Ultrasonic flowmeters use the transit-time method to measure the effects that flow velocity has on bi-directional acoustical signals. An upstream transducer sends a signal to a downstream transducer that then returns a signal. In the absence of refrigerant flow, the time for the signal to go from one transducer to other, in either direction, is constant. In the presence of refrigerant flow, the velocity causes the acoustical signal to increase speed in the direction of flow and reduces the acoustical signal speed in the upstream direction. This creates the time difference that correlates to the flow velocity.

(***Informative Note:*** See Informative Appendix A, Bibliography items A6 and A7 for additional information.)

7.8 Vortex-Shedding Flowmeters for Gaseous Phase, Liquid Phase, or Supercritical Phase Refrigerant Velocity Measurements. Vortex-shedding flowmeters are used to determine gaseous phase, liquid phase, or supercritical phase refrigerant velocities. Piezoelectric methods, strain-gage methods, or hot-film methods are used to sense dynamic pressure variations created by vortex shedding.

(***Informative Note:*** See Informative Appendix A, Bibliography item A8 for additional information.)

7.9 Drag-Force Flowmeters for Liquid Phase or Supercritical Phase Refrigerant Velocity Measurements. Drag-force flowmeters determine liquid phase or supercritical phase refrigerant velocity. Piezoelectric or strain-gage methods are used to sense dynamic drag-force variations. A body immersed in a flowing liquid phase or supercritical phase stream is subjected to a drag force given by Equation 7-15 in SI units and by Equation 7-16 in I-P units. The manufacturer designs the immersed element so that the drag coefficient is constant over the specified range of Reynolds numbers.

(***Informative Note:*** See Informative Appendix A, Bibliography item A9 for additional information.)

In SI units:

$$V = \sqrt{\frac{2\, f_d}{C_d A \rho}} \tag{7-15}$$

where

V = liquid phase or supercritical phase refrigerant velocity, m/s
f_d = drag force, N
C_d = drag coefficient, dimensionless
A = cross-section area, m^2
ρ = liquid phase or supercritical phase refrigerant density, kg/m^3

In I-P units:

$$V = \sqrt{\frac{2\, g_c f_d}{C_d A \rho}} \tag{7-16}$$

where

V = liquid phase or supercritical phase refrigerant velocity, ft/s
f_d = drag force, lb_f
C_d = drag coefficient, dimensionless
A = cross-section area, ft^2
ρ = liquid phase or supercritical phase refrigerant density, lb_m/ft^3
g_c = gravitational constant, 32.174 $[(lb_m\text{-}ft)/(lb_f\text{-}s^2)]$

7.10 Magnetic Flowmeters. Magnetic flow meters are volumetric flowmeters that measure liquid refrigerant flow rates if the refrigerant has a conductivity that is greater than 5 µS/cm. Magnetic flowmeters operate on the principle of Faraday's law of induction that states that the electromotive force induced in a circuit equals the negative of the time rate of change of the magnetic flux through the circuit. In a magnetic flowmeter, a magnetic field is generated and channeled into the liquid phase or supercritical phase refrigerant flowing through the pipe. Faraday's Law states that the voltage generated is proportional to the movement of the flowing liquid phase or supercritical phase streams. Electronics within a magnetic flowmeter sense voltage and determine the volumetric flow rate.

(***Informative Notes:***

a. Magnetic tube flowmeters have no flow obstructions, so the pressure loss in these flowmeters is less than for many other types of flowmeters.

b. See Informative Appendix A Reference A9 for additional information.

7.11 Positive-Displacement Flowmeters. Positive-displacement flowmeter types are gear, piston, and rotating vane. These flowmeters operate on a geometric principle using a known displacement volume divided by the cycle time to fill and evacuate that volume. For example, during one cycle in a gear flowmeter, liquid phase or supercritical phase refrigerant enters the gear housing of known volume through an intake. As the gear rotates, liquid phase is trapped between the gears and the housing in a space of known volume. Continued gear rotation then moves the trapped volume to the discharge side of the meter. The time required to complete this cycle is divided into the trapped volume to determine the volumetric flow rate. This process is expressed mathematically in Equation 7-17.

$$Q = \frac{V_t}{t} \qquad (7\text{-}17)$$

where

Q = liquid phase or supercritical phase flow rate, m^3/s (ft^3/sec)
V_t = trapped liquid phase or supercritical phase volume, m^3 (ft^3)
t = cycle time, s

8. LUBRICANT CIRCULATION RATE MEASUREMENTS

8.1 Symbols. Table 8-1 defines the symbols used in Section 8.

Table 8-1 Symbols Used in Section 8

Symbol	Description	SI Units	I-P Units
C_f	Lubricant circulation rate through the flowmeter	dimensionless	
C_s	Lubricant circulation rate through the lubricant separator	dimensionless	
C_{suut}	Lubricant circulation rate through the UUT	dimensionless	
$\dot{m}_{lf}$	Lubricant mass flow rate through the flowmeter	kg/s	lb$_m$/h
$\dot{m}_{ls}$	Lubricant mass flow rate through the auxiliary separator	kg/s	lb$_m$/h
$\dot{m}_{lt}$	Total lubricant mass flow rate	kg/s	lb$_m$/h
$\dot{m}_{rf}$	Refrigerant mass flow rate through the flowmeter	kg/s	lb$_m$/h
$\dot{m}_{rs}$	Refrigerant mass flow rate through the auxiliary separator	kg/s	lb$_m$/h
$\dot{m}_{rt}$	Total refrigerant mass flow rate	kg/s	lb$_m$/h
$\dot{m}_{rls}$	Total refrigerant plus lubricant mass flow rate through the auxiliary separator	kg/s	lb$_m$/h

8.2 Lubricant Circulation Rate Measurement without an Auxiliary Lubricant Separator. Apply the procedures prescribed in ANSI/ASHRAE 41.4[2] to determine the lubricant circulation rate through the flowmeter, C_f. Refer to Section 5.6 for sample port requirements.

8.3 Lubricant Circulation Rate Measurement with an Auxiliary Lubricant Separator

8.3.1 Figure 8 is a schematic of the auxiliary lubricant separator.

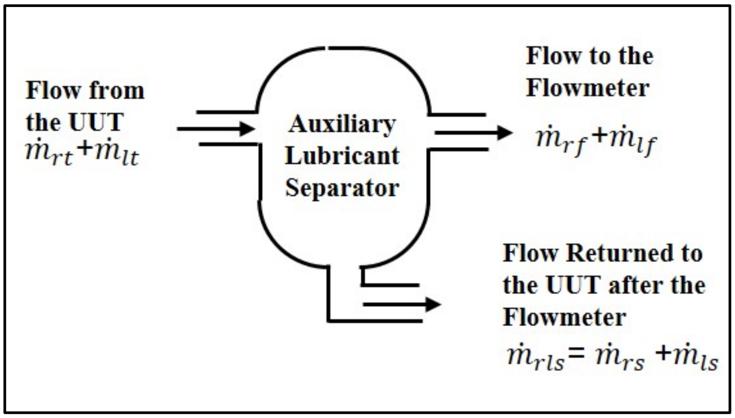

FIGURE 8-1 Auxiliary Lubricant Separator Schematic

8.3.2 Measure the refrigerant mass flow rate through the flowmeter, $\dot{m}_{rf}$, using one of the flowmeter test methods described in Section 7.

8.3.3 Apply the procedures in ANSI/ASHRAE 41.4[2] to determine the lubricant circulation rate through the flowmeter, C_f. Refer to Section 5.6 for sample port requirements.

$$C_f = \frac{\dot{m}_{lf}}{(\dot{m}_{rf}+\dot{m}_{lf})} \tag{8-1}$$

8.3.4 Measure the total refrigerant plus lubricant mass flow rate through the auxiliary lubricant separator, $\dot{m}_{rls}$, using a refrigerant flowmeter mass flow rate method in ANSI/ASHRAE 41.8[9] with a flowmeter accuracy not greater than ±1% of the reading.

