STANDARD

ASHRAE®

ANSI/ASHRAE Standard 41.8-2016
(Supersedes ASHRAE Standard 41.8-1989)

Standard Methods for Liquid Flow Measurement

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NOTE

Approved addenda, errata, or interpretations for this standard can be downloaded free of charge from the ASHRAE website at www.ashrae.org/technology.

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FOREWORD

The 1989 edition of Standard 41.8 was limited in scope to orifice flowmeters. For the 2016 edition, the scope has been expanded to cover the breadth of liquid flow measurement devices used for testing heating, ventilating, air-conditioning, and refrigeration (HVAC&R) systems and components, except for refrigerant liquid flow measurement devices, which are the focus of ASHRAE Standard 41.10. This standard now covers liquid flow measurements under both laboratory and field conditions and has been revised to meet ASHRAE's mandatory language requirements.

Selecting an appropriate liquid flow flowmeter can be a daunting task given the wide variety of operating principles, measurement precision, and costs of commercial products. Whether liquid flow measurements are to be taken in a laboratory or in the field, selecting the appropriate meter should be based on the required measurement accuracy. Once a liquid flowmeter has been selected, the user may need to consult with the meter manufacturer regarding installation specifics, operating range limits, calibration limits, and other similar specifics in order to obtain the expected measurement accuracy. For field test measurements, the manufacturer's installation specifics are often not achievable. Informative Annex D provides information regarding liquid flow measurement uncertainties for installations that do not meet the flowmeter manufacturer's requirements. Safety is an important consideration for all procedures involving liquids, particularly with regard to flammability, toxicity, and corrosiveness. As such, safety glasses and other personal protection equipment should be worn.

1. PURPOSE

This standard prescribes methods for liquid flow measurement.

2. SCOPE

This standard applies to laboratory and field liquid flow measurement for testing heating, ventilating, air-conditioning, and refrigerating systems and components. This standard is restricted to applications where the entire flow stream of liquid enters and exits the liquid flowmeter in a liquid-only state during data recording with the following exception:

a. This standard does not apply to liquid-phase refrigerant mass flow measurements where the liquid flow includes circulating lubricant. Those measurements are within the scope of ASHRAE Standard 41.10.

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.

mean, $\overline{X}_m$***:*** the arithmetic average of N readings.

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

sample size, N: the number of individual values in a sample.

test point: a specific set of test operating conditions and tolerances for recording data.

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

uncertainty: a measure of the potential error in a measurement or experimental result that reflects the lack of confidence in the result to a specified level.

unit under test: equipment that is subjected to liquid flow measurements.

4. CLASSIFICATIONS

4.1 Liquid Flow Operating State. As stated in Section 2, the entire flow stream of liquid entering and exiting the flowmeter shall be in a liquid-only state during liquid flow data recording. Verify that the total pressure is greater than the vapor pressure of the liquid at each test point, or use a sight glass upstream and a sight glass downstream of the flowmeter to verify that the entire flow stream is a liquid at both locations.

4.2 Liquid Flow Measurement Applications. Liquid flow measurement applications that are within the scope of this standard shall be classified as one of the types described in Sections 4.2.1 and 4.2.2.

4.2.1 Laboratory Applications. Liquid flow measurements under laboratory conditions are engineering development tests or tests to determine product ratings.

Informative Note: Laboratory liquid 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 Applications. Liquid flow measurements under field conditions are tests to determine installed system liquid flow rates.

Informative Note: Field liquid 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 Liquid Flowmeter Categories

4.3.1 Mass Flowmeters. Liquid flowmeters in this category perform direct measurement of liquid mass flow rates.

4.3.2 Volumetric Flowmeters. Liquid flowmeters in this category perform direct measurement of volumetric liquid flows. If liquid mass flow rates are required, each volumetric liquid flow measurement shall be multiplied by the liquid density at the flow measurement location to obtain the liquid mass flow rate measurement.

Informative Note: Ultrasonic flowmeters, vortex-shedding flowmeters, and drag-force flowmeters are examples of velocity measuring devices that can be used to determine volumetric flow rates.

TABLE 5-1 Measurement Values and Units of Measure

Quantity	Units of Measure SI	I-P	Note
Mass flow rate and uncertainty	Kilograms per second (kg/s)	Pound (avoirdupois) per second (lb_m/s)	No notes apply.
Volumetric flow rate and uncertainty	Cubic metres per second (m^3/s)	Cubic foot per second (ft^3/s)	Only if specified in test plan per Section 5.1.
Density and uncertainty	Kilograms per cubic metre (kg/m^3)	Pound (avoirdupois) per cubic foot (lb_m/ft^3)	Only if specified in test plan per Section 5.1.

4.4 Liquid Flow Measurement Methods. Liquid flow measurement methods that are within the scope of this standard are the methods listed below. Each of these liquid flow measurement methods are described in Section 7.5.

a. Coriolis flowmeters
b. Thermal flowmeters
c. Orifice meters
d. Flow nozzles
e. Venturi tubes
f. Turbine flowmeters
g. Variable-area flowmeters
h. Ultrasonic flowmeters
i. Vortex-shedding flowmeters
j. Drag-force flowmeters
k. Magnetic flowmeters
l. Fluidic oscillator
m. Positive displacement flowmeters
n. Averaging pitot-static tubes

5. REQUIREMENTS

5.1 Test Plan. A test plan is required. The test plan shall specify the test points and the required measurement system accuracy at each test point. A test plan is a document or other form of communication that specifies the tests to be performed and the required measurement accuracy for each test. Sources of the test plan are (a) the person or the organization that authorized the tests to be performed, (b) a method of test standard, (c) a rating standard, or (d) a regulation or code.

5.2 Values to Be Determined and Reported. The test values to be determined and reported shall be as shown in Table 5-1. Use the unit of measure in Table 5-1 unless otherwise specified in the test plan in Section 5.1.

5.3 Test Requirements

5.3.1 Accuracy. A selected liquid flowmeter shall meet or exceed the required liquid flow measurement accuracy specified in the test plan in Section 5.1 over the full range of operating conditions.

5.3.2 Uncertainty. The uncertainty in each liquid flow measurement shall be estimated using the method in Section 8 for each test point. Alternatively, the worst-case uncertainty for all test points shall be estimated and the same value reported for each test point.

5.3.3 Steady-State Tests. If the test plan in Section 5.1 requires liquid mass flow rate data points to be recorded at steady-state test conditions but does not specify the steady-state criteria, then the criteria in Equation 5-1 shall be met if the test plan specifies a target liquid mass flow rate for steady-state test conditions:

$$\left|\frac{\bar{\dot{m}} - \dot{m}_{target}}{\dot{m}}\right| \le 1.0\% \tag{5-1}$$

where

$\dot{m}_{target}$ = target liquid mass flow rate for the steady-state test conditions specified in the test plan, kg/s (lb_m/s)

$\bar{\dot{m}}$ = the mean liquid mass flow rate obtained from Equation 5-2, kg/s (lb_m/s)

n = number of measurement samples. There shall be at least 10 measurement samples as required by Equation 5-3.

$$\bar{\dot{m}} = \frac{1}{n}\sum_{i=1}^{n} \dot{m}_i, \text{ kg/s (lb/s)} \tag{5-2}$$

$$n \ge 10 \tag{5-3}$$

If the test plan in Section 5.1 requires liquid mass flow rate data points to be recorded at steady-state test conditions but does not specify the steady-state criteria, and if no specific target liquid mass flow rate is specified in the test plan, then steady-state conditions shall be established where at least three consecutive measurements of the mean liquid mass flow rate in accordance with Equation 5-2 are equal within ±1%.

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.

Informative Note: Informative Annex D provides information relative to uncertainties for flowmeter installations that do not meet the instrument manufacturer's requirements.

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

a. Temperature: ASHRAE Standard 41.1 [1] if temperature measurements are required
b. Pressure: ASHRAE Standard 41.3 [2] if pressure measurements are required

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

a. Temperature sensors within ±0.28°C (±0.5°F)
b. Temperature difference sensors within ±1.0% of the reading

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 measurement system accuracy shall be within ±1.0% of the reading 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 measurement system accuracy shall be within ±1.0% of the reading unless otherwise specified in the test plan. Pressure shall be measured in close proximity to the flowmeter in accordance with the flowmeter manufacturer's specifications.

6.3.2 Field Pressure Measurements

6.3.2.1 If pressure measurements are required by the test plan in Section 5.1, the measurement system accuracy shall be within ±3.0% of the reading 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 measurement system accuracy shall be within ±3.0% of the reading unless otherwise specified in the test plan. Pressure shall be measured in close proximity to the flowmeter in accordance with the flowmeter manufacturer's specifications.

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 liquid flow rate measurement system accuracy specified in the test plan.

6.5 Mass Measurements. If mass measurements are required by the test plan in Section 5.1, the measurement system accuracy shall be within ±0.2% of the reading unless otherwise specified in the test plan.

7. LIQUID FLOW MEASUREMENT METHODS

7.1 Liquid Properties. If not specified in the test plan in Section 5.1, the source of the liquid property data shall be recorded in the test report.

Informative Note: Documents cited in Informative Annex A[A1,A2] are potential sources of liquid refrigerant properties.

7.2 Operating Limits. Operating conditions during liquid flow data measurements shall not exceed limits for liquid velocity, temperature, pressure, pressure differential, or pressure pulsations specified in the test plan in Section 5.1 or by the liquid flowmeter manufacturer to achieve the measurement accuracy required by the test plan.

7.3 Leakage Requirement. Unless otherwise specified in the test plan in Section 5.1, there shall be no liquid leakage out of the test apparatus.

Informative Note: If leakage is permitted by the test plan, account for that leakage in the uncertainty analysis.

7.4 Liquid Flowmeter Installation. The selected liquid flowmeter shall be installed in accordance with instructions from the manufacturer, or the uncertainty calculations shall include estimated uncertainties for installations that are not in accordance with the manufacturer's instructions.

