BSR/ASHRAE Standard 41.8-2016R

___________________Public Review Draft

Standard Methods for Liquid Flow Measurement

First Public Review (August 2022)
(Complete Draft for Full Review)

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FOREWORD

Compared to the 2016 version, this version includes (a) updated methods for determining when steady-state operation has been achieved for data recording, (b) changes to make it easier for higher-tier standards to adopt this standard by reference, and (c) a new uncertainty example prepared in accordance with the latest uncertainty procedures. This revision of ASHRAE 41.8-2016 (RA2019) meets ASHRAE’s mandatory language requirements.

Selecting an appropriate liquid 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.

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.

error: the difference between the observed value of the measurand and its corresponding true value.

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

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 prior to 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.

**steady-state criteria**: the criteria that establish negligible change of liquid flow with time.

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

**targeted set point**: a specific set of test conditions where the required liquid flow rate is known and has an associated operating tolerance.

**test point**: a specific set of test operating conditions for recording data where the measured required liquid 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**: equipment that is the subject of liquid flow measurements.

4. CLASSIFICATIONS

4.1 Liquid Flow Measurement Applications. Liquid flow measurement applications that are within the scope of this standard shall be classified as one of the following types:

4.1.1 **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 meets the instrument manufacturer’s installation requirements.)*

4.1.2 **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.)*

4.2 Liquid Flow Meters

4.2.1 **Mass Flow Meters**. Liquid flow meters in this category perform direct measurement of liquid mass flow rates.

4.2.2 **Volumetric Flow Meters**. Liquid flow meters in this category perform direct measurement of liquid volumetric flows. If liquid mass flow rates are required, each liquid volumetric flow measurement shall be multiplied by the liquid density in the measurement plane to obtain the liquid mass flow rate measurement.
4.3 Liquid Flow Measurement Methods

Liquid flow measurement methods that are within the scope of this standard are listed in Table 1. Each of these liquid flow measurement methods are described in Section 7.

Table 4-1 Liquid Flow Rate Measurement Methods

<table>
<thead>
<tr>
<th>Liquid Flow Measurement Method</th>
<th>Section Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coriolis Flowmeters</td>
<td>7.2</td>
</tr>
<tr>
<td>Thermal Flowmeters</td>
<td>7.3</td>
</tr>
<tr>
<td>Orifice Meters, Flow Nozzles, and Venturi Flowmeters</td>
<td>7.4</td>
</tr>
<tr>
<td>Turbine Flowmeters</td>
<td>7.5</td>
</tr>
<tr>
<td>Variable-Area Flowmeters</td>
<td>7.6</td>
</tr>
<tr>
<td>Ultrasonic Flowmeters</td>
<td>7.7</td>
</tr>
<tr>
<td>Vortex-Shedding Flowmeters</td>
<td>7.8</td>
</tr>
<tr>
<td>Drag-Force Flowmeters</td>
<td>7.9</td>
</tr>
<tr>
<td>Magnetic Flowmeters</td>
<td>7.10</td>
</tr>
<tr>
<td>Positive-Displacement Flowmeters</td>
<td>7.11</td>
</tr>
<tr>
<td>Pitot-static Tube Flowmeters</td>
<td>7.12</td>
</tr>
</tbody>
</table>

5. REQUIREMENTS

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

a. A document provided by the person or the organization that authorized the tests.
c. A rating standard.
d. A regulation or code.
e. Any combination of items a. through d.

The test plan shall specify:

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

5.2 Values to be Determined and Reported
The values to be determined and reported if specified in the test plan in Section 5.1 using the units of measure listed in Table 1 unless otherwise specified in the test plan.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SI Units</th>
<th>I-P Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid mass flow rate</td>
<td>kilogram per second</td>
<td>pound (avoirdupois) per second</td>
</tr>
<tr>
<td>Liquid mass flow rate uncertainty</td>
<td>(kg/s)</td>
<td>(lbm/s)</td>
</tr>
<tr>
<td>Liquid volumetric flow rate</td>
<td>cubic meter per second</td>
<td>cubic foot per second</td>
</tr>
<tr>
<td>Liquid volumetric flow rate uncertainty</td>
<td>(m³/s)</td>
<td>(cfs)</td>
</tr>
</tbody>
</table>

5.3 Test Requirements

5.3.1 Liquid Flow Operating State. Liquid flow measurements shall be restricted to applications where the entire flow stream in the flowmeter is in a “liquid-only” state during data recording.

5.3.2 Accuracy or Measurement Uncertainty. A selected liquid flowmeter shall meet or exceed the required liquid 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 liquid flow test point prior to the conduct of that test in accordance with the pretest uncertainty analysis procedures in ASME PTC 19.11.

5.3.4 Post-test Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the expected liquid flow measurement uncertainty for each liquid flow test point in accordance with the post-test uncertainty analysis procedures in ASME PTC 19.11. 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 Steady-State Test Criteria for Liquid Mass Flow Rate Measurements. Liquid mass flow rate test data shall be recorded at steady-state conditions if specified in the test plan in Section 5.1.

5.3.5.1 Steady-State Test Criteria for Liquid Mass Flow Rate Measurements Under Laboratory Test Conditions. If the test plan requires liquid mass flow rate test data points to be recorded at steady-state 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 5.3.5.3 if the test plan provides test points for liquid mass flow rate measurement.
   b. Apply the steady-state criteria in Section 5.3.5.4 if the test plan provides targeted set points for liquid mass flow rate measurement.