8.3.5 Apply the procedures in ANSI/ASHRAE 41.4[2] to determine the lubricant circulation rate through the lubricant separator, C_s. Refer to Section 5.6 for sample port requirements.

$$C_s = \frac{\dot{m}_{ls}}{(\dot{m}_{rs}+\dot{m}_{ls})} \tag{8-2}$$

8.3.6 From the conservation of mass, the refrigerant plus lubricant mass flow rate through the auxiliary lubricant separator, $\dot{m}_{rls}$, is equal to the sum of the refrigerant mass flow rate through the auxiliary lubricant separator, $\dot{m}_{rs}$, and the lubricant mass flow rate through the auxiliary lubricant separator, $\dot{m}_{ls}$, as stated in Equation 8-3.

$$\dot{m}_{rls} = \dot{m}_{rs} + \dot{m}_{ls} \tag{8-3}$$

8.3.7 An expression for the refrigerant mass flow rate through the auxiliary lubricant separator, $\dot{m}_{rs}$, is obtained from Equation 8-4.

$$\dot{m}_{rs} = \dot{m}_{ls}\left(\frac{1-C_s}{C_s}\right) \tag{8-4}$$

8.3.8 Equation 34, the refrigerant mass flow rate through the auxiliary lubricant separator, $\dot{m}_{rs}$, is obtained by substituting Equation 8-4 into Equation 8-3.

$$\dot{m}_{rs} = \dot{m}_{rls}(1 - C_s) \qquad (8\text{-}5)$$

8.3.9 Equation 35, the lubricant mass flow rate through the auxiliary lubricant separator, $\dot{m}_{ls}$, is obtained by substituting Equation 8-5 into Equation 8-3.

$$\dot{m}_{ls} = C_s \dot{m}_{rls} \qquad (8\text{-}6)$$

8.3.10 From the conservation of mass, the total lubricant mass flow rate, $\dot{m}_{lt}$, is equal to the sum of the lubricant mass flow rate through the flowmeter, $\dot{m}_{lf}$, and the lubricant mass flow rate through the auxiliary lubricant separator, $\dot{m}_{ls}$.

$$\dot{m}_{lt} = \dot{m}_{lf} + \dot{m}_{ls} \qquad (8\text{-}7)$$

8.3.11 An expression for the lubricant mass flow rate through the flowmeter, $\dot{m}_{lf}$, is obtained from Equation 8-1.

$$\dot{m}_{lf} = \dot{m}_{rf}\left(\frac{C_f}{1-C_f}\right) \qquad (8\text{-}8)$$

8.3.12 Equation 38, the total lubricant mass flow rate, $\dot{m}_{lt}$, is obtained by substituting Equation 8-8 and Equation 8-6 into Equation 8-7.

$$\dot{m}_{lt} = \dot{m}_{rf}\left(\frac{C_f}{1-C_f}\right) + C_s \dot{m}_{rls} \qquad (8\text{-}9)$$

8.3.13 From the conservation of mass, the total refrigerant mass flow rate, $\dot{m}_{rt}$, is equal to the sum of the refrigerant mass flow rate through the flowmeter, $\dot{m}_{rf}$, and the refrigerant mass flow rate through the auxiliary lubricant separator, $\dot{m}_{rs}$.

$$\dot{m}_{rt} = \dot{m}_{rf} + \dot{m}_{rs} \qquad (8\text{-}10)$$

8.3.14 Equation 8-11 is obtained by substituting Equation 8-5 into Equation 8-10.

$$\dot{m}_{rt} = \dot{m}_{rf} + \dot{m}_{rls}(1 - C_s) \qquad (8\text{-}11)$$

8.3.15 The lubricant circulation rate for the UUT is provided in Equation 8-12.

$$C_{suut} = \frac{\dot{m}_{lt}}{(\dot{m}_{rt} + \dot{m}_{lt})} \qquad (8\text{-}12)$$

8.3.16 Equation 8-13 is obtained by substituting Equation 8-9 and Equation 8-11 into Equation 8-12. Then Equation 8-14 is obtained by simplifying the denominator of Equation 8-13.

$$C_{suut} = \left\{ \frac{\dot{m}_{rf}\left(\frac{C_f}{1-C_f}\right) + C_s \dot{m}_{rls}}{\dot{m}_{rf}\left(1 + \left(\frac{C_f}{1-C_f}\right)\right) + \dot{m}_{rls}} \right\} \qquad (8\text{-}13)$$

$$C_{suut} = \left\{ \frac{\dot{m}_{rf}\left(\frac{C_f}{1-C_f}\right)+C_s\dot{m}_{rls}}{\dot{m}_{rf}\left(\frac{1}{1-C_f}\right)+\dot{m}_{rls}} \right\} \tag{8-14}$$

9. UNCERTAINTY REQUIREMENTS

9.1 Post-Test Uncertainty Analysis. A post-test analysis of the measurement system uncertainty, performed in accordance with ANSI/ASME PTC 19.1[1], shall accompany each refrigerant mass flow rate measurement if specified in the test plan in Section 5.1. Installation effects on the accuracy of the instrument shall be included in the uncertainty analysis for each installation that does not conform to the instrument manufacturer's installation requirements.

(***Informative Note:*** Informative Appendix B contains an example of uncertainty calculations.)

9.2 Method to Express Uncertainty. Assumptions, parameters, and calculations used in estimating uncertainty shall be clearly documented prior to expressing any uncertainty values. Uncertainty shall be expressed as shown in Equation 9-1.

$$v = \bar{X}_m \pm U_{\bar{X}}\ (P\%) \tag{9-1}$$

where:

v = the variable that is a measurement or a calculated result
$\bar{X}_m$ = the best estimate of the true value
$U_{\bar{X}}$ = the uncertainty estimate for the variable
P = the confidence level, percent

(***Informative Note:*** For example: refrigerant mass flow rate = 2.538 kg/s ± 0.013 kg/s (5.595 $\mathrm{lb_m}$/s ± 0.029 $\mathrm{lb_m}$/s); 95% states that the measured refrigerant mass flow rate is believed to be 2.538 kg/s (5.595 $\mathrm{lb_m}$/s) with a 95% probability that the true value lies within ±0.013 kg/s (±0.029 $\mathrm{lb_m}$/s) of this value.)

10. TEST REPORT

If the test plan in Section 5.1 defines the test report requirements, the test report requirements in the test plan supersedes all the requirements in Section 10. Otherwise, Section 10 specifies the test report requirements.

10.1 Test Identification

a. Date, place, and time.
b. Operator.

10.2 Unit Under Test Description

a. Model number and serial number.
b. Refrigerant number.
c. Source of refrigerant thermodynamic and transport property data.
d. Lubricant description.

10.3 Instrument Description

a. Flowmeter description, model number, serial number, and location within the UUT.
b. Operating range.
c. Gaseous phase, liquid phase, or supercritical phase flowmeter.
d. Instrument accuracy based on specifications or calibration.

e. Documentational evidence of instrument calibrations.

10.4 Measurement System Description

a. Description of instrument installation specifics.
b. Measurement system accuracy based on specifications or calibration.
c. Documentational evidence of measurement system calibrations.

10.5 Test Conditions

a. Test conditions in accordance with the test plan in Section 5.1.
b. Ambient temperature, ºC (ºF).
c. Barometric pressure if pressures instruments are measuring gauge pressure, Pa, (psia)

10.6 Test Results. Test results are:

a. Refrigerant volumetric flow rate, m^3/s (ft^3/s)
b. Refrigerant volumetric flow rate pretest uncertainty, m^3/s (ft^3/s)
c. Refrigerant volumetric flow rate post-test uncertainty, m^3/s (ft^3/s)
d. Refrigerant mass flow rate if specified in the test plan in Section 5.1, kg/s (lb_m/h).
e. Refrigerant mass flow rate pretest uncertainty if specified in the test plan in Section 5.1, kg/s (lb_m/h).
f. Refrigerant mass flow rate post-test uncertainty, kg/s (lb_m/h) if specified in the test plan in Section 5.1, kg/s (lb_m/h).
g. Lubricant circulation rate through the flowmeter if required in Section 5.3.5.2, dimensionless.