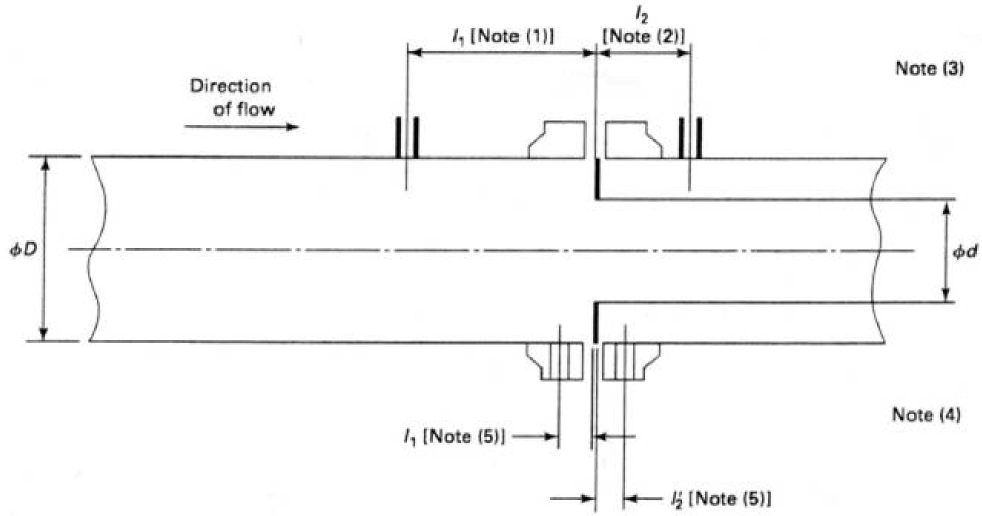
Informative Note: See Informative Annex D for information regarding uncertainties where installations are not in accordance with the manufacturer's instructions.

7.5 Liquid Flowmeter Descriptions

7.5.1 Coriolis Flowmeters. Coriolis liquid flowmeters provide direct measurement of liquid mass flow rates. In a Coriolis flowmeter, the liquid flows through a vibrating sensor tube within the meter. An electromagnetic coil located on the sensor tube vibrates the tube in cantilever motion at a known frequency. The liquid enters a vibrating tube and is given the vertical momentum of the tube. The liquid in the entry portion of the sensor tube resists in the downward direction when the tube is moving upward during half of the vibration cycle. Conversely, when the tube is moving downward during half of the vibration cycle, the liquid in the exit portion of the sensor tube resists in the upward direction. Combined, these effects create a symmetrical 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 liquid 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.

Informative Note: See Informative Annex A [A3] for additional information.

7.5.2 Thermal Flowmeters. Thermal flowmeters provide direct measurement of liquid mass flow rates. The basic ele-



NOTES:
(1) $l_1 = D \pm 0.1D$.
(2) $l_2 = 0.5D \pm 0.02D$ for $\beta > 0.6$.
$= 0.5D \pm 0.01D$ 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 section of an orifice flowmeter.
(Reprinted with permission of ASME)

ments 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 liquid. The liquid mass flow rate shall be obtained from Equation 7-1.

Informative Note: See Informative Annex A [A4] for additional information.

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

where

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

7.5.3 Orifice, Flow Nozzle, and Venturi Tube Flowmeters. Orifices, flow nozzles, and venturi tubes are liquid flowmeters that are based on empirical correlations of pressure differential to liquid flow rates. ASME PTC 19.5 [3] and ASME MFC-3M [4,5] describe measurement of fluid flow in pipes using orifices, flow nozzles, and venturi tube flowmeters.

7.5.3.1 Orifice, Flow Nozzle, and Venturi Tube Flowmeter Descriptions. Figure 7-1 illustrates an orifice section of an orifice flowmeter. Figure 7-2 illustrates examples of flow nozzles used in a nozzle flowmeter. Figure 7-3 illustrates geometric requirements for venturi tube flowmeters.

7.5.3.2 Liquid Mass Flow Rate Equations and Procedures. This section provides the equations and procedures for calculating liquid mass flow rates using long radius nozzles. This section provides reference information for calculating liquid flow rates using orifices, ISA 1932 nozzles, venturi nozzles, and venturi tube flowmeters.

Calculating a liquid 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 liquid flow velocity, and the average liquid flow velocity is not known until the liquid mass flow rate has been determined. ASME PTC 19.5 [3] includes an example of this iterative procedure, and ASME MFC-3M[4,5] 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.

Measurements required for this section shall be as follows:

a. Nozzle inlet pipe diameter (D), m (ft)
b. Nozzle throat diameter (d_2), m (ft)
c. Nozzle inlet absolute pressure (p_1), Pa (psia) for use in determining nozzle inlet density, kg/m^3 (lb_m/ft^3)
d. Nozzle differential pressure ($\Delta p = p_1 - p_2$), Pa (psia)
e. Nozzle inlet liquid temperature (t_1), °C (°F)

Liquid mass flow rates shall be obtained from Equation 7-2a (SI) or Equation 7-2b (I-P).

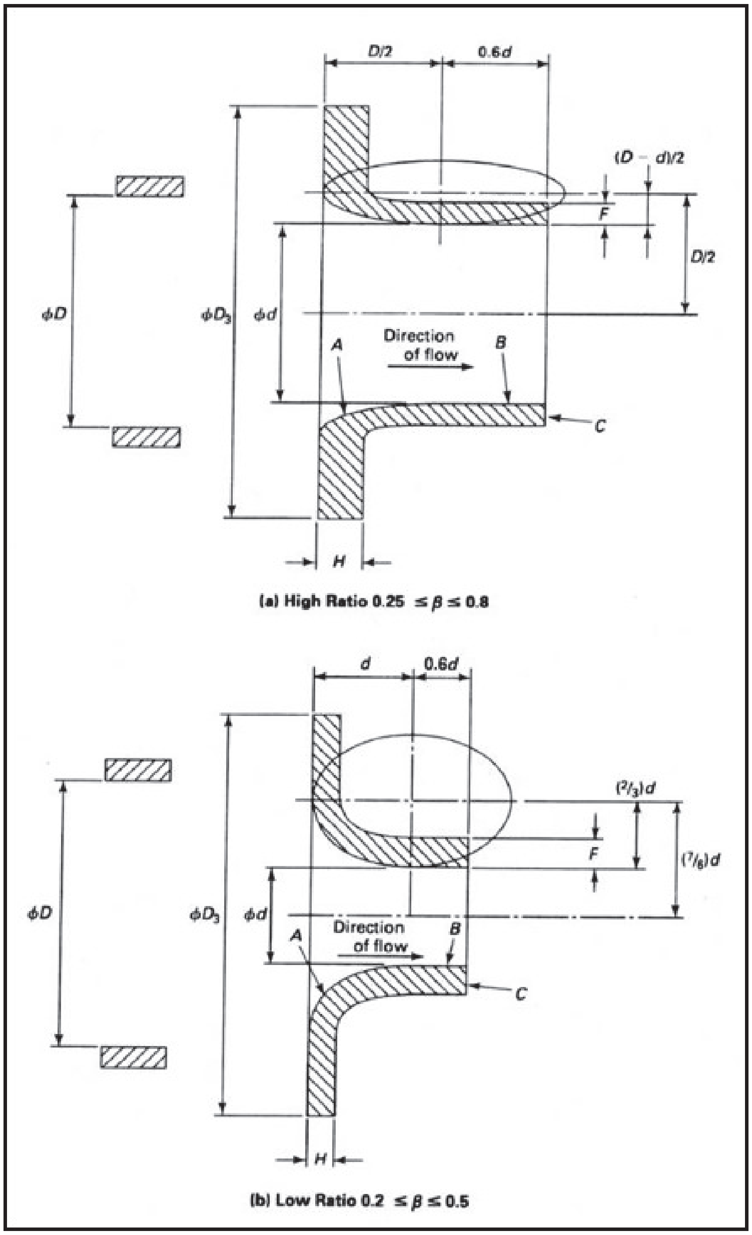


FIGURE 7-2 Examples of flow nozzles used in nozzle flowmeters.
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$$\dot{m} = C\left(\frac{\pi}{4}\right) d_2^2 \sqrt{\frac{2\rho_1(\Delta p)}{(1-\beta^4)}} \qquad (7\text{-}2a)$$

where

$\dot{m}$ = liquid mass flow rate, kg/s

C = discharge coefficient, dimensionless

d_2 = nozzle throat diameter, m

ρ_1 = nozzle inlet liquid density, kg/m^3

Δp = nozzle differential pressure, Pa

β = d/D, dimensionless

$$\dot{m} = C\left(\frac{\pi}{4}\right) d_2^2 \sqrt{\frac{2g_c\rho_1(\Delta p)}{(1-\beta^4)}} \qquad (7\text{-}2b)$$

where

$\dot{m}$ = liquid mass flow rate, lb_m/s

C = discharge coefficient, dimensionless

g_c = gravitational constant, 32.174 $(lb_m \cdot ft)/(lb_f \cdot s^2)$

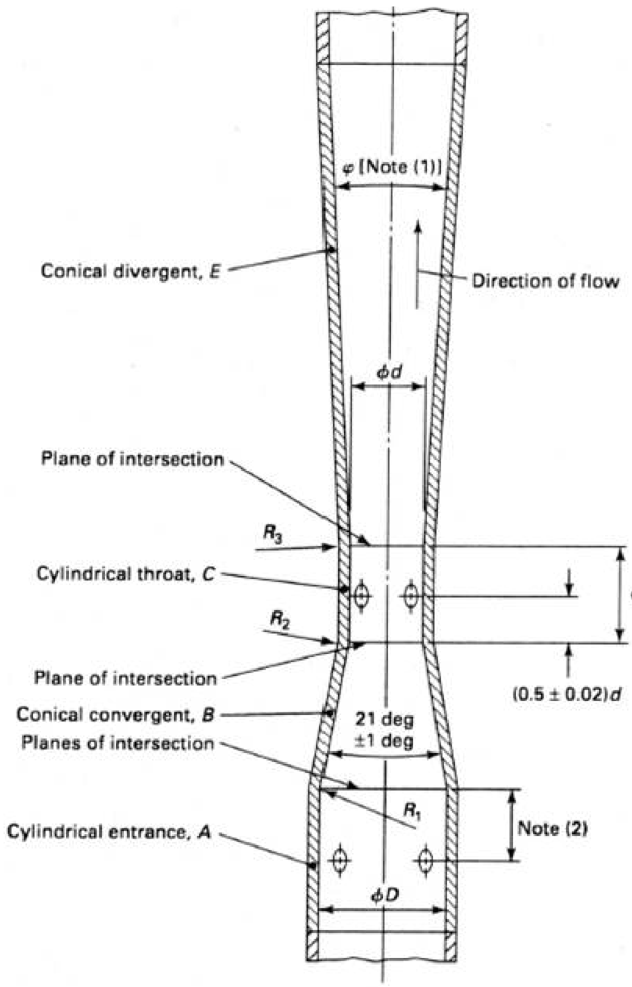
d_2 = nozzle throat diameter, ft

ρ_1 = liquid density, lb_m/ft^3

Δp = nozzle differential pressure, lb_f/ft^2

β = d/D, dimensionless

The inlet liquid density (ρ_1) shall be obtained from the liquid property data as a function of the inlet liquid temperature that shall be measured at each data point.