5.3.5.2 Steady-State Test Criteria for Liquid Mass Flow Rate Measurements Under Field Test Conditions. If the test plan requires liquid mass flow rate test data points to be recorded at steady-state test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, the methods in Section 5.3.5.1 are optional.
5.3.5.3 Steady-State Liquid Mass Flow Rate Criteria for Test Points

Starting with the time set to zero, sample not less than 30 liquid mass flow rate measurements \( N \) at equal time intervals \( \delta t \) over a test duration \( \Delta t \) where \( \Delta t \) is in time units. Equation 5-1 states the relationship of the test duration to the number of liquid mass flow rate samples and the equal time intervals.

\[
\Delta t = (N - 1)\delta t
\]  

(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 liquid mass flow rate fluctuations during operation near the steady-state conditions.)

Record each sampled liquid 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 liquid mass flow rate data trend line illustrated in Figure 5-1 using Equation 5-2.

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

(Informative Note: It should be noted that the units for the slope in Equation 5-2 are liquid mass flow rate, kg/s (lbm/s), divided by the units that the user has selected for time.)
Determine the mean offset $\mu$ of the sampled data using Equation 5-3, and then calculate the standard deviation $\sigma$ using Equation 5-4.

$$\mu = \frac{1}{N} \left[ \sum_{i=1}^{N} (\bar{m}_i - bt_i) \right] \text{kg/s (lbm/s)} \quad (5-3)$$

$$\sigma = \left[ \left( \frac{1}{(N-2)} \right) \sum_{i=1}^{N} (\bar{m}_i - bt_i - \mu)^2 \right]^{\frac{1}{2}} \text{kg/s (lbm/s)} \quad (5-4)$$

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

$$\bar{m} = \frac{1}{N} \left[ \sum_{i=1}^{N} (\bar{m}_i) \right] \text{kg/s (lbm/s)} \quad (5-5)$$

$\bar{m}$, as determined by Equation 5-5, represents the steady-state mean liquid mass flow rate provided that one of the following criteria is satisfied:

a. Apply Equation 5-6 if $2\sigma \geq \bar{m}_L$ where $\bar{m}_L$ is the specified operating tolerance limit for liquid mass flow rate, and if Equation 5-6 is satisfied by not less than 95% of the sampled liquid mass flow rates.

$$|\bar{m}_i - \mu| \leq 2\sigma \text{ kg/s (lbm/s)} \quad (5-6)$$
The horizontal dotted lines, that are located $2\sigma$ above and below $\mu$, are the boundaries of the 95\% sampled liquid mass flow rates scatter envelope.

b. Apply Equation 5-7 if $\hat{m}_L > 2\sigma$ where $\hat{m}_L$ is the specified operating tolerance limit for liquid mass flow rate, and if Equation 7 is satisfied by not less than 95\% of the sampled liquid mass flow rates.

$$|\hat{m}_i - \mu| \leq \hat{m}_L \text{ kg/s (lbm/s)} \quad (5-7)$$

The horizontal dashed lines, that are located $\hat{m}_L$ above and below $\mu$, are the boundaries of the 95\% sampled liquid mass flow rates scatter envelope.

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

**5.3.5.4 Steady-State Liquid Mass Flow Rate Criteria for Targeted Set Points**

Starting with the time set to zero, sample not less than 30 liquid mass flow rate measurements $N$ at equal time intervals $\delta t$ over a test duration $\Delta t$ where $\Delta t$ is in time units. Equation 5-8 states the relationship of the test duration to the number of samples and the equal time intervals.

$$\Delta t = (N - 1)\delta t \quad (5-8)$$

(*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 liquid mass flow rate fluctuations during operation near the steady-state conditions.)

Record each sampled liquid mass flow rate measurement $\hat{m}_i$ and the corresponding time $t_i$. Apply the least-squares line method to determine the slope $b$ of the liquid mass flow rate data trend line illustrated in Figure 5-2 using Equation 5-9.

$$b = \left\{ \frac{N(\sum_{i=1}^{N} t_i \hat{m}_i) - (\sum_{i=1}^{N} t_i)(\sum_{i=1}^{N} \hat{m}_i)}{N(\sum_{i=1}^{N} t_i^2) - (\sum_{i=1}^{N} t_i)^2} \right\} \quad (5-9)$$

(*Informative Note:* It should be noted that the units for the slope in Equation 5-9 are liquid mass flow rate, kg/s (lbm/s), divided by the units that the user has selected for time.)
Determine the mean offset $\mu$ of the sampled data using Equation 5-10 and calculate the standard deviation $\sigma$ using Equation 5-11.

$$\mu = \frac{1}{N} \left[ \sum_{i=1}^{N} (\bar{m}_i - bt_i) \right] \text{kg/s (lbm/s)} \quad (5-10)$$

$$\sigma = \left[ \left( \frac{1}{(N-2)} \right) \sum_{i=1}^{N} (m_i - bt_i - \mu)^2 \right]^{\frac{1}{2}} \text{kg/s (lbm/s)} \quad (5-11)$$

The mean of the sampled liquid mass flow rates, $\bar{m}$, is defined by Equation 5-12.

$$\bar{m} = \frac{1}{N} \left[ \sum_{i=1}^{N} (\bar{m}_i) \right] \text{kg/s (lbm/s)} \quad (5-12)$$

A tolerance on the fluctuations about the trend line represents a limit on the fluctuation level relative to the trend line of the sampled data. If the tolerance of fluctuations about the trend line is not specified in the test plan, the bounds for a 95% confidence limit for the fluctuations about the trend line shall then be determined according to Equation 5-13.