11. REFERENCES

1. ANSIASME PTC 19.1-2018, *Test Uncertainty*. ANSI/ASME, New York, NY
2. ANSI/ASHRAE Standard 41.4-2015, *Standard Methods for Measurement of Proportion of Lubricant in Refrigerant*. Atlanta: ASHRAE. See Note 1.
3. NIST Standard Reference Database 23: *NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP) Version 10*, National Institute of Standards and Technology, Gaithersburg, MD.
4. ANSI/ASHRAE Standard 41.11-2023, *Standard Methods for Power Measurement. Atlanta: ASHRAE*. See Note 2.
5. ANSI/ASHRAE Standard 41.1-2020, *Standard Methods for Temperature Measurement*. Atlanta: ASHRAE. See Note 3.
6. ANSI/ASHRAE Standard 41.3-2022, *Standard Methods for Pressure Measurement*. Atlanta: ASHRAE. See Note 4.
7. ANSIASME PTC 19.5-2004 (R2013), *Flow Measurement*. ANSI/ASME, New York, NY. See Note 5.
8. ANSI/ASME MFC-3M-2004 (R2017), *Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi*. ANSI/ASME, New York, NY. See Note 5.
9. Bohanon, H. R., *Fan Single- or multiple-nozzle chamber-Nozzle Coefficients*, ASHRAE Transactions No. 2334:104–122. See Note 6.
10. ANSI/ASHRAE 41.8-2016 (RA 2019), *Standard Methods for Flow Measurement*. Atlanta: ASHRAE. See Note 6.

(Informative Notes:

1. Reference 2 is not required if a lubricant circulation measurement is not required.
2. Reference 4 is not required unless power measurements are required by the test plan in Section 5.1.

3. Reference 5 is not required if there are no temperature measurements.
4. Reference 6 is not required if there are no pressure measurements.
5. References 7, 8, and 9 are only required if an orifice flowmeter, a nozzle flowmeter, or a venturi tube flowmeter is the selected test method in Section 7.
6. Reference 10 is only required if an auxiliary lubricant separator is used.)

(This appendix is not part of this standard. It is merely informative and does not contain requirements necessary for conformance to the standard. It has not been processed according to the ANSI requirements for a standard and may contain material that has not been subject to public review or a consensus process. Unresolved objectors on informative material are not offered the right to appeal at ASHRAE or ANSI.)

INFORMATIVE APPENDIX A: BIBLIOGRAPHY

A1. Kelley, Jeffrey D., and Hedengren, John D., "A Steady-State Detection (SSD) Algorithm to Detect Non-Stationary Drifts in Processes," BYU Scholars Archive, 2013.
A2. Miller, Steven J., The Method of Least Squares, Brown University, 2006.
A3. ANSI/ASME MFC-11-2006 (RA2014)*, Measurement of Fluid Flow by Means of Coriolis Mass Flowmeters.* ANSI/ASME, New York, NY.
A4. ANSI/ASME MFC-4M-1986 (RA2016)*, Measurement of Gas by Turbine Meters.* ANSI/ASME, New York, NY.
A5. ANSI/ASME MFC-18M-2001, *Measurement of Fluid Flow Using Variable Area Meters.* ANSI/ASME, New York, NY.
A6. ANSI/ANSI/ASME MFC-5.1-2011*, Measurement of Refrigerant Flow in Closed Conduits Using Transient-Time Ultrasonic Flowmeter.* ANSI/ASME, New York, NY.
A7. ANSI/ASME MFC-5.3, *Measurements of Refrigerant Flow in Closed Conduits Using Doppler Ultrasonic Flowmeters*. ANSI/ASME, New York, NY.
A8. ANSI/ASME MFC-6M-2013 *Measurement of Fluid Flow in Pipes Using Vortex Flow Meters.* ANSI/ASME, New York, NY.
A9. Doebelin, E. O., *Measurement Systems - Application and Design,* Fifth Edition. 2004. McGraw-Hill Book Company.

(This appendix is not part of this standard. It is merely informative and does not contain requirements necessary for conformance to the standard. It has not been processed according to the ANSI requirements for a standard and may contain material that has not been subject to public review or a consensus process. Unresolved objectors on informative material are not offered the right to appeal at ASHRAE or ANSI.)

INFORMATIVE APPENDIX B:
AN UNCERTAINTY ANALYSIS EXAMPLE FOR A DIFFERENTIAL PRESSURE FLOWMETER

Following ANSI/ASME PTC 19.1-2018 - *Test Uncertainty* procedures and terminology, estimate the uncertainty interval, at 95% confidence, about the measured result of a long-radius flow nozzle. Because long-radius flow nozzles require measurements followed by calculations to produce mass flow rate results, Section 5, *Uncertainty of a Measurement,* will be followed to determine individual measurement uncertainty that is fed into Section 6, *Uncertainty of a Result Calculated from Multiple Parameters*, for use in determining uncertainty propagation producing a final uncertainty estimate for the mass flow rate. Assume the long-radius flow nozzle is installed in compliance with Section 7.4.2 of this standard and output signals are appropriately conditioned to be read by a data acquisition system. R410A is the working fluid and the product application is a residential air-conditioning system. The uncertainty estimate is to be determined for a given differential pressure within the instrument operating range. Reported uncertainty units are kg/s (lb_m/s).

7.3.2.5 Nozzle Liquid Phase or Supercritical Phase Refrigerant Inlet Density. The nozzle liquid phase or supercritical phase refrigerant inlet density ρ shall be obtained from the refrigerant property data prescribed in Section 5.3.11 as a function of the nozzle inlet temperature t_1 and pressure p_1 at each data point.

7.3.2.6 Nozzle Liquid Phase or Supercritical Phase Volumetric Flow Rates. Nozzle liquid phase or supercritical phase volumetric flow rates shall be calculated from Equation 7-4 in SI units or Equation 7-5 in I-P units.

In SI units: A

$$Q = CAK_1\sqrt{\frac{2(\Delta p)}{\rho(1-\beta^4)}} \tag{7-4}$$

where

Q = nozzle liquid phase volumetric flow rate, m^3/s
C = nozzle discharge coefficient, dimensionless
A = nozzle throat area, m^2
K_1 = nozzle calibration coefficient, dimensionless
ρ = nozzle inlet liquid phase density, kg/m^3
Δp = nozzle differential pressure, Pa
β = d/D, dimensionless

In I-P units:

$$Q = 0.47268 \times CAK_1\sqrt{\frac{2(\Delta p)}{\rho(1-\beta^4)}} \tag{7-5}$$

where

Q = nozzle liquid phase volumetric flow rate, cfs
C = nozzle discharge coefficient, dimensionless
A = nozzle throat area, in^2
K_1 = nozzle calibration coefficient, dimensionless
ρ = nozzle inlet liquid phase density, $\text{lb}_\text{m}/\text{ft}^3$
Δp = nozzle differential pressure, psid
β = d/D, dimensionless
0.47268= units conversion coefficient, $\sqrt{\frac{(lb_m - ft^3)}{(psid - in^4 - s^2)}}$

7.3.2.8 Nozzle Liquid Phase or Supercritical Phase Refrigerant Mass Flow Rates. The nozzle liquid phase or supercritical phase refrigerant mass flow rate shall be obtained from Equation 7-7, where ρ is the nozzle liquid phase or supercritical phase inlet refrigerant density, kg/m^3 ($\text{lb}_\text{m}/\text{ft}^3$) and Q is the liquid phase or supercritical phase refrigerant volumetric flow rate, m^3/s (ft^3/s) using Equation 7-4 in SI units or Equation 7-5 in I-P units.