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

FIGURE 7-3 Geometric requirements for Venturi tube flowmeters.
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The parameter $\beta = d/D$ shall be calculated. If liquid flow operating temperatures are not the same as the liquid flow operating temperatures during calibration, parameters d, D_E, and β shall be corrected to account for thermal expansion in accordance with ASME PTC 19.5 [3], Section 3-10.

Limits for the use of long radius nozzle are as follows:

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 pipe.
c. $1(10^4) \leq \mathrm{Re}_D \leq 1(10^7)$, where Re_D is defined in Equation 7-3.

$$\mathrm{Re}_D = \frac{\rho_1 V D}{\mu} \tag{7-3}$$

where

ρ_1 = liquid density, kg/m^3 (lb$_m$/ft^3)

V = average liquid velocity $(4\dot{m}/\rho_1 \pi D^2)$, m/s (ft/s)

D = nozzle inlet diameter, m (ft)

μ = liquid dynamic viscosity, Ns/m^2 (lb$_m$/s·ft)

The dimensionless discharge coefficient (C) is a function of β and the Reynolds number based on the nozzle inlet diameter. The discharge coefficient (C) for long radius nozzles shall be obtained from Equation 7-4.

$$C = 0.9965 - (0.00653\beta^{0.5})\left(\frac{10^6}{\mathrm{Re}_D}\right)^{0.5} \tag{7-4}$$

The Reynolds number shall be calculated from Equation 7-3, but the average velocity is not known until the liquid mass flow rate has been determined. Iteration is required to determine the liquid mass flow rate. Choose $C = 1.0$ to begin the iterative calculation procedure for long radius nozzles, ISA 1932 nozzles, venturi nozzles, and 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.

TABLE 7-1 References in ASME MFC-3M [4,5] 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

To calculate liquid mass flow rates for orifices, ISA 1932 nozzles, venturi nozzles, or venturi tubes, refer to the sections of ASME MFC-3M[4,5] that are listed in Table 7-1, and use the same procedures that have been described for the long radius nozzles.

7.5.4 Turbine Flowmeters. Turbine flowmeters are volumetric flowmeters that have a turbine rotor suspended on low-friction bearings in the liquid stream. The rotational speed of the turbine is a linear function of the average liquid velocity and is therefore a linear function of the volumetric flow rate. Turbine rotation is sensed by the following methods: (a) reluctance sensors, (b) inductance sensors, (c) capacitance sensors, (d) Hall-effect sensors, or (e) mechanical sensors.

Informative Note: See Informative Annex A [A5] for additional information.

7.5.5 Variable-Area Flowmeters. 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 liquid to be metered enters at the narrow bottom end of the tube and moves 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 liquid pressure forces across the annulus acting upward and gravity acting downward on the float.

Informative Note: See Informative Annex A [A4] for additional information.

7.5.6 Ultrasonic Flowmeters. Ultrasonic flowmeters measure liquid flow velocity. Clamp-on ultrasonic flowmeters measure liquid velocity within a pipe or tube without being inserted into the flow stream.

Informative Note: Immersion-type ultrasonic flowmeters are also commercially available.

Ultrasonic flowmeters use the transit-time method to measure the effects that flow velocity has on bidirectional acoustical signals. An upstream transducer sends a signal to a downstream transducer that then returns a signal. When there is no flow, the time for the signal to go from one transducer to the other, in either direction, is constant. When liquid flow exists, 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 Annex A [A7] for additional information.

7.5.7 Vortex-Shedding Flowmeters. Vortex-shedding flowmeters are used to determine liquid velocities. Piezoelectric methods, strain-gage methods, or hot-film methods are used to sense dynamic pressure variations created by vortex shedding. The operating principle for these flowmeters is based on vortex shedding that occurs downstream of an immersed blunt-shaped solid body. As the liquid stream passes a blunt-shaped body, the liquid separates and generates small vortices that are shed alternately along and downstream of each side of the blunt-shaped body. Each vortex-shedding meter is designed to have a constant Strouhal number so that the vortex shedding frequency is proportional to the liquid flow velocity over a specified flow velocity range. The Strouhal number for each vortex shedding meter is experimentally determined by the flowmeter manufacturer and is provided with each vortex-shedding meter.

Informative Note: See Informative Annex A [A8] for additional information.

7.5.8 Fluidic Oscillator Flowmeters. Fluidic oscillators have no moving parts. The shape of the fluid path creates a self-induced oscillation that diverts the flow between two alternate channels. The frequency of the oscillation is linear with volumetric flow rate. Thermal or pressure sensors detect the flow alterations in these devices.

7.5.9 Drag-Force Flowmeters. Drag-force flowmeters determine liquid velocity. Piezoelectric or strain-gage methods are used to sense dynamic drag-force variations. A body immersed in a flowing liquid is subjected to a drag force given by Equation 7-5a (SI) and Equation 7-5b (I-P). The manufacturer designs the immersed element so that the drag coefficient is constant over the specified range of Reynolds numbers.

Informative Note: See Informative Annex A[A4] for additional information.

$$V = \sqrt{\frac{2 f_d}{C_d A \rho}} \tag{7-5a}$$

where

V = liquid velocity, m/s

f_d = drag force, N

C_d = drag coefficient, dimensionless

A = cross-section area, m^2

ρ = liquid density, kg/m^3

$$V = \sqrt{\frac{2 g_c f_d}{C_d A \rho}} \tag{7-5b}$$

where

V = liquid velocity, ft/s

f_d = drag force, lb_f

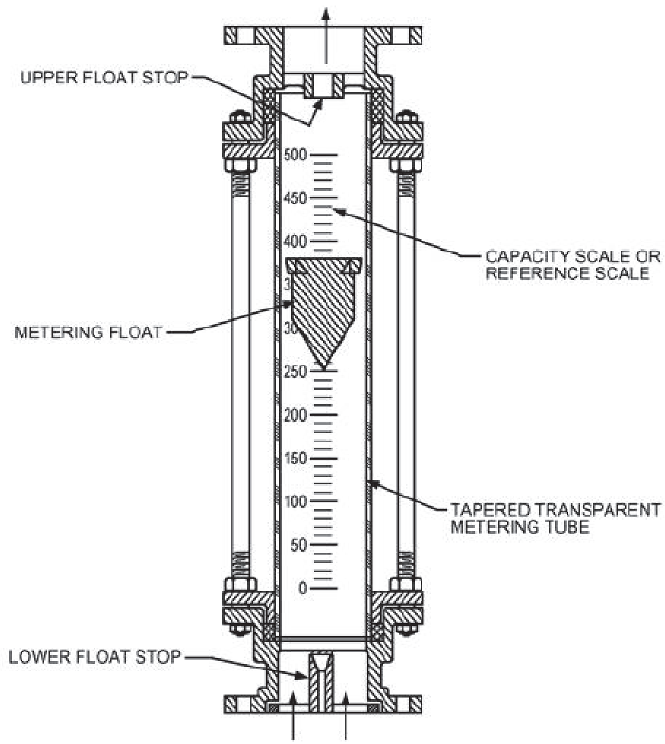


FIGURE 7-4 Variable-area flowmeter.

C_d = drag coefficient, dimensionless

A = cross-section area, ft^2

ρ = liquid density, lb_m/ft^3

g_c = gravitational constant, 32.174 $(lb_m \cdot ft)/(lb_f \cdot s^2)$

7.5.10 Magnetic Flowmeters. 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 flowing through the pipe. Faraday's law states that the voltage generated is proportional to the movement of the flowing liquid. Electronics within a magnetic flowmeter sense voltage and determine the volumetric flow rate.

Informative Notes:

1. Magnetic tube flowmeters have no flow obstructions, so the pressure loss in these flowmeters is less than for many other types of flowmeters.
2. Most heating, ventilating, air-conditioning, and refrigeration liquids have enough electrical conductivity to be used in these flowmeters.
3. See Informative Annex A [A9] for additional information.

7.5.11 Positive-Displacement Flowmeters. Positive-displacement flowmeter types are gear, rotating piston, or 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 enters the gear housing of known volume through an intake. As the gear rotates, liquid 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 7-6.

$$Q = V_t/t \qquad (7\text{-}6)$$

where

Q = liquid flow rate, m^3/s (ft^3/s)

V_t = trapped liquid volume, m^3 (ft^3)

t = cycle time, s

7.5.12 Pitot-Static Tube Liquid Flow Measurement Methods. Figure 7-5 shows an example pitot-static tube construction and the connections to manometers or pressure transducers. Sections 7.5.12.1, 7.5.12.2, and 7.5.12.3 describe three different methods to determine liquid velocity at measurement points in a liquid stream by measuring total and static pressures. Pitot-static tubes shall be aligned within ±10 degrees of the liquid flow direction, and any misalignment shall be included in the uncertainty estimate.

Informative Note: Negative values of the dynamic (or velocity) pressure readings result from misalignment of the probe and are due to the stagnation port pressure being lower than the static port pressure. This is a clear indication that the pitot-static tube is not properly aligned with the direction of liquid velocity.

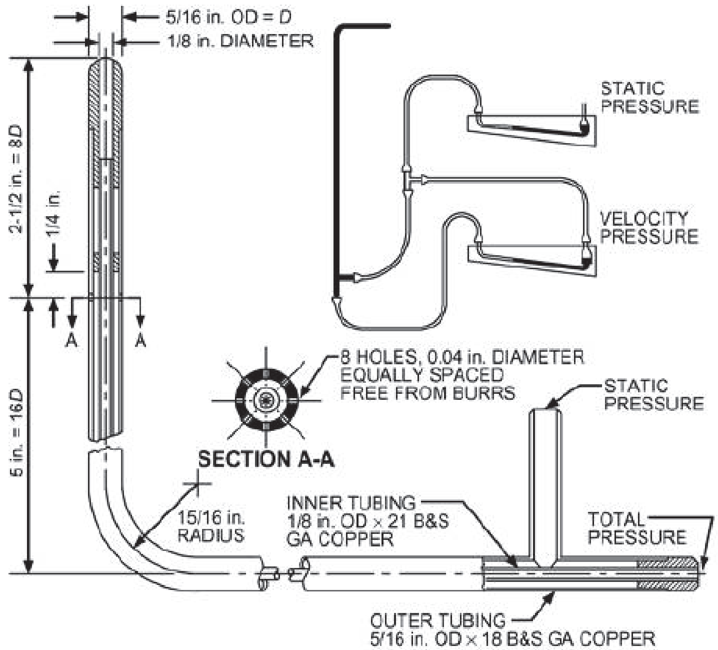


FIGURE 7-5 Example of a pitot-static tube.