$$|\bar{m} - \bar{m}_{SP}| + |b\Delta t| + 2\sigma \leq \bar{m}_L \text{ kg/s (lbm/min)} \quad (5-13)$$

The steady-state condition of the set point liquid mass flow rate, $\bar{m}_{SP}$, exists (a) where Equation 5-14 is satisfied by not less than 95% of the sampled liquid mass flow rates where $\bar{m}_L$ is the operating tolerance limit for liquid mass flow rate.
\( (\bar{m}_{SP} - \bar{m}_L) \leq \bar{m}_i \leq (\bar{m}_{SP} + \bar{m}_L), \text{ kg/s (lbm/s)} \) \hspace{1cm} (5-14)

(b) where

\[-0.50 \bar{m}_L \leq (\bar{m} - \bar{m}_{SP}) \leq 0.50 \bar{m}_L \text{ kg/s (lbm/s)} \] \hspace{1cm} (5-15)

and (c) where

\[ |b\Delta t| \leq 0.50\bar{m}_L \text{ kg/s (lbm/s)} \] \hspace{1cm} (5-16)

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

5.3.6 Unsteady Liquid Mass Flow Rate Measurements. If required by the test plan in Section 5.1, liquid 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.

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

5.3.7.1 Steady-State Test Criteria for Liquid Volumetric Flow Rate Measurements Under Laboratory Test Conditions. If the test plan requires liquid volumetric flow rate test data points to be recorded at steady-state 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 5.3.7.3 if the test plan provides test points for liquid volumetric flow rate measurement.
b. Apply the steady-state criteria in Section 5.3.7.4 if the test plan provides targeted set points for liquid volumetric flow rate measurement.

5.3.7.2 Steady-State Test Criteria for Liquid Volumetric Flow Rate Measurements Under Field Test Conditions. If the test plan requires liquid volumetric flow rate test data points to be recorded at steady-state test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, the methods in Section 5.3.7.1 are optional.

\((Informative \ Note:) \) The steady-state methods in Section 5.3.7.1 are likely to be impractical under field test conditions. Section 5.3.8 provides instructions for making measurements that are not at steady state conditions.)

5.3.7.3 Steady-State Liquid Volumetric Flow Rate Criteria for Test Points

Starting with the time set to zero, sample not less than 30 liquid volumetric flow rate measurements \( N \) at equal time intervals \( \delta t \) over a test duration \( \Delta t \) where \( \Delta t \) is in time units. Equation 5-17 states the relationship of the test duration to the number of liquid volumetric flow rate samples and the equal time intervals.

\[ \Delta t = (N - 1)\delta t \] \hspace{1cm} (5-17)

\((Informative \ Note:) \) 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 liquid volumetric flow rate fluctuations during operation near the steady-state conditions.)

Record each sampled liquid 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 liquid volumetric flow rate data trend line illustrated in Figure 5-3 using Equation 5-18.

\[
b = \left\{ \frac{[N \sum_{i=1}^{N} Q_i t_i - (\sum_{i=1}^{N} t_i) \sum_{i=1}^{N} Q_i]}{[N \sum_{i=1}^{N} t_i^2 - (\sum_{i=1}^{N} t_i)^2]} \right\} \tag{5-18}
\]

**Informative Note:** It should be noted that the units for the slope in Equation 5-18 are liquid volumetric flow rate, \( \text{m}^3/\text{s} \) (cfs), divided by the units that the user has selected for time.

![Graphical Illustration of the Method for Determining the Steady-State Liquid Volumetric Flow Rate Criteria for Test Points](image)

Determine the mean offset \( \mu \) of the sampled data using Equation 5-19, and then calculate the standard deviation \( \sigma \) using Equation 5-20.

\[
\mu = \frac{1}{N} \left[ \sum_{i=1}^{N} (Q_i - bt_i) \right] \text{ m}^3/\text{s} \text{ (cfs)} \tag{5-19}
\]
\[ \sigma = \left[ \frac{1}{(N-2)} \sum_{i=1}^{N} (Q_i - b t_i - \mu)^2 \right]^{1/2} \text{ m}^3/\text{s} \quad (5-20) \]

The mean of the sampled liquid volumetric flow rates \( \bar{Q} \) is defined by Equation 5-21.

\[ \bar{Q} = \frac{1}{N} \left[ \sum_{i=1}^{N} (Q_i) \right] \text{ m}^3/\text{s} \quad (5-21) \]

\( \bar{Q} \), as determined by Equation 5-21, represents the steady-state mean liquid volumetric flow rate provided that one of the following criteria is satisfied:

a. Apply Equation 5-22 if \( 2\sigma \geq Q_L \) where \( Q_L \) is the specified operating tolerance limit for liquid volumetric flow rate, and if Equation 5-22 is satisfied by not less than 95% of the sampled liquid volumetric flow rates.

\[ |Q_i - \mu| \leq 2\sigma \text{ m}^3/\text{s} \quad (5-22) \]

The horizontal dotted lines, that are located \( 2\sigma \) above and below \( \mu \), are the boundaries of the 95% sampled liquid volumetric flow rate scatter envelope.

b. Apply Equation 5-23 if \( Q_L > 2\sigma \) where \( Q_L \) is the specified operating tolerance limit for liquid volumetric flow rate, and if Equation 5-23 is satisfied by not less than 95% of the sampled liquid volumetric flow rates.

\[ |Q_i - \mu| \leq Q_L \text{ m}^3/\text{s} \quad (5-23) \]

The horizontal dashed lines, that are located \( Q_L \) above and below \( \mu \), are the boundaries of the 95% sampled liquid volumetric flow rates scatter envelope.