$$\dot{m} = \rho Q, \text{ kg/s (lb}_\text{m}\text{/s)} \tag{7-7}$$

Table B-1. Independent Parameters Descriptions

Symbol	Independent Parameter	Nominal Value	Expected Range	Initial Selected Instrument
d	Nozzle Throat Diameter	20.32 mm (0.80 in)	10 to 30 mm (0.394 to 1.181in.)	Inside Diameter Micrometer
D	Pipe Diameter	49.276 mm (1.940 in.)	48.768 to 49.530 mm (1.920 to 1.950in.)	Inside Diameter Micrometer
t_1	Inlet Liquid Temperature	36.1°C (97°F)	32.2 to 43.3 °C (90 to 110°F)	Type T thermocouple
p_1	Inlet Liquid Pressure	2206 kPa (320 psia)	2068 to 2758 kPa (300 to 400 psia)	Strain Gage Pressure Transducer
ΔP	Nozzle Pressure Drop	35.85 kPa (5.2 psid)	34.5 to 172.4 kPa (5.00 to 25.00) psid	Strain Gage Differential Pressure Transducer
C	Discharge Coefficient	0.995 dimensionless	Not applicable	Calibration from an ISO 17025 Certified Lab

Table B-2. Relationship of the Calculated Parameters

Symbol	Calculated Parameter	Functional Relation	Functional Calculation	Nominal Value
A	Nozzle Throat Area	$f(d)$	$= \pi d^2/4$	0.0003243 m^2 (0.503 in^2)
β	Nozzle Ratio	$f(d, D)$	$= d/D$	0.4124 dimensionless
p_2	Absolute Throat Pressure	$f(p_1, \Delta P)$	$= p_1 - \Delta P$	2170 kPa (314.8 psia)
ρ	Nozzle Inlet Liquid Density	$f(p_1, t_1)$	None: Property Data	998.6 kg/m^3 (62.34 lb$_m$/ft^3)

Table B-3. Uncertainty of Each Measured Parameter

Parameter	Nominal Random Value	Error Origin	Calibration Error		Data Acquisition Error		Data Reduction Error	
			Elemental Systematic Standard Uncertainty	Elemental Random Standard Uncertainty	Elemental Systematic Standard Uncertainty	Elemental Random Standard Uncertainty	Elemental Systematic Standard Uncertainty	Elemental Random Standard Uncertainty
d, mm (in)	20.32 (0.80)	See Note 1 below	0.0305 (0.0012)	0	0	0	0	0
D, mm (in)	49.276 (1.940)	See Note 1 below	0.0508 (0.002)	0	0	0	0	0
t_1, °C (°F)	36.1 (97)	Calibration	0.2389 (0.4299)	0.0345 (0.0621)	0	0	0	0
		Ice Reference Junction	0	0	0.1638 (0.2948)	0.0689 (0.1241)	0	0
		Data Acquisition	0	0	0.2056 (0.3701)	0.0542 (0.0975)	0	0
		Data Reduction/ Curve Fit	0	0	0	0	0.0751 (0.1352)	0.0111 (0.0199)
p_1, kPa (psia)	2206 (320)	Excitation Voltage	0.0039 (0.00056)	0.0027 (0.00039)	0	0	0	0
		Signal Conditioning	0.0666 (0.0097)	0.0240 (0.0035)	0	0	0	0
		Calibration	16.0142 (2.3227)	0.0159 (0.0023)	0	0	0	0
		Data Acquisition	0	0	0.1068 (0.0155)	0.1336 (0.0194)	0	0
		Data Reduction/ Curve Fit	0	0	0	0	0.0321 (0.0047)	0
ΔP, kPa (psid)	2170 (314.8)	Excitation Voltage	0.0054 (0.00078)	0.00073 (0.00011)	0	0	0	0
		Signal Conditioning	0.0394 (0.0057)	0.0025 (0.00036)	0	0	0	
		Calibration	0.2151 (0.0312)	0.0072 (0.00104)	0	0	0	
		Data Acquisition	0	0	0.0226 (0.0033)	0.0861 (0.0125)	0	
		Data Reduction/ Curve Fit	0	0	0	0	0.0538 (0.0078)	

C, dimensionless	0.995	Uncertainty from an ISO17025 lab calibration	0.0025	0	0	0	0	0

Note 1 – Because this meter was calibrated, error effects in the throat and pipe diameters are eliminated provided the same dimensions used during the calibration are also used in the test calculations and they have not changed due to damage such as erosion. Calibration systematic uncertainties included to allow calculation of the systematic standard uncertainties.

Note 2 – Nominal random values in Table B-3 are the results of ten (10) readings for each parameter. 30 readings would be required to be statistically significant, but users are likely to consider 30 readings to be a burden. 10 readings appear to be a reasonable compromise.

Estimation of the uncertainty interval, at 95% confidence, about the measured mass flow rate of a differential pressure flowmeter is done following a five-step procedure based on ANSI/ASME PTC 19.1-2018 - *Test Uncertainty*. Each step is detailed using SI units and I-P units.

B1. Calculate the Random and Systematic Standard Uncertainties for Each Parameter

For each parameter in Equation 7-7, the random and systematic standard uncertainties must be first calculated. Following ANSI/ASME PTC 19.1-2018 - *Test Uncertainty*, these uncertainties are respectively given as follows:

$$s_{\bar{X}} = \pm \frac{1}{\sqrt{N}} \sqrt{\sum_{k=1}^{K} (s_{\bar{X}_k})^2} \qquad \text{(B-1)}$$

$$b_{\bar{X}} = \pm \sqrt{\sum_{k=1}^{K} (b_{\bar{X}_k})^2} \qquad \text{(B-2)}$$

where $\bar{X}$ represents a parameter, $K$is the total number of elemental uncertainty sources for a given parameter, N is the number of readings, $s_{\bar{X}_k}$ is an elemental random standard uncertainty and $b_{\bar{X}_k}$ is an elemental systematic standard uncertainty. Numerical values of $s_{\bar{X}}$ and $b_{\bar{X}}$ are calculated in the next two sections using elemental standard uncertainties from Table B-3. Calculated values are presented with three significant figures after the decimal point; the exact values are used in calculations. The random and systematic standard uncertainties for t_1 and p_1 are calculated for later estimation of the uncertainty of the inlet liquid phase density only.

B1.1 SI Units

Using Equations B-1 and B-2, and Table B-3, the following random and systematic standard uncertainties are calculated for each parameter:

$s_d = 0.000$ m $b_d = 3.05 \times 10^{-5}$ m
$s_D = 0.000$ m $b_D = 5.08 \times 10^{-5}$ m
$s_{t_1} = 0.0300$ °C $b_{t_1} = 0.363$ °C
$s_{p_1} = 43.210$ Pa $b_{p_1} = 16{,}014.685$ Pa
$s_{\Delta P} = 27.318$ Pa $b_{\Delta P} = 226.384$ Pa
$s_C = 0.000$ $b_C = 0.00250$

B1.2 I-P Units

Using Equations B-1 and B-2, and Table B-3, the following random and systematic standard uncertainties are calculated for each parameter:

$s_d = 0.000$ in.	b_d = 0.00120 in.
$s_D = 0.000$ in.	b_D = 0.00200 in.
s_{t_1} = 0.0540 °F	b_{t_1} = 0.653 °F
s_{p_1} = 0.00630 psia	b_{p_1} = 2.3227 psia
$s_{\Delta P}$ = 0.00400 psid	$b_{\Delta P}$ = 0.0328 psid
$s_C = 0.000$	$b_C = 0.00250$

B2. Calculate the Random and Systematic Standard Uncertainties of the Working Fluid Density