7.5.12.1 Pitot-Static Tube Traverse Liquid Flow Measurement. The process of sequentially positioning a Pitot-static tube at different measuring points within a pipe cross section to measure liquid velocities is called a Pitot-static tube traverse. The traverse measuring points shall be in accordance with Figure 7-6.

7.5.12.1.1 Velocity Pressure. The total pressure (P_t) is the sum of the static pressure (P_s) and the velocity pressure (P_v), so it follows that

$$P_v = P_t - P_s\text{, Pa (in. of water)} \tag{7-7}$$

7.5.12.1.2 Average Velocity Pressure. The average velocity pressure (P_{va}) shall be obtained from Equation 7-8, where n is the number of velocity pressure sampling points.

$$P_{va} = \left(\frac{\sum_{i=1}^{n}\sqrt{P_{vi}}}{n}\right)^2\text{, Pa (in. of water)} \tag{7-8}$$

7.5.12.1.3 Average Liquid Velocity. The average liquid velocity shall be obtained from the density at the traverse plane and the average velocity pressure from Equation 7-9a (SI) and Equation 7-9b (I-P).

$$V_a = K\sqrt{\frac{2P_{va}}{\rho}} \tag{7-9a}$$

where

V_a = average liquid velocity, m/s

K = calibration factor provided by the manufacturer, dimensionless

P_{va} = pressure, Pa

ρ = liquid density, kg/m^3

$$V_a = 1097.8\sqrt{\frac{P_{va}}{\rho}} \tag{7-9b}$$

where

V_a = average liquid velocity, ft/min

K = calibration factor provided by the manufacturer, dimensionless

P_{va} = pressure, in. of water

ρ = liquid density, lb_m/ft^3

7.5.12.1.4 Volumetric Liquid Flow. The volumetric liquid flow at the pitot-static tube traverse plane shall be obtained from Equation 7-10

$$Q = V_a A \tag{7-10}$$

where

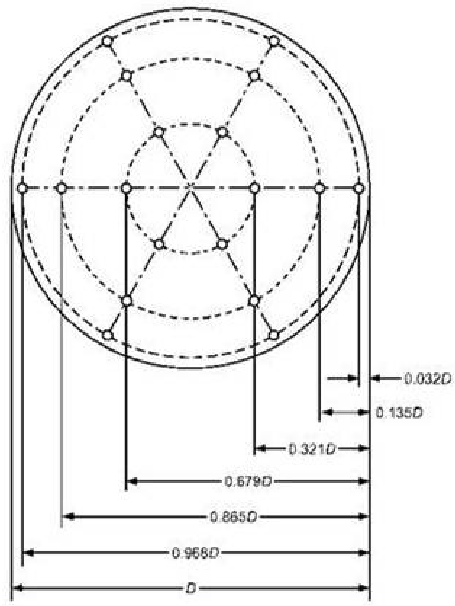
Q = volumetric liquid flow rate, m^3/s (ft^3/min)

V_a = average liquid velocity, m/s (ft/min)

A = measurement plane cross section area, m^2 (ft^2)

7.5.12.2 Self-Averaging Array Liquid Flow Measurement. Self-averaging arrays consist of multiple bifurcated or extruded tubes spread out over a measurement plane that have holes to sample and self-average both total and static pressure across the measurement plane. The self-averaged total pressure is connected to one side of a differential pressure transducer, and the self-averaged static pressure is connected to the other side of the same pressure transducer.

7.5.12.2.1 Average Velocity Pressure. The average velocity pressure shall be obtained from Equation 7-11.



No. of Measuring Points per Diameter	Position Relative to Inner Wall
6	0.032, 0.135, 0.321, 0.679, 0.865, 0.968
8	0.021, 0.117, 0.184, 0.345, 0.655, 0.816, 0.883, 0.979
10	0.019, 0.077, 0.153, 0.217, 0.361, 0.639, 0.783, 0.847, 0.923, 0.981

Log-Linear Rule for Circular Ducts

FIGURE 7-6 Pitot-tube traverse measuring points.

$$P_{va} = P_{ta} - P_{sa} \tag{7-11}$$

where

P_{va} = average velocity pressure, Pa (in. of water)

P_{ta} = measured average total pressure, Pa (in. of water)

P_{sa} = measured average static pressure, Pa (in. of water)

7.5.12.2.2 Average Liquid Velocity. The average liquid velocity shall be obtained from Equation 7-12a (SI) or Equation 7-12b (I-P):

$$V_a = K\sqrt{\frac{2P_{va}}{\rho}} \tag{7-12a}$$

where

V_a = average liquid velocity, m/s

K = calibration factor provided by the manufacturer, dimensionless

P_{va} = pressure, Pa

ρ = liquid density, kg/m^3

$$V_a = 1097.8K\sqrt{\frac{P_{va}}{\rho}} \tag{7-12b}$$

where

V_a = average liquid velocity, ft/min

K = calibration factor provided by the manufacturer, dimensionless

P_{va} = pressure, in. of water

ρ = liquid density, lb$_m$/ft^3

7.5.12.2.3 Volumetric Liquid flow. The volumetric liquid flow at the pitot-static tube array measurement plane shall be obtained from Equation 7-13.

$$Q = V_a A \tag{7-13}$$

where

Q = volumetric liquid flow rate, m^3/s (ft^3/min)

V_a = average liquid velocity, m/s (ft/min)

A = measurement plane cross section area, m^2 (ft^2)

7.5.12.3 Self-Averaging Probe Liquid Flow Measurement. Self-averaging probes include multiple total and static pressure ports along a straight line or around a circumference within the airstream. The self-averaged total pressure is connected to one side of a differential pressure transducer, and the self-averaged static pressure is connected to the other side of the same pressure transducer.

7.5.12.3.1 Average Velocity Pressure. The average velocity pressure shall be obtained from Equation 7-14.

$$P_{va} = P_{ta} - P_{sa} \tag{7-14}$$

where

P_{va} = average velocity pressure, Pa (in. of water)

P_{ta} = measured average total pressure, Pa (in. of water)

P_{sa} = measured average static pressure, Pa (in. of water)

7.5.12.3.2 Average Liquid Velocity. The average liquid velocity shall be obtained from Equation 7-15a (SI) or Equation 7-15b (I-P):

$$V_a = K\sqrt{\frac{2P_{va}}{\rho}} \tag{7-15a}$$

where

V_a = average liquid velocity, m/s

K = calibration factor provided by the manufacturer, dimensionless

P_{va} = pressure, Pa

ρ = liquid density, kg/m^3

$$V_a = 1097.8K\sqrt{\frac{P_{va}}{\rho}} \tag{7-15b}$$

where

V_a = average liquid velocity, ft/min

K = calibration factor provided by the manufacturer, dimensionless

P_{va} = pressure, in. of water

ρ = liquid density, lb$_m$/ft^3

7.5.12.3.3 Volumetric Liquid flow. The volumetric liquid flow at the pitot-static tube array measurement plane shall be obtained from Equation 7-16.

$$Q = V_a A \tag{7-16}$$

where

Q = volumetric liquid flow rate, m^3/s (ft^3/min)

V_a = average liquid velocity, m/s (ft/min)

A = measurement plane cross section area, m^2 (ft^2)

8. UNCERTAINTY REQUIREMENTS

8.1 An estimate of the measurement uncertainty, performed in accordance with ASME PTC 19.1 [6], shall accompany each liquid flow measurement. Installation effects on the accuracy of the instrument shall be included in the uncertainty estimate for each installation that does not conform to the instrument manufacturer's installation requirements.

Informative Notes:

1. This procedure is illustrated in the uncertainty analysis that is provided in Informative Annex B.
2. Informative Annex D provides information regarding liquid flow measurement uncertainties where a liquid flowmeter installation does not conform to the instrument manufacturer's installation requirements.

8.2 Method to Express Uncertainty. All assumptions, parameters, and calculations used in estimating uncertainty shall be clearly documented prior to expressing any uncertainty values. Uncertainty shall be expressed as follows:

$$v = \overline{X}_m \pm U_{\overline{X}} \ (P\%)$$

where

v = the variable that is a measurement or a calculated result

$\overline{X}_m$ = the best estimate of the true value

$U_{\overline{X}}$ = the uncertainty estimate for the variable

P = the confidence level, %

Informative Note: For example, liquid mass flow rate = 2.538 ± 0.013 kg/s (5.595 ± 0.029 lb$_m$/s); 95% states that the measured liquid flow is believed to be 2.538 kg/s (5.595 lb$_m$/s) with a 95% probability that the true value lies within ±0.013 kg/s (±0.029 lb$_m$/s) of this value.

9. TEST REPORT

9.1 Test Identification

a. Test report number if required in the test plan.
b. Unit under test identification number
c. Source of liquid property data
d. Date, test facility description, start time, and duration of test
e. Operator identification
f. Attach a copy of the test plan

9.2 Liquid Flow Measurement System Description

a. Flow measurement equipment description, model number, and serial number
b. Calibration date
c. Operating range
d. Accuracy across the operating range

9.3 Ambient Test Conditions

a. Ambient temperature, °C (°F)
b. Barometric pressure (required if a pressure sensing device is referenced to atmospheric pressure; not required if a pressure sensing device is referenced to absolute pressure)

9.4 Test Operating Conditions if Required by the Flowmeter

a. Pressure of the liquid flow entering the flowmeter, kPa (psia)
b. Temperature of the liquid flow entering the flowmeter, °C (°F)
c. Differential pressure, kPa (psi)
d. Pressure of the liquid flow leaving the flowmeter, kPa (psia)
e. Temperature of the liquid flow leaving the flowmeter, °C (°F)

9.5 Test Results

9.5.1 Liquid mass flow rate unless otherwise specified by the test plan in Section 5.1:

a. Liquid mass flow rate, kg/s (lb_m/s)
b. Uncertainty in liquid mass flow rate, kg/s (lb_m/s)

9.5.2 Volumetric liquid flow if specified by the test plan in Section 5.1:

a. Volumetric liquid flow, m^3/s (ft^3/s)
b. Uncertainty in volumetric liquid flow, m^3/s (ft^3/s)

10. REFERENCES

1. ASHRAE. 2013. ANSI/ASHRAE Standard 41.1, *Standard Methods for Temperature Measurement*. Atlanta: ASHRAE.
2. ASHRAE. 2014. ANSI/ASHRAE Standard 41.3, *Standard Methods for Pressure Measurement*. Atlanta: ASHRAE. See Note 2.
3. ASME. 2013. ANSI/ASME PTC 19.5-2004 (R2013), *Flow Measurement.* New York: The American Society of Mechanical Engineers. See Note 3.
4. ASME. 2004. ASME MFC-3M, *Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi*. New York: The American Society of Mechanical Engineers. See Note 3.
5. ASME. 2007. MFC-3Ma, *Addenda to ASME MFC-3M-2004*. The American Society of Mechanical Engineers. See Note 3.
6. ASME. 2013. ASME PTC 19.1, *Test Uncertainty.* The American Society of Mechanical Engineers.