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

5.3.7.4 Steady-State Liquid Volumetric Flow Rate Criteria for Targeted Set Points

Starting with the time set to zero, sample not less than 30 liquid volumetric flow rate measurements \( N \) at equal time intervals \( \delta t \) over a test duration \( \Delta t \) where \( \Delta t \) is in time units. Equation 5-24 states the relationship of the test duration to the number of samples and the equal time intervals.

\[ \Delta t = (N - 1)\delta t \quad (5-24) \]

(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 liquid volumetric flow rate fluctuations during operation near the steady-state conditions.)

Record each sampled liquid 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 liquid volumetric flow rate data trend line illustrated in Figure 5-4 using Equation 5-25.

\[ b = \frac{\left[ N(\sum_{i=1}^{N} t_i Q_i) - (\sum_{i=1}^{N} t_i)(\sum_{i=1}^{N} Q_i) \right]}{N(\sum_{i=1}^{N} t_i^2) - (\sum_{i=1}^{N} t_i)^2} \quad (5-25) \]

(Informative Note: It should be noted that the units for the slope in Equation 5-25 are liquid volumetric...
flow rate, m³/s (cfs) divided by the units that the user has selected for time.

![Graphical illustration of the method for determining the steady-state liquid volumetric flow rate criteria for targeted set points](image)

Figure 5-4 Graphical illustration of the method for determining the steady-state liquid volumetric flow rate criteria for targeted set points

Determine the mean offset μ of the sampled data using Equation 5-26 and calculate the standard deviation σ using Equation 5-27.

\[
\mu = \frac{1}{N} \left[ \sum_{i=1}^{N} (Q_i - b t_i) \right] \text{ m}^3/\text{s (cfs)} \quad (5-26)
\]

\[
\sigma = \left[ \left( \frac{1}{(N-2)} \right) \sum_{i=1}^{N} (Q_i - b t_i - \mu)^2 \right]^{1/2} \text{ m}^3/\text{s (cfs)} \quad (5-27)
\]

The mean of the sampled liquid volumetric flow rates \( \bar{Q} \) is defined by Equation 5-28.

\[
\bar{Q} = \frac{1}{N} \left[ \sum_{i=1}^{N} Q_i \right] \text{ m}^3/\text{s (cfs)} \quad (5-28)
\]

A tolerance on the fluctuations about the trend line represents a limit on the fluctuation level relative to the trend line of the sampled data. If the tolerance of fluctuations about the trend line is not specified in the test plan, the bounds for a 95% confidence limit for the fluctuations about the trend line shall then be determined according to Equation 5-29.

\[
|\bar{Q} - Q_{SP}| + |b \Delta t| + 2\sigma \leq Q_L \text{ m}^3/\text{s (cfs)} \quad (5-29)
\]
The steady-state condition of the set point liquid volumetric flow rate, \( Q_{SP} \), exists (a) where Equation 5-30 is satisfied by not less than 95% of the sampled liquid volumetric flow rates where \( Q_L \) is the operating tolerance limit for liquid volumetric flow rate

\[
(Q_{SP} - Q_L) \leq Q_i \leq (Q_{SP} + Q_L) \text{ m}^3/\text{s (cfs)} \tag{5-30}
\]

(b) where

\[
-0.50 Q_L \leq (\bar{Q} - Q_{SP}) \leq 0.50 Q_L \text{ m}^3/\text{s (cfs)} \tag{5-31}
\]

and (c) where

\[
|b\Delta t| \leq 0.50 Q_L \text{ m}^3/\text{s (cfs)} \tag{5-32}
\]

(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 Unsteady Liquid Volumetric Flow Rate Measurements. If required by the test plan in Section 5.1, liquid mass flow rate test data or liquid volumetric flow rate data shall be recorded:

1. at operating conditions that are not steady state,
2. at the time intervals specified in the test plan,
3. within the test condition limits specified in the test plan,
4. using instrument response times specified in the test plan.

5.3.9 Liquid Properties. If not specified in the test plan in Section 5.1, the liquid property data shall be obtained from the NIST Standard Reference Database 23 (REFPROP)\(^2\) or from the source of the liquid and shall be recorded in the test report.

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 Notes:

a. For further reading, ISO/IEC 17025, General Requirements for the Competence of Testing and Calibration Laboratories\(^A^4\), defines good test laboratory practices.

b. Informative Appendix 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 41.13 if temperature measurements are required.
   b. Pressure – ASHRAE Standard 41.34 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 in Section 5.1, 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 flow meter in accordance with the flow meter 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 in Section 5.1, 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 flow meter in accordance with the flow meter 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 Constraint on All Liquid Flow Rate Measurement Methods. A selected liquid flow measurement plane
(a) shall exceed 10 inside pipe diameters downstream of an obstruction or any change in the liquid flow direction and (b) shall exceed 5 inside pipe diameters upstream of an obstruction or change in the liquid flow direction unless otherwise specified by the liquid flowmeter instrument manufacturer or by the flowmeter supplier.

7.2 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.