The random and systematic standard uncertainties for ρ cannot be calculated directly from Table B-3 unlike the other parameters in Equation 7-7. However, the random and systematic standard uncertainties were calculated for state variables t_1 and p_1 and will be used here to calculate the random and systematic standard uncertainties of ρ. Extremum values of t_1 and p_1 within a 95% confidence interval must be calculated to estimate extremum values of ρ, which are then used to estimate the random and systematic standard uncertainties of ρ. In order to determine the 95% confidence interval of t_1 and p_1, the combined and expanded uncertainties are calculated. These uncertainties are respectively given as follows:

$$u_{\bar{X}} = \pm\sqrt{(s_{\bar{X}})^2 + (b_{\bar{X}})^2} \quad \text{(B-3)}$$

$$U_{\bar{X}} = k \times u_{\bar{X}} \quad \text{(B-4)}$$

where k is the coverage factor. The coverage factor value is selected based on the appropriate degrees of freedom and confidence level in the Student's t table – see ANSI/ASME PTC 19.1-2018 - *Test Uncertainty* Annex B. The degree of freedom used is a combined degree of freedom on the separate degree of freedom for the random standard uncertainties and the elemental systematic standard uncertainties. If the degrees of freedom for the random standard uncertainties and the elemental systematic standard uncertainties are known or estimated, one can refer to ANSI/ASME PTC 19.1-2018 - *Test Uncertainty* Annex B to calculate the exact degree of freedom. In most engineering applications, a coverage factor of 2 is used for 95% confidence intervals, assuming a large degrees of freedom.

B2.1 SI Units

Assuming a large degree of freedom and using the previously calculated random and systematic standard uncertainties of t_1 and p_1, the expanded uncertainties are:

U_{t_1} = 0.729 °C
U_{p_1} = 32,029.487 Pa

The extreme values of t_1 and p_1 and the corresponding values of ρ are presented in Table B-4.1.

Table B-4.1. Liquid phase density extreme values – SI units

	Minimum value	**Maximum value**
t_1 (°C)	95.857	98.103
p_1 (kPa)	312.987	326.920
ρ (kg/m^3)	62.121	62.577

Based on previous experience, the variations for ρ is assumed to be entirely systematic errors. Using Equation B-3 and defining half the difference between ρ extremums as equal to the expanded uncertainty, the random and systematic standard uncertainties are:

s_ρ = 0.000 kg/m^3
b_ρ = 0.700 kg/m^3

B2.2 I-P Units

Assuming a large degree of freedom and using the previously calculated random and systematic standard uncertainties of t_1 and p_1, the expanded uncertainties are:
U_{t_1} = 1.311 °F
U_{p_1} = 4.646 psia

The extreme values of t_1 and p_1 and the corresponding values of ρ are presented in Table B-4.2.

Table B-4.2. Liquid phase density extreme values – I-P units

	Minimum value	**Maximum value**
t_1 (°F)	188.689	191.311
p_1 (psia)	208.704	217.996
ρ (lb$_m$/ft^3)	3.652	3.827

Based on previous experience, the variations for ρ is assumed to be entirely systematic errors. Using Equation B-3 and defining half the difference between ρ extremums as equal to the expanded uncertainty, the random and systematic standard uncertainties are:
s_ρ = 0.000 lb$_m$/ft^3
b_ρ = 0.0437 lb$_m$/ft^3

B3. Calculate and Evaluate the Partial Derivative of the Mass Flow Rate for Each Parameter

The random and systematic standard uncertainties of the mass flow rate are a non-linear combination of the random and systematic standard uncertainties of the parameters in Equation 7-7. The random and systematic standard uncertainties of the mass flow rate are respectively given as follows:

$$s_{\dot{m}} = \pm\sqrt{\sum_{i=1}^{l}\left(\theta_i s_{\bar{X}_i}\right)^2 + (random\ correlation\ terms)} \tag{B-5}$$

$$b_{\dot{m}} = \pm\sqrt{\sum_{i=1}^{l}\left(\theta_i b_{\bar{X}_i}\right)^2 + (systematic\ correlation\ terms)} \tag{B-6}$$

where θ_i is the evaluated partial derivative of $\dot{m}$ with respect to the ith parameter, l is the number of parameters in Equation 7-7, $s_{\bar{X}_i}$ and $b_{\bar{X}_i}$ are the corresponding random and systematic standard uncertainties of the ith parameter previously calculated in Sections B1.1 and B1.2. If necessary, correlation terms can be added for both the random and systematic standard uncertainty of the mass flow rate. These terms account for random and systematic standard uncertainties that are not independent of one another for a given parameter. If these terms are needed, one can refer to Section 7 of ANSI/ASME PTC 19.1-2018 - *Test Uncertainty* for the methodology. Explicitly, θ_i is expressed as follows:

$$\theta_i = \frac{\partial \dot{m}}{\partial \bar{X}_i} \tag{B-7}$$

Once calculated, the partial derivative is then evaluated considering the value of each parameter. In Equation 7-7, A must be expressed in terms of d, and β must be expressed in terms of d and D. Partial derivatives are calculated and evaluated in the next two sections. Note that, in general, using a commercial equation solver software, such as MATLAB or EES, significantly reduces the time and effort required to complete an uncertainty analysis.

Skip this section if you are using a commercial equation solver.

B3.1.1 Derive the Partial Derivative $\frac{\partial \dot{m}}{\partial d}$

$$Q = CAK_1\sqrt{\frac{2(\Delta P)}{\rho(1-E\beta^4)}} \tag{7-4}$$

where $A = \frac{\pi d^2}{4}$ and $\beta = \frac{d}{D}$

$$\dot{m} = \rho Q \tag{7-7}$$

Combining Equations 7-4 and 7-7 yields Equation B-8.

$$\dot{m} = \rho C\left(\frac{\pi d^2}{4}\right)K_1\sqrt{\frac{2(\Delta P)}{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}} \tag{B-8}$$

or $\dot{m} = \mathrm{A} \times \mathrm{B}$ where (B-9)

$$\mathrm{A} = C\left(\frac{\pi d^2}{4}\right)K_1\sqrt{2\Delta P\rho} \text{ and} \tag{B-10}$$

$$\mathrm{B} = \left(1 - E\left(\frac{d}{D}\right)^4\right)^{-\frac{1}{2}} = \left(1 - \mathrm{E}\frac{d^4}{D^4}\right)^{-\frac{1}{2}} \tag{B-11}$$

The derivative of $\dot{m}$ with respect to *d* can be solved by the product rule in Equation B-12.

$$\frac{\partial \dot{m}}{\partial d} = \mathrm{A}\frac{\partial \mathrm{B}}{\partial d} + \mathrm{B}\frac{\partial \mathrm{A}}{\partial d} \tag{B-12}$$

$$\frac{\partial \mathrm{A}}{\partial d} = 2C\left(\frac{\pi}{4}\right)K_1\sqrt{2\Delta P\rho}\, d \tag{B-13}$$

The partial derivative of B with respect to *d* is solved by the chain rule in Equation B-14.

$$\frac{\partial}{\partial x}[f(x)^n] = n[f(x)]^{n-1} \times \frac{\partial}{\partial x}[f(x)] \tag{B-14}$$

$$\frac{\partial \mathrm{B}}{\partial d} = -\frac{1}{2}\left(1 - \mathrm{E}\frac{d^4}{D^4}\right)^{-\frac{3}{2}}\left(-4E\frac{d^3}{D^4}\right) \tag{B-15}$$

Rearranging Equation B-15 yields Equation B-16.

$$\frac{\partial \mathrm{B}}{\partial d} = 2\left(1 - \mathrm{E}\frac{d^4}{D^4}\right)^{-\frac{3}{2}}\left(E\frac{d^3}{D^4}\right) \tag{B-16}$$

The next step is to combine Equations B-10, B-11, B-13 and B-16 into Equation B-17.

$$\frac{\partial \dot{m}}{\partial d} = C\left(\frac{\pi d^2}{4}\right)K_1\sqrt{2\Delta P\rho}\, d^2 2\left(1 - \mathrm{E}\frac{d^4}{D^4}\right)^{-\frac{3}{2}}\left(E\frac{d^3}{D^4}\right) + \left(1 - \mathrm{E}\frac{d^4}{D^4}\right)^{-\frac{1}{2}} 2C\left(\frac{\pi}{4}\right)K_1\sqrt{2\Delta P\rho}\, d \tag{B-17}$$