Informative Notes:

1. Reference 1 is not required if there are no temperature measurements.
2. Reference 2 is not required if there are no pressure measurements.
3. References 3, 4, and 5 are only required if using an orifice, flow nozzle, or venturi tube flowmeter (Section 7.5.3) as the selected test method.

(This annex 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 ANNEX A
INFORMATIVE REFERENCES AND BIBLIOGRAPHY

A1. NIST. 2013. NIST Standard Reference Database 23: *NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP) Version 9.1*. National Institute of Standards and Technology, Gaithersburg, MD.

A2. Melinder, A. 2010. *Properties of Secondary Working Fluids for Indirect Systems*. Paris: International Institute of Refrigeration (IIR).

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A8. ASME. 2013. ANSI/ASME MFC-6, *Measurement of Fluid Flow in Pipes Using Vortex Flow Meters*. New York: American Society of Mechanical Engineers.

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A10. ASME. 2014. ANSI/ASME MFC-12M-2006 (R2014), *Measurement of Fluid Flow in Closed Conduits Using Multiport Averaging Pitot Primary Elements*. New York: American Society of Mechanical Engineers.

A11. ASME. 1971. *Fluid Meters Their Theory and Application*, Sixth Edition. Ed. H.S. Bean. New York: ASME.

A12. ASME. 2011. ANSI/ASME Standard MFC-10-2000 (R2011), *Method for Establishing Installation Effects on Flowmeters*. New York: American Society of Mechanical Engineers.

A13. ASHRAE. 2014. ANSI/ASHRAE Guideline 2-2010 (RA2014), *Engineering Analysis of Experimental Data*. Atlanta: ASHRAE.

A14. ISO. 2005. ISO/TR 5168, *Measurement of Fluid Flow - Evaluation on Uncertainties*. Geneva: International Organization for Standardization.

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INFORMATIVE ANNEX B
AN UNCERTAINTY ANALYSIS EXAMPLE FOR A CORIOLIS FLOWMETER

A Coriolis flowmeter is installed in accordance with the flowmeter manufacturer's instructions. The output electronics are connected to a frequency meter that is read automatically by a computer-based data acquisition system. This setup will be used to measure various water flow mass flow rates from 5% to 100% of the full-scale output. Determine the expected measurement uncertainty at 100% of the full-scale reading, and determine the worst-case uncertainty over the expected operating range.

According to the step-by-step procedure outlined in ASME PTC 19.1 [6], Section 4.2, do the following.

B1. DEFINE THE MEASUREMENT PROCESS

B1.1 Review the Test Objectives and Duration. The test objectives are clearly stated in the description above.

B1.2 List All Independent Measurement Parameters and Their Nominal Levels. The only independent measurement is the frequency output from the Coriolis flowmeter. The full-scale output of the flowmeter was set by the manufacturer to 4.0 kg/s (8.82 lbm/s), so the nominal flow at 5% of the range is 0.2 kg/s (0.44 lb_m/s).

B1.3 List All Calibrations and Instrumentation Setups that Will Effect Each Parameter. The manufacturer verified basic flowmeter operation on its test facility that has a stated uncertainty (U_{RSS}) of ±0.05% per ISO 5168 [A11]. The calibration data provided when the meter was initially delivered is shown in Table B-1. The calibration was a water calibration that uses the total weight collected at a given time period to determine a total flow rate.

Items to note from Table B-1:

a. The calibration data are in terms of mass only, not mass per unit time. The manufacturer states that the uncertainty related to determining time in the calibration is insignificant.
b. Frequency output data from the meter's electronics were not provided; the manufacturer stated that the frequency output is identical to the electronic internal digital value.
c. Hysteresis is not well defined—only the 100% flow rate has a repeated point.
d. The minimum flow rate measured was 25% due to testing limitation of the meter's manufacturer.
e. Since the meter's performance at 5% needs to be determined, either this existing data will need to be extrapolated or, preferably, an additional calibration will be required to better define the low-flow performance. Extrapolation at low flows on Coriolis flowmeters should not be done as the error typically increases exponentially.

Figure B-1 shows a typical accuracy estimate from the flowmeter manufacturer with the actual calibrated flow points plotted. As can be seen, the expected error will be around 2.5% at a 5% flow rate condition. As the actual meter's data appears to be much better than nominal manufacturer's data, an extended calibration should give results with a significantly lower error. Another calibration was performed at an independent calibration lab that also had a stated uncertainty (U_{RSS}), of ±0.05%, and the error was determined to be –1.13% at 0.2 kg/s (0.44 lb_m/s) flow rate.

B1.4 Define the Functional Relationship between the Independent Measurement Parameters and the Test Results. As the mass flow is a direct measurement, there is no functional relationship between multiple measurements and the final test result.

B2. LIST ELEMENTAL ERROR SOURCES

B2.1 Make a Complete List of All Possible Measurement Error Sources. The number of possible error sources for this system is small due to the simplicity of the overall system. Measurement error sources may include the manufacturer's calibration results, frequency meter measuring error, and data reduction errors in converting from frequency to flow rate.

B2.2 Group the Error Sources According to the Following Categories

a. **Calibration Errors.** The meter calibration was provided with an uncertainty estimate, so elemental error hierarchy does not need to be estimated for each possible error source.
b. **Data Acquisition Errors.** Data acquisition errors for the frequency meter include those from the meter calibration that was performed at an accredited calibration lab. The meter will be operated in an ambient temperature that is outside of the instrument's nominal operating range, so temperature effects should be considered.

   The communications between the frequency meter and the computer are digital, and it is assumed there is no error associated with transferring these values. This is a logical assumption in this case because a computer error would have been generated if there were a problem in the transmission.
c. **Data Reduction Errors.** Data reduction errors include the inaccuracy between the curve fit that is used to convert the measured frequency to the flow rate in engineering units.

B3. ESTIMATE ELEMENTAL ERRORS

B3.1 Obtain an estimate of each error identified in Section B2.2(b).

B3.2 If data are available to estimate the precision index, tentatively classify the error as a precision error. Otherwise, classify it as a bias error.

a. **Calibration Error Estimate.** The manufacturer stated that the flowmeter test facility calibration error was

TABLE B-1 Manufacturer's Initial Liquid Flowmeter Calibration Data

Flow, %	Nominal Flow Rate, kg/s (lb_m)	Meter Total, kg (lb_m)	Scale Total, kg (lb_m)	Error, %
100	4.000 (8.818)	307.64 (678.23)	307.57 (678.08)	0.023
50	2.000 (4.409)	306.44 (675.59)	305.67 (673.89)	0.250
25	1.000 (2.205)	304.89 (672.17)	305.07 (672.56)	–0.059
100	4.000 (8.818)	305.04 (672.50)	304.97 (672.34)	0.022

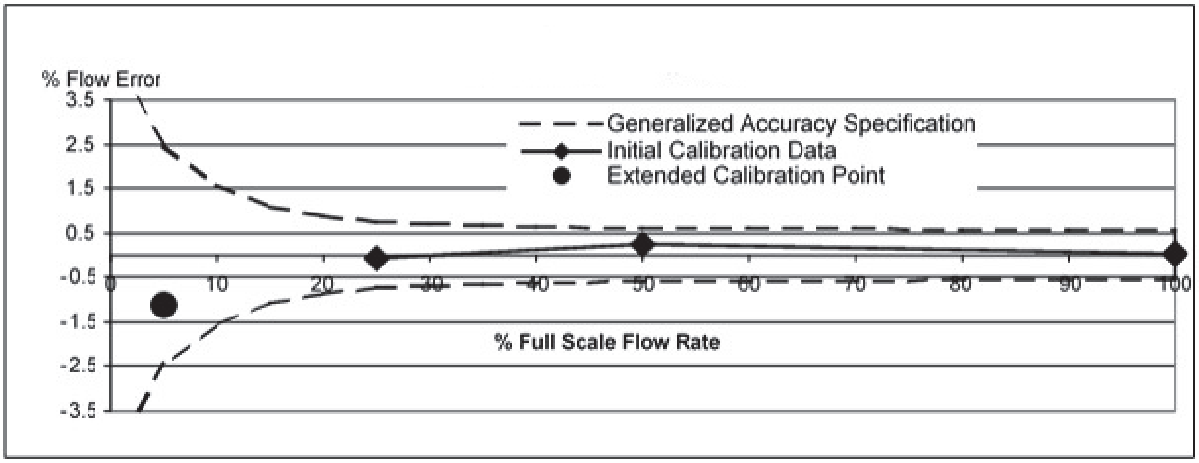

FIGURE B-1 Flow error vs. flow rate.

TABLE B-2 Error Estimates as a Function of Flow Rates

Flow Rate, kg/s (lb_m/s)	0.200 (0.441)	1.000 (2.205)	2.000 (4.409)	4.000 (8.818)
$B_{Calibration\ Error\ \#2}$	–1.13%	–0.06%	0.25%	0.02%

0.05%. Upon further investigation of their calibration uncertainty analysis, the error appears to mainly consist of a bias error that can be expressed as follows:

$$B_{Calibration\ Error\ \#1} = 0.035\%$$

$$S_{Calibration\ Error\ \#1} = 0.015\%$$

Degrees of freedom > 30

Using these values for the four calibration points that were reported, Table B-2 gives an estimate of error as a function of flow rate. The entire error is attributed to bias, as there are insufficient data available to estimate the precision component.

b. **Data Acquisition Error Estimate.** The frequency meter that will be used was specified by the manufacturer to be ±0.010% of the reading for readings greater than 40 Hz. Because the inaccuracy in determining frequency was only specified as a percent reading and did not include a separate term for percent of the measurement range, this error will be assumed to be only a bias error:

$$B_{Data\ Acquisition\ Error\ \#1} = 0.010\%$$

$$S_{Data\ Acquisition\ Error\ \#1} = 0.000\%$$

The meter also has a temperature coefficient of ±0.001% per degree Celsius (±0.0018% per degree Fahrenheit) for temperatures greater than 28°C (82.4°F). This needs to be considered because the instrumentation console where the meter is located will reach a maximum temperature of 40°C (104°F). Again, as the inaccuracy specification did not break up the error into precision and bias components, the error will be assumed to have only a bias component:

$$B_{Data\ Acquisition\ Error\ \#2} = 0.001\% \times (40 - 28) = 0.012\%$$

$$S_{Data\ Acquisition\ Error\ \#2} = 0.000\%$$

(I-P: = 0.0018% × [104 – 82.4] = 0.012%)

c. **Data Reduction Error Estimate.** The mass flow will be a function related to the measured frequency as shown in the first two columns of Table B-3. Various linear curve fits were reviewed to determine which had the smallest error over the entire operating range. The manufacturer states it is a simple linear relationship that is forced to go through zero, and that is how the transmitter was set up. The flow and error associated using this curve fit is shown in the next two columns in Table B-3. The next two columns are the results of a least-square curve fit that