7.3 Thermal Flowmeters. Thermal flowmeters provide direct measurement of liquid mass flow rates. The basic elements of thermal mass flowmeters are two temperature sensors that are located on opposite sides of a known heat source that supplies a constant heat input to the liquid. The liquid mass flow rate shall be obtained from Equation 7-1.

\[ \dot{m} = \frac{Kq}{C_p(T_2-T_1)} \]  

(7-1)

where

\[ \dot{m} = \text{liquid mass flow rate, kg/s (lbm/s)} \]

\[ K = \text{meter coefficient provided by the manufacturer, dimensionless} \]

\[ q = \text{constant heat flux rate, kJ/s (Btu/s)} \]

\[ C_p = \text{specific heat of the liquid, kJ/(kg- °C) (Btu/(lbm-°F))} \]

\[ T_1 = \text{entering liquid temperature, °C (°F)} \]

\[ T_2 = \text{exiting liquid temperature, °C (°F)} \]

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

7.4.1 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.
FIGURE 7-1. Orifice Section of an Orifice Flowmeter
Reprinted with Permission of ASME.
FIGURE 7-2. Examples of Flow Nozzles Used in Nozzle Flowmeters
Reprinted with Permission of ASME.
7.4.2 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\(^5\) includes an example of this iterative procedure on page 25, and 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.

7.4.2.1 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 $\geq 10$ nozzle inlet inside diameters. The required straight length downstream from the nozzle flowmeter discharge shall be $\geq 5$ nozzle inlet inside diameters.\(^6\)
7.4.2.2 Measurements: Measurements required for this nozzle liquid flow shall be:
   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)

7.4.2.3 Nozzle Limits for Use and Reynolds Number. Limits for the use for long radius nozzle are:
   a. \( 50 \text{ mm (2 in.)} \leq D \leq 630 \text{ mm (25 in.)} \)
   b. \( \frac{R_s}{D} \leq 3.2 \left(10^{-4}\right) \) where \( R_s \) is the mean of the surface roughness in the upstream duct
   c. \( 1 \left(10^4\right) \leq Re_D \leq 1000 \left(10^7\right) \) where \( Re_D \) is defined in Equation 7-2.

\[
Re_D = \frac{\rho V D}{\mu}
\]  
(7-2)

where
\( \rho = \) nozzle inlet liquid density, kg/m³ (lbm/ft³)
\( V = \) nozzle throat average liquid velocity, m/s (ft/s)
\( D = \) nozzle inlet inside diameter, m (ft)
\( \mu = \) nozzle inlet dynamic viscosity, kg/(m-s) (lbm/(ft-s))

7.4.2.4 Nozzle Beta Ratio. The nozzle beta ratio shall be obtained from Equation 7-3. If liquid flow operating temperatures are not within ±6°C (±10°F) of the of the ambient temperature during the dimensional measurements, parameters \( d, D, \) and \( \beta \) shall be corrected to account for thermal expansion in compliance with ASME PTC 19.56 Section 3-10.

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

7.4.2.5 Nozzle Inlet Liquid Density. The nozzle inlet liquid density \( \rho \) shall be obtained from the liquid property data prescribed in Section 5.3.7 as a function of the nozzle inlet temperature \( t_1 \) and pressure \( p_1 \) at each data point.

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

In SI units:

\[
Q = C A K_1 \sqrt{\frac{2(\Delta p)}{\rho(1-\beta^4)}}
\]  
(7-4)

where
\( Q = \) nozzle liquid volumetric flow rate, m³/s
\( C = \) nozzle discharge coefficient, dimensionless
\( A = \) nozzle throat area, m²
\( K_1 = \) nozzle calibration coefficient, dimensionless
In I-P units:

\[
Q = 0.47268 \times CAK_1 \sqrt{\frac{2(\Delta p)}{\rho(1-\beta^4)}}
\]

(7-5)

where

- \( Q = \) nozzle liquid volumetric flow rate, cfs
- \( C = \) nozzle discharge coefficient, dimensionless
- \( A = \) nozzle throat area, ft
- \( K_1 = \) nozzle calibration coefficient, dimensionless
- \( \rho = \) nozzle inlet liquid density, lbm/ft³
- \( \Delta p = \) nozzle differential pressure, psid
- \( \beta = d/D, \) dimensionless
- 0.47268 = units conversion coefficient, \( \sqrt{\frac{(lb\cdot m^2/ft^3)}{(psid-in^4/sec^2)}} \)

If the liquid flow operating temperatures are not the same as the liquid flow operating temperatures during calibration, parameters \( d, D, \) and \( \beta \) shall be corrected to account for thermal expansion in accordance with ASME PTC 19.55 Sections 3-10.

### 7.4.2.7 Nozzle Discharge Coefficient

The dimensionless nozzle discharge coefficient \( C \) is a function of \( \beta \) 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.

\[
C = 0.9965 - (0.00653\beta^{0.5}) \left( \frac{10^6}{Re_D} \right)^{0.5}
\]

(7-6)

The Reynolds number shall be calculated from Equation 7-2, 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 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 mass flow rates for orifices, ISA 1932 nozzles, venturi nozzles, or venturi tubes, refer to the paragraphs in ASME MFC-3M 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 ASME MFC-3M® for ISA 1932 Nozzles, Venturi Nozzles, and Venturi Tubes

<table>
<thead>
<tr>
<th>Flowmeter Type</th>
<th>Limit of Use Section Number</th>
<th>Discharge Coefficient Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orifices</td>
<td>2-4.3.1</td>
<td>2-4</td>
</tr>
<tr>
<td>ISA 1932 Nozzles</td>
<td>3-4.1.6.1</td>
<td>3-6</td>
</tr>
<tr>
<td>Venturi Nozzles</td>
<td>3-4.3.4.1</td>
<td>3-16</td>
</tr>
<tr>
<td>Venturi Tubes</td>
<td>4-4.5.1</td>
<td>4-4.5.1, 4-5.4.2, or 4-4.5.3</td>
</tr>
</tbody>
</table>