Simplifying Equation B-17 yields Equation B-18.

$$\frac{\partial \dot{m}}{\partial d} = \frac{1}{2}C\pi K_1\sqrt{2\Delta P\rho}\left[\left(d^5\frac{E}{D^4}\right)\left(1 - \mathrm{E}\frac{d^4}{D^4}\right)^{-\frac{3}{2}} + d\left(1 - \mathrm{E}\frac{d^4}{D^4}\right)^{-\frac{1}{2}}\right] \tag{B-18}$$

The solution to the partial derivative $\frac{\partial \dot{m}}{\partial d}$ is shown in Equation B-18. Equations B-20 through B-26 show how Equation B-18 is equivalent to the form of the solution obtained by an equation-solving software program that is shown in Equation B-19.

$$\frac{\partial \dot{m}}{\partial d} = \frac{1}{2}\left(\sqrt{2}CK_1 d\pi\sqrt{\frac{-\Delta P\rho}{\left(\frac{Ed^4}{D^4}-1\right)}}\right) + \frac{\sqrt{2}CEK_1\Delta Pd^5\rho\pi}{\left(2D^4\left(\frac{Ed^4}{D^4}-1\right)^2\times\sqrt{\frac{-\Delta P\rho}{\left(\frac{Ed^4}{D^4}-1\right)}}\right)} \tag{B-19}$$

Expressing the second term in Equation B-18 in a different form proceeds sequentially as shown in Equations B-20, B-21, and B-22 to equal the first term in Equation B-19.

$$\frac{1}{2}C\pi K_1\sqrt{2\Delta P\rho}\left(1-E\left(\frac{d^4}{D^4}\right)\right)^{-\frac{1}{2}}d \tag{B-20}$$

$$\frac{1}{2}\sqrt{2}CK_1 d\pi\frac{\sqrt{\Delta P\rho}}{\sqrt{1-E\left(\frac{d^4}{D^4}\right)}} \tag{B-21}$$

$$\frac{1}{2}\sqrt{2}CK_1 d\pi\frac{\sqrt{-\Delta P\rho}}{\sqrt{E\left(\frac{d^4}{D^4}\right)-1}} \tag{B-22}$$

Expressing the first term in Equation B-18 in a different form proceeds sequentially as shown in Equations B-23, B-24, and B-25 to equal the second term in Equation B-19.

$$\frac{1}{2}C\pi K_1\sqrt{2\Delta P\rho}\left(d^5\frac{E}{D^4}\right)\left(1-E\left(\frac{d^4}{D^4}\right)\right)^{-\frac{3}{2}}\times\frac{\sqrt{\Delta P\rho}}{\sqrt{\Delta P\rho}}\times\frac{\sqrt{1-E\left(\frac{d^4}{D^4}\right)}}{\sqrt{1-E\left(\frac{d^4}{D^4}\right)}} \tag{B-23}$$

$$\frac{\sqrt{2}CEK_1\Delta Pd^5\rho\pi}{2D^4\left(1-E\left(\frac{d^4}{D^4}\right)\right)^2\times\sqrt{\frac{\Delta P\rho}{1-E\left(\frac{d^4}{D^4}\right)}}} \tag{B-24}$$

$$\frac{\sqrt{2}CEK_1\Delta Pd^5\rho\pi}{2D^4\left(1-E\left(\frac{d^4}{D^4}\right)\right)^2\times\sqrt{\frac{-\Delta p\rho}{E\left(\frac{d^4}{D^4}\right)-1}}} \tag{B-25}$$

Because $\left(1-E\left(\frac{d^4}{D^4}\right)\right)^2 = \left(E\left(\frac{d^4}{D^4}\right)-1\right)^2$, Equation B-25 equals the second term in Equation B-26.

Therefore, the partial derivative $\frac{\partial \dot{m}}{\partial d}$ is shown in Equation B-26.

$$\frac{\partial \dot{m}}{\partial d} = \frac{1}{2}\left(\sqrt{2}CK_1 d\pi\sqrt{\frac{-\Delta P\rho}{\frac{Ed^4}{D^4}-1}}\right) + \frac{\sqrt{2}CEK_1\Delta Pd^5\rho\pi}{\left(2D^4\left(\frac{Ed^4}{D^4}-1\right)^2\times\sqrt{\frac{-\Delta P\rho}{\frac{Ed^4}{D^4}-1}}\right)} \tag{B-26}$$

B3.1.2 Derive the Partial Derivative $\frac{\partial \dot{m}}{\partial D}$

Combining Equations 7-4 and 7-7 yields Equation B-27.

$$\dot{m} = \rho C\left(\frac{\pi d^2}{4}\right)K_1\sqrt{\frac{2\Delta P}{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}} \tag{B-27}$$

Define A = $\sqrt{2\Delta P\rho}\,C\left(\frac{\pi d^2}{4}\right)K_1$ and B = $\left(1-E\left(\frac{d}{D}\right)^4\right)^{-\frac{1}{2}}$ then $\frac{\partial \dot{m}}{\partial D} = \mathrm{A}\frac{\partial B}{\partial D} + \mathrm{B}\frac{\partial A}{\partial D}$ (B-28)

Because there is no D in A then $\frac{\partial A}{\partial D} = 0$. Therefore, $\frac{\partial \dot{m}}{\partial D} = \mathrm{A}\frac{\partial B}{\partial D}$ (B-29)

Use the chain rule for $\frac{\partial B}{\partial D}$ where $\frac{d}{dx}[f(x)^n] = n[f(x)]^{n-1} \times \frac{d}{dx}[f(x)]$ (B-30)

$$\frac{\partial \dot{m}}{\partial D} = \sqrt{2\Delta P\rho}\, C\left(\frac{\pi d^2}{4}\right)K_1 \times -\left(\frac{1}{2}\right)\left(1 - \mathrm{E}\left(\frac{d^4}{D^4}\right)\right)^{-\frac{3}{2}} \times (-4)Ed^4D^{-5} \qquad \text{(B-31)}$$

Rearranging Equation B-31 yields Equation B-32.

$$\frac{\partial \dot{m}}{\partial D} = -\frac{\sqrt{2\Delta P\rho}CEK_1d^6\pi}{\left[2\left(1-\mathrm{E}\left(\frac{d^4}{D^4}\right)\right)^{\frac{3}{2}}D^5\right]} \qquad \text{(B-32)}$$

Equation B-32 is the solution to the partial derivative $\frac{\partial \dot{m}}{\partial D}$. Equations B-34 and B-35 show how Equation B-32 is equivalent to the form of the solution obtained by an equation-solving software program that is shown in Equation B-33.

$$\frac{\partial \dot{m}}{\partial D} = \frac{-\sqrt{2}CEK_1\Delta Pd^6\rho\pi}{\left[2D^5\left(E\frac{d^4}{D^4}-1\right)^2 \times \sqrt{\frac{-\Delta P\rho}{\left(E\frac{d^4}{D^4}-1\right)}}\right]} \qquad \text{(B-33)}$$

Multiply Equation B-32 by two constants that both equal one to get Equation B-34.

$$\frac{\partial \dot{m}}{\partial D} = -\frac{\sqrt{2\Delta P\rho}CEK_1d^6\pi}{\left[2\left(1-\mathrm{E}\left(\frac{d^4}{D^4}\right)\right)^{\frac{3}{2}}D^5\right]} \times \frac{\sqrt{\Delta P\rho}}{\sqrt{\Delta P\rho}} \times \sqrt{\frac{\left(1-\mathrm{E}\left(\frac{d^4}{D^4}\right)\right)}{\left(1-\mathrm{E}\left(\frac{d^4}{D^4}\right)\right)}} \qquad \text{(B-34)}$$