TABLE B-3 Data Reduction Curve Fit Error Comparison

Calibration		Transmitter Curve Fit		Zero Flow Curve Fit		No Zero Flow Curve Fit	
Output Hertz	Measured Flow, kg/s (lb_m/s)	Calculated Flow, kg/s (lb_m/s)	% Flow Error	Calculated Flow, kg/s (lb_m/s)	% Flow Error	Calculated Flow, kg/s (lb_m/s)	% Flow Error
0	0	0.00	0.00	–0.00049 (–0.0011)	0.00	–0.00080 (–0.0018)	0.00
100	0.19777 (0.4360)	0.20 (0.4409)	–1.130%	0.19967 (0.4402)	–0.96%	0.19937 (0.4395)	–0.813%
500	0.9994 (2.2033)	1.00 (2.2046)	–0.060%	1.00028 (2.2056)	–0.09%	1.00007 (2.2048)	–0.067%
1000	2.0050 (4.4203)	2.00 (4.4092)	0.249%	2.00104 (4.4115)	0.20%	2.00094 (4.4113)	0.203%
2000	4.0009 (8.8205)	4.00 (8.815)	0.022%	4.00257 (8.8242)	–0.04%	4.00268 (8.8844)	–0.044%
Linear Curve Fit Coefficients ($y = mx + b$, where y = measured flow and x = output)							
	m	0.00200000 (0.00440925)		0.0020015 (0.0044126)		0.002002 (0.0044137)	
	b	0.00000000		–0.0004853 (–0.001070)		–0.000801 (–0.001766)	

TABLE B-4 Bias and Precision Error Summary

	Bias Errors			Precision Errors		
Flow Rate, kg/s (lb_m/s)	Calibration Facility	Transmitter and/or Application	Summed Errors	Calibration Facility	Transmitter and/or Application	Summed Errors
	#1	#2		#1	#2	
0.200 (0.441)	0.035%	–1.130%	1.131%	0.015%	0	0.015%
1.000 (2.205)	0.035%	–0.060%	0.069%	0.015%	0	0.015%
2.000 (4.409)	0.035%	0.249%	0.251%	0.015%	0	0.015%
4.000 (8.818)	0.035%	0.022%	0.041%	0.015%	0	0.015%
	Data Acquisition					
	#1	#2		#1	#2	
	0.01%	0.012%	0.016%	0	0	0
	Data Reduction					
0.200 (0.441)	–0.813%		0.813%	0		0
1.000 (2.205)	–0.067%		0.067%	0		0
2.000 (4.409)	0.203%		0.203%	0		0
4.000 (8.818)	–0.044%		0.044%	0		0

TABLE B-5 Propagation and Final Uncertainty Estimate

Flow Rate, kg/s (lb_m/h)	Propagated Errors		95% Confidence Uncertainty Estimate
	Bias	Precision	U_{RSS}
0.200 (0.441)	1.393%	0.015%	1.393%
1.000 (2.205)	0.098%	0.015%	0.0989%
2.000 (4.409)	0.324%	0.015%	0.3239%
4.000 (8.818)	0.063%	0.015%	0.0646%

includes a point at zero flow. The last two columns are the results of a least-square curve fit that excludes the point at zero flow. Based on the results in Table B-3, it was decided to use the no zero flow curve fit. All of this error will be a bias error since it is fixed for a given frequency input in the equation.

B3.3 Calculate the Bias and Precision Errors for Each Parameter. The results from the previously defined elements are summarized at each of the four calibrated flow rates in Table B-4. The summing of the terms is by the root-sum-square method, as a 95% confidence level is desired.

B4. PROPAGATE THE BIAS AND PRECISION ERRORS

B4.1 The bias and precision errors of the independent parameters are propagated separately all the way to the final test result. The individual terms are now summed together again by the root-sum-square method, as a 95% confidence level is desired as shown in the second and third columns of Table B-4.

B4.2 Error propagation is performed, according to the functional relationship of Section B1.4, via a Taylor series. This requires a calculation of the sensitivity factors, either by differentiation or by computer perturbation. As the mass flow rate is the only independent parameter, this step is not required. The values determined in the last step are the ones that will be used in the next step to calculate uncertainty.

B5. CALCULATE UNCERTAINTY

Select U_{ADD} or U_{RSS} as a model for combining the bias and precision errors of the test result, and obtain the uncertainty. U_{RSS} will be used, as a 95% confidence level is desired. The value of t for the student's t function is taken to be 2.00 because the degrees of freedom for the meter calibration are greater than 30. The final estimate is shown in the fourth column of Table B-5.

B6. REPORT

B6.1 The report summary shall contain the nominal level of the test result, bias limit, precision index, degrees of freedom, and uncertainty of the test result, stating the model used.

B6.2 The report shall include a table of the elemental errors included in the uncertainty analysis along with the bias limit, precision index, and degrees of freedom of each parameter. The report for this analysis would include the average value determined per ASME PTC 19.1 [6] at the actual test condition and the appropriate values from Tables B-3 and B-4.

(This annex 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 ANNEX C
AN UNCERTAINTY ANALYSIS EXAMPLE FOR A DIFFERENTIAL PRESSURE FLOWMETER

A stainless steel ASME long-radius flow nozzle is installed downstream in a stainless steel pipe in accordance with the guidelines presented in ASHRAE Guideline 2 [A13] and Section 7.6.3 of this standard. A laboratory test facility will measure liquid water flow at a nominal pressure of 380 kPa (55.1 psia) and 20°C (68°F). Determine if the measurement system can meet an uncertainty of ±0.75% at a 95% confidence level for mass flow using the thirteen-step procedure outlined in ASHRAE Guideline 2, Section 5. Mass flow rate will be reported in kg/s (lb_m/s).

C1. IDENTIFY EXPERIMENTAL GOALS AND ACCEPTABLE ACCURACY

The initial problem statement defines the main objective of having an uncertainty level of ±0.75% at a 95% confidence level. This statement does not specify if the uncertainty ±0.75% refers to the full-scale reading of the meter or of the actual reading. It is assumed that the uncertainty will be based on the actual reading.

C2. IDENTIFY THE IMPORTANT VARIABLES AND APPROPRIATE RELATIONSHIPS

The equation used to calculate mass flow rate comes from ASME PTC 19.5 [3] and is shown in Equation 7-2a (SI) and Equation 7-2b (I-P).

$$\dot{m} = C\left(\frac{\pi}{4}\right)d_2^2\sqrt{\frac{2\rho_1(\Delta p)}{(1-\beta^4)}} \quad \text{(7-2a)}$$

$$\dot{m} = C\left(\frac{\pi}{4}\right)d_2^2\sqrt{\frac{2g_c\rho_1(p_1-p_2)}{(1-\beta^4)}} \quad \text{(7-2b)}$$

C3. ESTABLISH THE QUANTITIES THAT MUST BE MEASURED AND THEIR EXPECTED RANGE OF VARIATION

The independent parameters, their nominal values, and expected range and variations are listed in the first five columns of Table C-1. Table C-2 shows relationships of the calculated parameters.

C4. TENTATIVELY SELECT SENSORS/ INSTRUMENTATION APPROPRIATE FOR THE TASK

These are listed in the last column of Table C-1.

C5. DOCUMENT UNCERTAINTY OF EACH MEASURED VARIABLE

Individual sources of errors are detailed in Table C-3.

C6. PERFORM A PRELIMINARY UNCERTAINTY ANALYSIS

In order to perform the preliminary uncertainty analysis, the functional relationship between the independent measurement parameters and the test results must be determined. The two main equations stated in Section C2 define the overall measurement relationships. Six other dependent parameters that are related to the parameters in Table B-1 are shown in Table C-3.

C6.1 Calculate the Bias and Precision Errors for Each Parameter. The estimates from the previously defined elements in Table C-3 are now summarized for each elemental term using the root-sum-square method, as 95% confidence is desired. The degrees of freedom for each parameter is greater than 30, so the student's t function will be 2.

For t_1 (SI):

$$B_{t_1} = [(0.194)^2 + (0.133)^2 + (0.167)^2 + (0.061)^2]^{1/2}$$
$$= [(0.0378) + (0.0178) + (0.0278) + (0.0037)]^{1/2} = 0.295$$

$$S_{t_1} = [(0.028)^2 + (0.056)^2 + (0.044)^2 + (0.009)^2]^{1/2}$$
$$= [(0.00077) + (0.00309) + (0.00198) + (0.00009)]^{1/2}$$
$$= 0.0770$$

$$U_{t_1} = [(B_{t_1})^2 + (2 \times S_{t_1})^2]^{1/2}$$
$$= [(0.295)^2 + (2 \times 0.0770)^2]^{1/2} = 0.333$$

For t_1 (I-P):

$$B_{t_1} = [(0.35)^2 + (0.24)^2 + (0.3)^2 + (0.11)^2]^{1/2}$$
$$= [(0.1225) + (0.0576) + (0.090) + (0.0121)]^{1/2} = 0.531$$

$$S_{t_1} = [(0.05)^2 + (0.1)^2 + (0.08)^2 + (0.017)^2]^{1/2}$$
$$= [(0.0025) + (0.010) + (0.0064) + (0.00029)]^{1/2}$$
$$= 0.139$$

$$U_{t_1} = [(B_{t_1})^2 + (2 \times S_{t_1})^2]^{1/2}$$
$$= [(0.531)^2 + (2 \times 0.139)^2]^{1/2} = 0.599$$

For p_1 (SI):

$$B_{p_1} = \begin{bmatrix}(0.001)^2 + (0.0172)^2 + (4.1369)^2 + (0.0276)^2 \\ + (0.0083)^2\end{bmatrix}^{1/2}$$
$$= \left[\begin{pmatrix}[1.07] + [297.1] + [17113564] \\ + [760.6] + [68.45]\end{pmatrix} \times 10^{-6}\right]^{1/2}$$
$$= 4.137$$

$$S_{p_1} = [(0.0007)^2 + (0.0062)^2 + (0.0041)^2 + (0.0345)^2]^{1/2}$$
$$= [([0.47] + [38.5] + [17.11] + [1188] \times 10^{-6})]^{1/2}$$
$$= 0.0352$$