7.4.2.8 Nozzle Liquid Mass Flow Rates. The nozzle liquid mass flow rate shall be obtained from Equation 7-9, where \( \rho \) is the nozzle inlet liquid density, kg/m³ (lbm/ft³) and \( Q \) is the liquid volumetric flow rate, m³/s (cfs), using Equation 7-4 in SI units or Equation 7-5 in I-P units.

\[
\dot{m} = \rho Q, \text{ kg/s (lbm/s)}
\]  

7.5 Turbine Flow Meters. Turbine flowmeters are volumetric flow meters 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 these methods: (a) reluctance sensors, (b) inductance sensors, (c) capacitance sensors, (d) Hall-effect sensors, or (e) mechanical sensors.

7.6 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.
7.7 Ultrasonic Flowmeters. Ultrasonic flowmeters measure liquid flow velocity. Clamp-on ultrasonic flow meters measure liquid velocity within a pipe or tube without being inserted into the flow stream. 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 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.

7.8 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.

7.9 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 7-8 in SI units and by Equation 7-9 in I-P units. The manufacturer designs the immersed element so that the drag coefficient is constant over the specified range of Reynolds numbers.

In SI units:

\[ V = \frac{2 f_d}{\sqrt{C_d \Delta \rho}} \]  

(7-8)

where

- \( V \) = liquid velocity, m/s
- \( f_d \) = drag force, N
$C_d =$ drag coefficient, dimensionless
$A =$ cross-section area, $\text{m}^2$
$\rho =$ liquid density, $\text{kg/m}^3$

In I-P units:

$$V = \sqrt{\frac{2 f_d \rho}{C_d A \rho}}$$

where

$V =$ liquid velocity, $\text{ft/s}$
$f_d =$ drag force, $\text{lb}$
$C_d =$ drag coefficient, dimensionless
$A =$ cross-section area, $\text{ft}^2$
$\rho =$ liquid density, $\text{lbm/ft}^3$
$g_c =$ gravitational constant, $32.174 \ (\text{lbm-ft)/(lbf-s}^2)$

### 7.10 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:**

- Magnetic tube flowmeters have no flow obstructions, so the pressure loss in these flowmeters is less than for many other types of flowmeters.
- Most heating, ventilating, air-conditioning, and refrigeration liquids have enough electrical conductivity to be used in these flowmeters.
- 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 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 7-10.

$$Q = \frac{V_i}{t}$$

where

$Q =$ liquid flow rate, $\text{m}^3/\text{s (cfs)}$
$V_i =$ trapped liquid volume, $\text{m}^3 \ (\text{ft}^3)$
$t =$ cycle time, $\text{s}$

### 7.12 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 7.13.1, 7.13.2, and 7.13.3 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: An Example of a Pitot-Static Tube

7.12.1 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.
7.12.1.1 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

$$P_v = P_t - P_s, \text{ Pa (psia)}$$  \hspace{1cm} (7-11)

7.12.1.2 Average Velocity Pressure. The average velocity pressure $P_{va}$ shall be obtained from Equation 7-12 where $n$ is the number of velocity pressure sampling points.

$$P_{va} = \left( \frac{\sum_{i=1}^{n} P_{vi}}{n} \right)^2, \text{ Pa (psia)}$$  \hspace{1cm} (7-12)

7.12.1.3 Average Liquid Velocity. The average liquid velocity shall be obtained from the density at the traverse plane and the average velocity pressure from Equation 45 in SI units and from Equation 46 in I-P units.

In SI units:
\[ V_a = K_2 \sqrt{\frac{2P_{va}}{\rho}} \]  

(7-13)

where

\[ V_a = \text{average liquid velocity, m/s} \]
\[ K_2 = \text{calibration factor provided by the manufacturer, dimensionless} \]
\[ P_{va} = \text{average velocity pressure, Pa} \]
\[ \rho = \text{liquid density in the measurement plane, kg/m}^3 \]

In I-P units:

\[ V_a = 68.0666K_2 \sqrt{\frac{2P_{va}}{\rho}} \]  

(7-14)

where

\[ V_a = \text{average liquid velocity, ft/s} \]
\[ K_2 = \text{calibration factor provided by the manufacturer, dimensionless} \]
\[ P_{va} = \text{average velocity pressure, psia} \]
\[ \rho = \text{liquid density in the measurement plane, lbm/ft}^3 \]
\[ 68.0666 = \text{units conversion factor coefficient, } \frac{(lbm-in^2)}{(lb-ft-s^2)} \]

7.12.1.4 Liquid Volumetric Flow. The liquid volumetric flow at the Pitot-static tube traverse plane shall be obtained from Equation 7-15.

\[ Q = V_a A \]  

(7-15)

where

\[ Q = \text{liquid volumetric flow rate, m}^3/\text{s (cfs)} \]
\[ V_a = \text{average liquid velocity, m/s (ft/s)} \]
\[ A = \text{measurement plane cross section area, m}^2 (\text{ft}^2) \]

7.12.2.2 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.