Combining and rearranging terms in Equation B-34 yields Equation B-35.

$$\frac{\partial \dot{m}}{\partial D} = \frac{-\sqrt{2}CEK_1\Delta Pd^6\rho\pi}{\left[2D^5\left(E\frac{d^4}{D^4}-1\right)^2 \times \sqrt{\frac{-\Delta P\rho}{\left(E\frac{d^4}{D^4}-1\right)}}\right]} \qquad \text{(B-35)}$$

B3.1.3 Derive the Partial Derivative $\frac{\partial \dot{m}}{\partial C}$

Combining Equations 7-4 and 7-7 yields Equation B-36.

$$\dot{m} = \rho C\left(\frac{\pi d^2}{4}\right)K_1\sqrt{\frac{2\Delta P}{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}} \qquad \text{(B-36)}$$

$$\frac{\partial \dot{m}}{\partial C} = \frac{\rho\pi d^2K_1}{4}\sqrt{\frac{2\Delta P}{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}} \qquad \text{(B-37)}$$

Rearranging terms in Equation B-37 yields Equation B-38.

$$\frac{\partial \dot{m}}{\partial C} = \frac{\sqrt{2}\pi d^2K_1}{4}\sqrt{\frac{-\Delta P\rho}{\left(E\frac{d^4}{D^4}-1\right)}} \qquad \text{(B-38)}$$

Equation B-38 is the solution to the partial derivative $\frac{\partial \dot{m}}{\partial C}$. Equations B-38 exactly matches the solution obtained by an equation-solving software program that is shown in Equation B-39.

$$\frac{\partial \dot{m}}{\partial C} = \frac{\sqrt{2}\pi d^2 K_1}{4}\sqrt{\frac{-\Delta P \rho}{\left(E\frac{d^4}{D^4}-1\right)}} \tag{B-39}$$

B3.1.4 Derive the Partial Derivative $\frac{\partial \dot{m}}{\partial \rho}$

Combining Equations 7-4 and 7-7 yields Equation B-40.

$$\dot{m} = \rho C\left(\frac{\pi d^2}{4}\right)K_1\sqrt{\frac{2\Delta P}{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}} \tag{B-40}$$

Isolating the ρ terms in Equation B-40 yields Equation B-41.

$$\dot{m} = \frac{\rho^{\frac{1}{2}}C\pi d^2 K_1}{4}\sqrt{\frac{2\Delta P}{\left(1-E\left(\frac{d}{D}\right)^4\right)}} \tag{B-41}$$

Then it follows that the $\frac{\partial \dot{m}}{\partial \rho}$ is as shown Equation B-42.

$$\frac{\partial \dot{m}}{\partial \rho} = \frac{\frac{1}{2}\rho^{-\frac{1}{2}}C\pi d^2 K_1}{4}\sqrt{\frac{2\Delta P}{\left(1-E\left(\frac{d}{D}\right)^4\right)}} \tag{B-42}$$

Equation B-42 is the solution to the partial derivative $\frac{\partial \dot{m}}{\partial \rho}$. Equations B-44 through B-46 show how Equation B-42 is equivalent to the solution provided by an equation-solving software package that is shown in Equation B-43.

$$\frac{\partial \dot{m}}{\partial \rho} = -\frac{\sqrt{2}\Delta P C\pi d^2 K_1}{8\left(E\frac{d^4}{D^4}-1\right)\sqrt{\frac{-\rho\Delta P}{\left(E\frac{d^4}{D^4}-1\right)}}} \tag{B-43}$$

Rearranging terms in Equation B-42 leads first to Equation B-44 and then to Equation B-45 and then to Equation B-46.

$$\frac{\partial \dot{m}}{\partial \rho} = \frac{\sqrt{2}C\pi d^2 K_1}{8}\sqrt{\frac{\Delta P}{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}} \times \frac{\sqrt{\Delta P}}{\sqrt{\Delta P}} = \frac{\sqrt{2}\Delta P C\pi d^2 K_1}{8\sqrt{\rho\Delta P\left(1-E\left(\frac{d}{D}\right)^4\right)}} \tag{B-44}$$

$$\frac{\partial \dot{m}}{\partial \rho} = \frac{\sqrt{2}\Delta P C\pi d^2 K_1}{8\sqrt{\rho\Delta P\left(1-E\left(\frac{d}{D}\right)^4\right)}} \times \left(\frac{-1}{\sqrt{-1}\times\sqrt{-1}}\right) \times \frac{1}{\frac{\sqrt{\left(E\frac{d^4}{D^4}-1\right)}}{\sqrt{\left(E\frac{d^4}{D^4}-1\right)}}} \tag{B-45}$$

$$\frac{\partial \dot{m}}{\partial \rho} = -\frac{\sqrt{2}\Delta P C\pi d^2 K_1}{8\left(E\frac{d^4}{D^4}-1\right)\sqrt{\frac{-\rho\Delta P}{\left(E\frac{d^4}{D^4}-1\right)}}} \tag{B-46}$$

B3.1.5 Derive the Partial Derivative $\frac{\partial \dot{m}}{\partial \Delta P}$

Combining Equations 7-4 and 7-7 yields Equation B-47, that can be rearranged as shown in Equation B-48.

$$\dot{m} = \rho C\left(\frac{\pi d^2}{4}\right)K_1\sqrt{\frac{2\Delta P}{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}} \tag{B-47}$$

$$\dot{m} = \frac{\sqrt{2}C\pi\rho d^2 K_1}{4\sqrt{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}}(\Delta P)^{\frac{1}{2}} \tag{B-48}$$

$$\frac{\partial \dot{m}}{\partial \Delta P} = \frac{1}{2}\frac{\sqrt{2}C\pi\rho d^2 K_1}{4\sqrt{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}}(\Delta P)^{-\frac{1}{2}} = \frac{\sqrt{2}C\pi\rho d^2 K_1(\Delta P)^{-\frac{1}{2}}}{8\sqrt{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}} \qquad \text{(B-49)}$$

Equation B-49 is the solution to the partial derivative $\frac{\partial \dot{m}}{\partial \Delta P}$. Equation B-50 shows how Equation B-49 is equivalent to the solution provided by an equation-solving software package that is shown in Equation B-51.

$$\frac{\partial \dot{m}}{\partial \Delta P} = \frac{\sqrt{2}C\pi\rho d^2 K_1(\Delta P)^{-\frac{1}{2}}}{8\sqrt{\rho\left(1-E\left(\frac{d}{D}\right)^4\right)}} \qquad \text{(B-50)}$$

Multiplying Equation B-50 by $\frac{1}{\sqrt{\frac{\left(E\frac{d^4}{D^4}-1\right)}{\left(E\frac{d^4}{D^4}-1\right)}}}$ and by $\left(\frac{-1}{\sqrt{-1}\times\sqrt{-1}}\right)$ yields Equation B-51.

$$\frac{\partial \dot{m}}{\partial \Delta P} = \frac{-\sqrt{2}CK_1\rho d^2\pi}{8\left(E\frac{d^4}{D^4}-1\right)\sqrt{\frac{-\Delta P\rho}{\left(E\frac{d^4}{D^4}-1\right)}}} \qquad \text{(B-51)}$$