TABLE C-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 1.181 in.)	Inside diameter micrometer
D	Pipe diameter	49.276 mm (1.940 in.)	48.768 to 49.530 mm (1.920 to 1.950 in.)	Inside diameter micrometer
t_1	Inlet liquid temperature	20°C (68.0°F)	10 to 30 °C (50.0 to 86.0°F)	Type T thermocouple
p_1	Inlet liquid pressure	380 kPa (55.1 psia)	275 to 825 kPa (39.9 to 119.7 psia)	Strain gage pressure transducer
ΔP	Nozzle pressure drop	68.95 kPa (10.0 psia)	34.5 to 172.4 kPa (5.00 to 25.00 psia)	Strain gage differential pressure transducer
C	Discharge coefficient	0.995 dimensionless	Not applicable	Calibration from an ISO 17025 certified lab

TABLE C-2 Relationship of the Calculated Parameters

Symbol	Dependent Parameter	Functional Relation	Functional Calculation	Nominal Value
A	Nozzle throat area	$f(d)$	$= \pi d^2/4$	324.3 mm² (0.503 in.²)
β	Nozzle ratio	$f(d, D)$	$= d/D$	0.4123 dimensionless
p_2	Absolute throat pressure	$f(p_1, \Delta P)$	$= p_1 - \Delta P$	311.5 kPa (45.1 psia)
ρ	Inlet liquid density	$f(p_1, t_1)$	None: property data	998.33 kg/m³ (62.324 lb$_m$/ft³)

$$U_{p_1} = [(B_{p_1})^2 + (2 \times S_{p_1})^2]^{1/2}$$
$$= [(4.137)^2 + (2 \times 0.0352)^2]^{1/2} = 4.138$$

For p_1 (I-P):

$$B_{p_1} = \begin{bmatrix} (0.00015)^2 + (0.0025)^2 + (0.6)^2 + (0.004)^2 \\ + (0.0012)^2 \end{bmatrix}^{1/2}$$
$$= \left[\begin{pmatrix} [0.0225] + [6.25] + [36000] \\ + [16.0] + [1.44] \end{pmatrix} \times 10^{-6}\right]^{1/2}$$
$$= 0.600$$

$$S_{p_1} = [(0.0001)^2 + (0.0009)^2 + (0.0006)^2 + (0.005)^2]^{1/2}$$
$$= [([0.01] + [0.810] + [0.360] + [25.0]) \times 10^{-6}]^{1/2}$$
$$= 0.00512$$

$$U_{p_1} = [(B_{p_1})^2 + (2 \times S_{p_1})^2]^{1/2}$$
$$= [(0.600)^2 + (2 \times 0.00512)^2]^{1/2} = 0.600$$

For ΔP (SI):

$$B_{\Delta P} = \begin{bmatrix} (0.0103)^2 + (0.0758)^2 + (0.4137)^2 \\ + (0.0434)^2 + (0.1034)^2 \end{bmatrix}^{1/2}$$
$$= \left[\begin{pmatrix} [0.107] + [5.752] + [171.1] \\ + [1.887] + [10.7] \end{pmatrix} \times 10^{-3}\right]^{1/2}$$
$$= 0.4354$$

$$S_{\Delta P} = \begin{bmatrix} (0.0014)^2 + (0.0048)^2 + (0.0138)^2 \\ + (0.1655)^2 \end{bmatrix}^{1/2}$$
$$= \left[\begin{pmatrix} [1.902] + [23.29] + [190.2] \\ + [27380] \end{pmatrix} \times 10^{-6}\right]^{1/2} = 0.1661$$

$$U_{\Delta p} = [(B_{\Delta p})^2 + (2 \times S_{\Delta p})^2]^{1/2}$$
$$= [(0.4354)^2 + (2 \times 0.1661)^2]^{1/2} = 0.548$$

For ΔP (I-P):

$$B_{\Delta P} = \begin{bmatrix} (0.0015)^2 + (0.011)^2 + (0.060)^2 \\ + (0.0063)^2 + (0.015)^2 \end{bmatrix}^{1/2}$$
$$= \left[\begin{pmatrix} [2.25] + [121] + [3600] \\ + [39.7] + [225] \end{pmatrix} \times 10^{-6}\right]^{1/2}$$
$$= 0.06315$$

$$S_{\Delta P} = \begin{bmatrix} (0.0002)^2 + (0.0007)^2 + (0.002)^2 \\ + (0.024)^2 \end{bmatrix}^{1/2}$$
$$= \left[\begin{pmatrix} [0.04] + [0.49] \\ + [4.00] + [576.0] \end{pmatrix} \times 10^{-6}\right]^{1/2} = 0.0241$$

$$U_{\Delta p} = [(B_{\Delta p})^2 + (2 \times S_{\Delta p})^2]^{1/2}$$
$$= [(0.06315)^2 + (2 \times 0.0241)^2]^{1/2} = 0.0794$$

For C:

$$B_C = [(0.0025)^2]^{1/2} = (6.25 \times 10^{-6})^{1/2} = 0.0025$$

$$S_C = 0.00$$

$$U_C = [(B_C)^2 + (2 \times S_C)^2]^{1/2}$$
$$= [(0.0025)^2 + (2 \times 0.0)^2]^{1/2} = 0.0025$$

Note: The uncertainty is calculated at this time for t_1, p_1, and ΔP so that they may be used in estimating errors in ρ and ε in Section C6.2.

TABLE C-3 Uncertainty of Each Measured Parameter

Parameter	Nominal Value	Error Origin	Calibration Error		Data Acquisition Error		Data Reduction Error	
			Bias Index	Precision Index	Bias Index	Precision Index	Bias Index	Precision Index
d, mm (in.)	20.32 (0.80)	See Note 1	0.0305 (0.0012)					
D, mm (in.)	49.276 (1.940)	See Note 1	0.0508 (0.002)					
t_1, °C (°F)	20 (68.0)	Calibration	0.194 (0.35)	0.028 (0.05)				
		Ice reference junction			0.133 (0.24)	0.056 (0.10)		
		Data acquisition			0.167 (0.30)	0.044 (0.080)		
		Data reduction/ curve fit					0.061 (0.11)	0.009 (0.017)
p_1, kPa (psia)	380 (55.1)	Excitation voltage	0.0010 (0.00015)	0.0007 (0.0001)				
		Signal conditioning	0.0172 (0.0025)	0.0062 (0.0009)				
		Calibration	4.1369 (0.60)	0.0041 (0.0006)				
		Data acquisition			0.0276 (0.004)	0.0345 (0.005)		
		Data reduction/ curve fit					0.0083 (0.0012)	
ΔP, kPa (psia)	68.95 (10.0)	Excitation voltage	0.0103 (0.0015)	0.0014 (0.0002)				
		Signal conditioning	0.0758 (0.011)	0.0048 (0.0007)				
		Calibration	0.4137 (0.06)	0.0138 (0.002)				
		Data acquisition			0.0434 (0.0063)	0.1655 (0.024)		
		Data reduction/ curve fit					0.1034 (0.015)	
C, dimensionless	0.995	Uncertainty from an ISO17025 lab calibration	0.0025					

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. The Calibration Bias Index is included to allow calculation of β and ε.

TABLE C-4 Calculated Density at Minimum, Nominal, and Maximum Temperature and Pressure

	t_1	p_1	ρ
Nominal value	20 °C (68.0°F)	380.0 kPa (55.1 psia)	998.33 kg/m^3 (62.324 lb$_m$/ft^3)
Max value	20.33°C (68.6°F)	384.1 kPa (55.51 psia)	998.27 kg/m^3 (62.320 lb$_m$/ft^3)
Min value	19.67°C (67.4°F)	375.9 kPa (54.52 psia)	998.40 kg/m^3 (62.328 lb$_m$/ft^3)

C6.2 Propagate the Bias and Precision Errors. The individual parameter errors are propagated into the flow rate according to a Taylor series expansion. The relative bias limit for the mass flow equation is as follows:

$$\frac{B_w}{\dot m} = \left[\begin{matrix}\left(1 \times \frac{B_C}{C}\right)^2 + \left(\frac{2}{1-\beta^4} \times \frac{B_d}{d}\right)^2 + \left(\frac{2}{1-\beta^4} \times \frac{B_D}{D}\right)^2 \\ + \left(\frac{1}{2} \times \frac{B_\rho}{\rho}\right)^2 + \left(\frac{1}{2} \times \frac{B_{\Delta P}}{\Delta P}\right)^2\end{matrix}\right]^{1/2}$$

Similarly, the relative precision index for the flow rate can be written as follows:

$$\frac{S_w}{\dot m} = \left[\begin{matrix}\left(1 \times \frac{S_C}{C}\right)^2 + \left(\frac{2}{1-\beta^4} \times \frac{S_d}{d}\right)^2 + \left(\frac{2}{1-\beta^4} \times \frac{S_D}{D}\right)^2 \\ + \left(\frac{1}{2} \times \frac{S_\rho}{\rho}\right)^2 + \left(\frac{1}{2} \times \frac{S_{\Delta P}}{\Delta P}\right)^2\end{matrix}\right]^{1/2}$$

Because d and D are already accounted for in the C term, the second and third terms of the above equations are zero. The density term (ρ) is a function of t_1 and p_1, and the variation is estimated by observing the change in density properties at the extremes of expected t_1 and p_1 as shown in Table C-4.