7.12.2.1 Average Velocity Pressure. The average velocity pressure shall be obtained from Equation 7-16.

\[ P_{va} = P_{ta} - P_{sa} \]  

(7-16)

where

\[ P_{va} = \text{average velocity pressure, Pa (psia)} \]
\[ P_{ta} = \text{measured average total pressure, Pa (psia)} \]
\[ P_{sa} = \text{measured average static pressure, Pa (psia)} \]
7.12.2.2 **Average Liquid Velocity.** The average liquid velocity shall be obtained from Equation 7-17 in SI units or from Equation 7-18 in I-P units:

In SI units:

\[ V_a = K_3 \sqrt{\frac{2P_{va}}{\rho}} \]  

(7-17)

where

- \( V_a \) = average liquid velocity, m/s
- \( K_3 \) = calibration coefficient, dimensionless
- \( P_{va} \) = average velocity pressure, Pa
- \( \rho \) = liquid density in the measurement plane, kg/m³

In I-P units:

\[ V_a = 68.0666K_3 \sqrt{\frac{2P_{va}}{\rho}} \]  

(7-18)

where

- \( V_a \) = average liquid velocity, ft/s
- \( K_3 \) = calibration coefficient, dimensionless
- \( P_{va} \) = average velocity pressure, psia
- \( \rho \) = liquid density in the measurement plane, lbm/ft³

68.0666 = units conversion factor coefficient, \( \sqrt{\left(\frac{lbm-in^2}{lb-ft-s^2}\right)} \)

7.12.2.4 **Liquid Volumetric flow.** The liquid volumetric flow at the Pitot-static tube array measurement plane shall be obtained from Equation 7-19.

\[ Q = V_a A \]  

(7-19)

where

- \( Q \) = liquid volumetric flow rate, m³/s (cfs)
- \( V_a \) = average liquid velocity, m/s (ft/s)
- \( A \) = measurement plane cross section area, m² (ft²)

7.12.3 **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.

7.12.3.1 **Average Velocity Pressure.** The average velocity pressure shall be obtained from Equation 7-20.

\[ P_{va} = P_{ta} - P_{sa} \]  

(7-20)

where
\( P_{va} = \) average velocity pressure, Pa (psia)  
\( P_{ta} = \) measured average total pressure, Pa (psia)  
\( P_{sa} = \) measured average static pressure, Pa (psia)

### 7.12.3.2 Average Liquid Velocity

The average liquid velocity shall be obtained from Equation 7-21 in SI units or from Equation 7-22 in I-P units:

**In SI units:**

\[
V_a = K_4 \sqrt{ \frac{2 P_{va}}{\rho}} \quad (7-21)
\]

where

\( V_a \) = average liquid velocity, m/s  
\( K_4 \) = calibration coefficient, dimensionless  
\( P_{va} \) = average velocity pressure, Pa  
\( \rho \) = liquid density in the measurement plane, kg/m\(^3\)

**In I-P units:**

\[
V_a = 68.0666 K_4 \sqrt{ \frac{2 P_{va}}{\rho}} \quad (7-22)
\]

where

\( V_a \) = average liquid velocity, ft/s  
\( K_4 \) = calibration coefficient, dimensionless  
\( P_{va} \) = average velocity pressure, psia  
\( \rho \) = liquid density in the measurement plane, lbm/ft\(^3\)  
68.0666 = units conversion factor coefficient, \( \sqrt{ \frac{\text{lbm} \cdot \text{in}^2}{\text{lb} \cdot \text{ft} \cdot \text{s}^2}} \)

### 7.12.3.3 Liquid Volumetric flow

The liquid volumetric flow at the Pitot-static tube array measurement plane shall be obtained from Equation 7-23:

\[
Q = V_a A \quad (7-23)
\]

where

\( Q \) = liquid volumetric flow rate, m\(^3\)/s (cfs)  
\( V_a \) = average liquid velocity, m/s (ft/s)  
\( A \) = measurement plane cross section area, m\(^2\) (ft\(^2\))

### 8. Uncertainty Requirements

**8.1 Post-Test Uncertainty Analysis**

A post-test analysis of the measurement system uncertainty, performed in accordance with ASME PTC 19.1, shall accompany each liquid flow 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 Notes:)*

- This procedure is illustrated in the uncertainty analysis that is provided in Informative Appendix B.
b. Informative Appendix C provides information regarding additional 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:

\[ v = \bar{X}_m \pm U_{\bar{X}} \left( P\% \right) \]  

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: liquid mass flow rate = 2.538 kg/s ± 0.013 kg/s (5.595 lbm/s ± 0.028 lbm/s); 95% states that the measured liquid flow is believed to be 2.538 kg/s (5.595 lbm/s) with a 95% probability that the true value lies within ± 0.013 kg/s (± 0.028 lbm/s) of this value.)

9. 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 of the requirements in Section 9. Otherwise, Section 9 specifies the test report requirements.

9.1 Test Identification

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

9.2 Unit Under Test Description

a. Model number and serial number.
b. Liquid specification.
c. Source of liquid properties.

9.3 Instrument Description

a. Flowmeter description, model number, serial number, and location within the UUT.
b. Operating range.
c. Instrument accuracy based on specifications or calibration.
d. Documentational evidence of instrument calibration.

9.4 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.