B3.2 Evaluation of Partial Derivatives in SI Units

$$\frac{\partial \dot{m}}{\partial d} = \frac{1}{2}\left(\sqrt{2}CK_1 d\pi\sqrt{\frac{-\Delta P\rho}{\frac{Ed^4}{D^4}-1}}\right) + \frac{\sqrt{2}CEK_1\Delta P d^5\rho\pi}{\left(2D^4\left(\frac{Ed^4}{D^4}-1\right)^2\times\sqrt{\frac{-\Delta P\rho}{\frac{Ed^4}{D^4}-1}}\right)} \qquad \text{(B-52)}$$

$$\frac{\partial \dot{m}}{\partial d} = 71.530 \text{ kg/(m-s)} \qquad \text{(B-53)}$$

$$\frac{\partial \dot{m}}{\partial D} = \frac{-\sqrt{2}CEK_1\Delta P d^6\rho\pi}{\left(2D^5\left(\frac{Ed^4}{D^4}-1\right)^2\times\sqrt{\frac{-\Delta P\rho}{\frac{Ed^4}{D^4}-1}}\right)} \qquad \text{(B-54)}$$

$$\frac{\partial \dot{m}}{\partial D} = -0.890 \text{ kg/(m-s)} \qquad \text{(B-55)}$$

$$\frac{\partial \dot{m}}{\partial C} = \frac{\sqrt{2}K_1 d^2\pi}{4}\sqrt{\frac{-\Delta P\rho}{\frac{Ed^4}{D^4}-1}} \qquad \text{(B-56)}$$

$$\frac{\partial \dot{m}}{\partial C} = 0.708 \text{ kg/s} \qquad \text{(B-57)}$$

$$\frac{\partial \dot{m}}{\partial \rho} = \frac{\sqrt{2}CK_1\Delta P d^2\pi}{\left(8\left(\frac{Ed^4}{D^4}-1\right)\times\sqrt{\frac{-\Delta P\rho}{\frac{Ed^4}{D^4}-1}}\right)} \qquad \text{(B-58)}$$

$$\frac{\partial \dot{m}}{\partial \rho} = 0.00590 \text{ m}^3\text{/s} \qquad \text{(B-59)}$$

$$\frac{\partial \dot{m}}{\partial \Delta P} = \frac{-\sqrt{2}CK_1\rho d^2\pi}{\left(8\left(\frac{Ed^4}{D^4}-1\right)\times\sqrt{\frac{-\Delta P\rho}{\frac{Ed^4}{D^4}-1}}\right)} \qquad \text{(B-60)}$$

$\frac{\partial \dot{m}}{\partial \Delta P} = 9.83 \times 10^{-6}$ kg/(Pa-s) (B-61)

B3.3 Evaluation of Partial Derivatives in I-P Units

The calculated partial derivatives in I-P units are the same as in SI units; however, a factor of 0.47268 must multiply each partial derivative for the correct unit conversion.

$\frac{\partial \dot{m}}{\partial d} = 4.006$ lb_m/(in-s) (B-62)
$\frac{\partial \dot{m}}{\partial D} = -0.050$ lb_m/(in-s) (B-63)
$\frac{\partial \dot{m}}{\partial C} = 1.562$ lb_m/s (B-64)
$\frac{\partial \dot{m}}{\partial \rho} = 0.208$ ft^3/s (B-65)
$\frac{\partial \dot{m}}{\partial \Delta P} = 0.149$ lb_m/(psid-s) (B-66)

B4. Calculate the Random and Systematic Standard Uncertainties of the Mass Flow Rate

Equations B-5 and B-6 are evaluated in the Sections B4.1 and B4.2.

B4.1 SI Units

$s_{\dot{m}} = 0.000269$ kg/s (B-67)
$b_{\dot{m}} = 0.00546$ kg/s (B-68)

B4.2 I-P Units

$s_{\dot{m}} = 0.000592$ lb_m/s (B-69)
$b_{\dot{m}} = 0.0120$ lb_m/s (B-70)

B5. Calculate the Combined and Expanded Uncertainties of the Mass Flow Rate

Equations B-3 and B-4 are evaluated for the mass flow rate in Sections B5.1 and B5.2. A large degree of freedom is considered ($k = 2$).

B5.1 SI Units

$u_{\dot{m}} = 0.00547$ kg/s (B-71)
$U_{\dot{m}} = 0.0109$ kg/s (B-72)

The mass flow rate, at 95% confidence level, is:
$\dot{m} = (0.7048 \pm 0.0109)$ kg/s (B-73)

B5.2 I-P Units

$u_{\dot{m}} = 0.0121$ lb_m/s (B-74)
$U_{\dot{m}} = 0.0241$ lb_m/s (B-75)

The mass flow rate, at 95% confidence level, is:
$\dot{m} = (1.5539 \pm 0.0241)$ lb_m/s (B-76)

(This appendix is not part of this standard. It is merely informative and does not contain requirements necessary for conformance to the standard. It has not been processed according to the ANSI requirements for a standard and may contain material that has not been subject to public review or a consensus process. Unresolved objectors on informative material are not offered the right to appeal at ASHRAE or ANSI.)

INFORMATIVE APPENDIX C:
PRESSURE COMPENSATION REQUIRED FOR AN ELEVATION DIFFERENCE

C1. Pressure Compensation Required for an Elevation Difference. Refrigerant in a connecting tube between the source of pressure and the measurement point creates a measurement error if the two points are not at the same elevation. Pressure measurements made above the source of pressure will be less than the source of pressure by a constant amount, while pressure measurements made below the source of pressure will be greater than the source of pressure by a constant amount. Apply Equation C-1 in SI units or Equation D-2 in I-P units to determine the value needed to compensate for this error.
In SI units:

$$P_c = \rho_l g \Delta y \tag{C-1}$$

where

P_c = pressure compensation, Pa
ρ_l = refrigerant density, kg/m^3
g = local gravitation constant, m/s^2
Δy = elevation difference between the measurement point and the source of pressure, m

In I-P units:

$$P_c = \rho_l \left(\frac{g}{g_c}\right) \Delta y \tag{C-2}$$

where

P_c = compensation pressure, psia
ρ_l = refrigerant density, lb$_m$/ft^3
g = local gravitational acceleration, ft/s^2
g_c = gravitational constant, 32.174 [(lb$_m$-ft)/(lb$_f$·s^2)]
Δy = elevation difference between the measurement point and the source of pressure, ft

Refrigerants will create a refrigerant column if the tubing ambient temperature is less than the saturation temperature of the fluid being measured even if the pressure is being measured on gas within the system.

C2. Example. Compressor discharge pressure in an R410a system is measured by a pressure transducer that is elevated 1.27 m (50 in.) above the source of pressure. The refrigerant saturation temperature is 41.2ºC (107ºF) and the ambient temperature is 35ºC (95ºF). The refrigerant density is 944 kg/m^3 (59 lb$_m$/ft^3).

Applying Equation C-2 results in a pressure compensation of 12 kPa (1.7 psia). Section D.1 states that pressure measurements made above the source of pressure will be less than the source pressure. If, for example, the measured pressure reading is 2.515 MPa (350 psig), the pressure at the source is 2.526 MPa (351.7 psig).

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INFORMATIVE APPENDIX D
FLOWMETER ACCURACY COMPARISONS

Table D-1 provides examples of the accuracy of commercial refrigerant flowmeters for comparison purposes.

TABLE D-1 Examples of commercial refrigerant flowmeter accuracies for comparison purposes

Refrigerant Flow Measurement Method	Refrigerant Gas Phase Flow Measurement Accuracy	Refrigerant Liquid Phase Flow Measurement Accuracy	Refrigerant Supercritical Phase Flow Measurement Accuracy
Coriolis Flowmeters	±0.10%	±0.05%	±0.10%
Thermal Flowmeters	±1%	±1%	±1%
Volume-Displacement Flowmeters	±0.5%	±0.5%	±0.5%
Orifice Meters	±0.5%	±0.5%	±0.5%
Flow Nozzles	±0.5%	±0.5%	±0.5%
Venturi Tubes	±0.5%	±0.5%	±0.5%
Turbine Flowmeters	±0.25%	±0.25%	±0.25%
Variable-Area Flowmeters	±2%	±2%	±2%
Ultrasonic Flowmeters	±1%	±1%	±1%
Vortex-Shedding Flowmeters	±0.75%	±1%	±1%
Drag-Force Flowmeters	N/A	±2%	±2%
Magnetic Flowmeters	±3%	±3%	±3%
Positive Displacement Flowmeters	±0.5%	±0.5%	±0.5%