Using the maximum and minimum values to define the variation:

$$\rho = 998.33 \pm 0.0665, \text{ kg/m}^3 \quad \text{(SI)}$$

$$\rho = 62.324 \pm 0.004, \text{ lb}_m/\text{ft}^3 \quad \text{(I-P)}$$

Based on previous experience, the variations for ρ will be assumed to be entirely bias errors.

a. The bias and precision errors of the independent parameters are propagated separately all the way to the final test result.

b. Error propagation is performed, according to the functional relationship of Section C6.1, via a Taylor series. This requires a calculation of the sensitivity factors, either by differentiation or by computer perturbation. The individual terms are now summed together by the root-sum-square method, as a 95% confidence level is desired as shown below.

$$\frac{B_w}{\dot m} = \left[\begin{matrix}\left(1 \times \frac{B_C}{C}\right)^2 + \left(\frac{2}{1-\beta^4} \times \frac{B_d}{d}\right)^2 + \left(\frac{2}{1-\beta^4} \times \frac{B_D}{D}\right)^2 \\ + \left(\frac{1}{2} \times \frac{B_\rho}{\rho}\right)^2 + \left(\frac{1}{2} \times \frac{B_{\Delta P}}{\Delta P}\right)^2\end{matrix}\right]^{1/2}$$

SI:

$$\frac{B_w}{\dot m} = \left[\begin{matrix}\left(\frac{0.0025}{0.9950}\right)^2 + (0)^2 + (0)^2 \\ + \left(\frac{1}{2} \times \frac{0.0665}{998.33}\right)^2 + \left(\frac{1}{2} \times \frac{0.435}{68.95}\right)^2\end{matrix}\right]^{1/2}$$

$$\frac{B_w}{\dot m} = \left[\left(\begin{matrix}[6.313] + [0] + [0] \\ + [0.001109] + [9.969]\end{matrix}\right) \times 10^{-6}\right]^{1/2} = 0.004035$$

$$\frac{S_w}{\dot m} = \left[(0)^2 + (0)^2 + (0)^2 + (0)^2 + \left(\frac{1}{2} \times \frac{0.1661}{68.95}\right)^2\right]^{1/2}$$

$$= [(0.001205)^2]^{1/2} = 0.001205$$

$$U_m = \sqrt{(B_m^2 + 2S_m^2)} = \sqrt{0.00435^2 + 2 \times 0.001205^2}$$

$$= \sqrt{(16.283 + 2.904) \times 10^{-6}} = 0.0044 = 0.44\%;\ P = 95\%$$

I-P:

$$\frac{B_w}{\dot m} = \left[\begin{matrix}\left(\frac{0.0025}{0.9950}\right)^2 + (0)^2 + (0)^2 \\ + \left(\frac{1}{2} \times \frac{0.0043}{62.3240}\right)^2 + \left(\frac{1}{2} \times \frac{0.0632}{10}\right)^2\end{matrix}\right]^{1/2}$$

$$\frac{B_w}{\dot m} = \left[\left(\begin{matrix}[6.313] + [0] + [0] \\ + [0.00119] + [9.970]\end{matrix}\right) \times 10^{-6}\right]^{1/2} = 0.00435$$

$$\frac{S_m}{\dot m} = \left[(0)^2 + (0)^2 + (0)^2 + (0)^2 + \left(\frac{1}{2} \times \frac{0.02409}{10}\right)^2\right]^{1/2}$$

$$= [(0.001205)^2]^{1/2} = 0.001205$$

$$U_{\dot m} = \sqrt{(B_{\dot m}^2 + 2S_{\dot m}^2)} = \sqrt{0.00435^2 + 2 \times 0.001205^2}$$

$$= \sqrt{(16.283 + 2.904) \times 10^{-6}} = 0.0044 = 0.44\%;\ P = 95\%$$

C7. STUDY UNCERTAINTY RESULTS AND REASSESS THE ABILITY OF THE MEASUREMENT METHODS AND INSTRUMENTATION TO MEET ACCEPTABLE ACCURACY

The overall uncertainty is under the 0.75% goal at 0.44%. The selected system should meet the 0.75% uncertainty goal initially presented in the problem statement.

C8. INSTALL SELECTED INSTRUMENTATION IN ACCORD WITH RELEVANT STANDARDS OR BEST PRACTICES

All the initially specified measurement system will be used with the exception of the differential pressure measurement

TABLE C-5 Summary of Calculations

Fixed Nozzle Measurements				
Parameter	**Units**	**Value**		
d	mm (in.)	20.33 (0.80)		
D	mm (in.)	49.276 (1.940)		
C	Dimensionless	0.995		
Calculated Fixed Nozzle Parameters				
Parameter	**Units**	**Value**		
A	mm^2 ($in.^2$)	324.3 (0.503)		
β	Dimensionless	0.4126		
Data Round Measurements				
Round Number		**1**	**2**	**3**
t_1	°C (°F)	19.9 (67.82)	20.2 (68.36)	20.0 (68.00)
p_1	kPa (psia)	380.5 (55.19)	381.2 (55.29)	380.8 (55.23)
ΔP	kPa (psid)	69.11 (10.02)	69.15 (10.03)	68.96 (10.00)
Calculated Parameters for each data round				
p_2	kPa (psia)	311.39 (45.16)	312.05 (45.26)	311.84 (45.23)
ρ	kg/m^3 (lb_m/ft^3)	998.335 (62.324)	998.268 (62.320)	998.401 (62.328)
$\dot{m}$	kg/s (lb_m/s)	3.85 (8.480)	3.851 (8.482)	3.846(8.471)

that will use a sensor that is twice as accurate as initially specified.

C9. PERFORM INITIAL VERIFICATION OF DATA QUALITY

A data acquisition system is assembled and a data reduction program was developed and verified to match hand calculations for the flow measurement.

C10. COLLECT EXPERIMENTAL DATA SUBJECT TO ONGOING QUALITY CONTROL CRITERIA

Three rounds of data were taken as required by the test plan.

C11. ACCOMPLISH DATA REDUCTION AND ANALYSIS

A summary of all the data and calculations for this test run are shown in Table C-5.

C12. PERFORM FINAL UNCERTAINTY ANALYSIS

As the actual test parameters are very close to the initially estimated values, the initial analysis should still be valid.

C13. REPORT EXPERIMENTAL RESULTS

The final report would include all the data from Table B-5 and sufficient information to accurately define the testing installation. This would include the associated supporting documentation such as calibration reports on the pressure and temperature instrumentation, data acquisition equipment, technician responsible for the data, test date, time, and location. The final value for flow rate would be described as:

$$\dot{m} = 3.849 \text{ kg/s} \pm 0.017 \text{ kg/s}; P = 95\% \text{ (SI)}$$

$$\dot{m} = 8.478 \text{ lb}_m\text{/s} \pm 0.037 \text{ lb}_m\text{/s}; P = 95\% \text{ (I-P)}$$

The ±0.017 kg/s (0.037 lb_m/h) is found by taking the average value, 3.849 kg/s (8.478 lb_m/s), and multiplying by the uncertainty percentage determined in Section C6.2, 0.44%.

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INFORMATIVE ANNEX D INFORMATION REGARDING LIQUID FLOW MEASUREMENT UNCERTAINTIES FOR INSTALLATIONS THAT DO NOT MEET THE FLOWMETER MANUFACTURER'S REQUIREMENTS

D1. INTRODUCTION

Liquid flow measurements performed on installed products under field conditions generally involve installation constraints that are not in accordance with flowmeter manufacturer's installation requirements. More specifically, the piping configuration upstream and/or downstream of the flowmeter does not provide adequate straight lengths (in terms of a number of inside pipe diameters) that are needed to provide the uniform velocity profiles that the flowmeter manufacturer requires, which means that the actual uncertainties are much greater than the uncertainties that are provided by the liquid flowmeter manufacturer and do not apply.

Users of this standard could perform computational fluid dynamics (CFD) analyses as a step toward determining the liquid flow measurement uncertainty for each installation, but that may not be a viable approach due to cost and/or time constraints, and it would be difficult to translate the results into uncertainty predictions.

ASME Standard MFC-10M [A12]defines laboratory test methods for measuring velocity profiles with multiple piping configurations (installation effects). These tests are not routinely performed on commercial liquid flowmeters.

Some limited research was performed several years ago to quantify the effects of insufficient straight lengths over a range of straight lengths (inside pipe diameters) upstream and downstream of some types of liquid flowmeters. More specifically, NIST sponsored an industry cooperative research program on flowmeter installation effects between 1987 and 1996 and published a number of reports.

This annex provides brief descriptions of the work that was performed and the corresponding websites for the reports and/or technical papers.

New research work is needed to first assess what has been done previously and to extend the work to experimentally determine the actual uncertainties for different types of liquid flowmeters over a range of less-than-ideal flowmeter installation conditions that span the range of HVAC&R field installations.

This annex points the user to existing research reports and technical papers, but the committee has not performed a technical assessment of these documents. Web searches revealed other studies conducted by manufacturers, but ASHRAE's noncommercial policy prevents listing links to those sites.

D2. PREVIOUS RESEARCH RESULTS AND TECHNICAL PAPERS

D2.1 Technical Paper: ***Flowmeter Installation Effects—Wild Claims, Bright Ideas, and Stark Realities.*** The authors of this 1995 paper describe an eight-year project sponsored by a NIST-industry consortium that addressed the pipe flow distortions produced by selected piping configurations.

D2.2 ***Laser Doppler Velocimeter Studies of the Pipe Flow Produced by a Generic Header.*** This 1995 paper reported Laser Doppler Velocimeter measurements for the pipe flows produced downstream of a header with and without a conventional 19-tube concentric tube bundle flow conditioner.

D2.3 ***Effects of a Conventional 45-degree Elbow.*** This report describes the effects of a conventional 45-degree elbow and includes discussion regarding a 19-tube and 7-tube concentric tube bundle flow conditioner.

D2.4 ***Pipe Elbow Effects on the V-Cone Flowmeter.*** This 1993 paper presents installation effects on a special type of flowmeter with baseline comparisons to orifice plate differential pressure flowmeters.

POLICY STATEMENT DEFINING ASHRAE'S CONCERN FOR THE ENVIRONMENTAL IMPACT OF ITS ACTIVITIES

ASHRAE is concerned with the impact of its members' activities on both the indoor and outdoor environment. ASHRAE's members will strive to minimize any possible deleterious effect on the indoor and outdoor environment of the systems and components in their responsibility while maximizing the beneficial effects these systems provide, consistent with accepted Standards and the practical state of the art.

ASHRAE's short-range goal is to ensure that the systems and components within its scope do not impact the indoor and outdoor environment to a greater extent than specified by the Standards and Guidelines as established by itself and other responsible bodies.

As an ongoing goal, ASHRAE will, through its Standards Committee and extensive Technical Committee structure, continue to generate up-to-date Standards and Guidelines where appropriate and adopt, recommend, and promote those new and revised Standards developed by other responsible organizations.

Through its *Handbook*, appropriate chapters will contain up-to-date Standards and design considerations as the material is systematically revised.

ASHRAE will take the lead with respect to dissemination of environmental information of its primary interest and will seek out and disseminate information from other responsible organizations that is pertinent, as guides to updating Standards and Guidelines.

The effects of the design and selection of equipment and systems will be considered within the scope of the system's intended use and expected misuse. The disposal of hazardous materials, if any, will also be considered.

ASHRAE's primary concern for environmental impact will be at the site where equipment within ASHRAE's scope operates. However, energy source selection and the possible environmental impact due to the energy source and energy transportation will be considered where possible. Recommendations concerning energy source selection should be made by its members.

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