9.5 Test Conditions

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

9.6 Test Results.
If specified in the Test Plan in Section 5.1:
   a. Liquid mass flow rate, kg/s (lbm/s).
   b. Liquid mass flow rate pretest uncertainty, kg/s (lbm/s).
   c. Liquid mass flow rate post-test uncertainty, kg/s (lbm/s).
   d. Liquid volumetric flow rate, m³/s (cfs)
   e. Liquid volumetric flow rate pretest uncertainty, m³/s (cfs)
   f. Liquid volumetric flow rate post-test uncertainty, m³/s (cfs)

10. REFERENCES
4. ANSI/ASHRAE Standard 41.3-2022, Standard Methods for Pressure Measurement. ASHRAE, Atlanta, GA. See Note 2

Note 1: Reference 3 is not required if there are no temperature measurements.
Note 2: Reference 4 is not required if there are no pressure measurements.
Note 3: References 5 and 6 are only required if using an Orifice, Flow Nozzle, or Venturi Tube
(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


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

Following 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 7.4.2.5 of this standard, and output signals are appropriately conditioned to be read by a data acquisition system. Water is the working fluid. The uncertainty estimate is to be determined for a given differential pressure within the instrument operating range. Reported uncertainty units are kg/s (lbm/s).

### 7.4.2.5 Nozzle Liquid Volumetric Flow Rates

Nozzle liquid volumetric flow rates shall be calculated from Equation 7-4 in SI units or Equation 7-5 in I-P units.

In SI units:

\[
Q = CAK_1 \sqrt{\frac{2(\Delta p)}{\rho(1-\beta^2)}} 
\]

(7-4)

where

- \(Q\) = nozzle liquid volumetric flow rate, m³/s
- \(C\) = nozzle discharge coefficient, dimensionless
- \(A\) = nozzle throat area, m²
- \(K_1\) = nozzle calibration coefficient, dimensionless
- \(\rho\) = nozzle inlet liquid density, kg/m³
- \(\Delta p\) = nozzle differential pressure, Pa
- \(\beta\) = \(d/D\), dimensionless

In I-P units:

\[
Q = CAK_1 \sqrt{\frac{2(\Delta p)}{\rho(1-\beta^2)}} \times \frac{1}{(32.174 \times g)} 
\]

(7-5)
In I-P units:

\[ Q = 0.47268 \times CAK_1 \sqrt{\frac{2(\Delta p)}{\rho(1-\beta^4)}} \]  

(7-5)

where

- \( Q \) = nozzle liquid volumetric flow rate, cfs
- \( C \) = nozzle discharge coefficient, dimensionless
- \( A \) = nozzle throat area, in\(^2\)
- \( K_1 \) = nozzle calibration coefficient, dimensionless
- \( \rho \) = nozzle inlet liquid density, lbm/ft\(^3\)
- \( \Delta p \) = nozzle differential pressure, psid
- \( \beta = \frac{d}{D} \), dimensionless
- 0.47268 = units conversion coefficient, \( \sqrt{\frac{(lbm-ft^3)}{(psid-in^4-s^2)}} \)

### 7.4.2.7 Nozzle Liquid Mass Flow Rates.

The nozzle liquid mass flow rate shall be obtained from Equation 7-7, where \( \rho \) is the nozzle inlet liquid density, kg/m\(^3\) (lbm/ft\(^3\)) and \( Q \) is the liquid volumetric flow rate, m\(^3\)/s (cfs), using Equation 7-5 in SI units or Equation 7-6 in I-P units.

\[ \dot{m} = \rho Q, \text{ kg/s (lbm/s)} \]  

(7-7)
### Table B-1. Independent Parameters Descriptions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Independent Parameter</th>
<th>Nominal Value</th>
<th>Expected Range</th>
<th>Initial Selected Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d )</td>
<td>Nozzle Throat Diameter</td>
<td>20.32 mm (0.80 in)</td>
<td>10 to 30 mm (0.394 to 1.181 in.)</td>
<td>Inside Diameter Micrometer</td>
</tr>
<tr>
<td>( D )</td>
<td>Pipe Diameter</td>
<td>49.276 mm (1.940 in.)</td>
<td>48.768 to 49.530 mm (1.920 to 1.950 in.)</td>
<td>Inside Diameter Micrometer</td>
</tr>
<tr>
<td>( t_1 )</td>
<td>Inlet Liquid Temperature</td>
<td>20°C (68°F)</td>
<td>10°C (86°F)</td>
<td>Type T thermocouple</td>
</tr>
<tr>
<td>( p_1 )</td>
<td>Inlet Liquid Pressure</td>
<td>380 kPa (55.1 psia)</td>
<td>275 to 825 kPa (39.9 to 119.7 psia)</td>
<td>Strain Gage Pressure Transducer</td>
</tr>
<tr>
<td>( \Delta P )</td>
<td>Nozzle Pressure Drop</td>
<td>68.95 kPa (10.0 psid)</td>
<td>34.5 to 172.4 kPa (5.00 to 25.00) psid</td>
<td>Strain Gage Differential Pressure Transducer</td>
</tr>
<tr>
<td>( C )</td>
<td>Discharge Coefficient</td>
<td>0.995 dimensionless</td>
<td>Not applicable</td>
<td>Calibration from an ISO 17025 Certified Lab</td>
</tr>
</tbody>
</table>

### Table B-2. Relationship of the Calculated Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Calculated Parameter</th>
<th>Functional Relation</th>
<th>Functional Calculation</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>Nozzle Throat Area</td>
<td>( f(d) )</td>
<td>( \pi d^2/4 )</td>
<td>0.0003243 m² (0.503 in²)</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Nozzle Ratio</td>
<td>( f(d, D) )</td>
<td>( d/D )</td>
<td>0.4124 dimensionless</td>
</tr>
<tr>
<td>( p_2 )</td>
<td>Absolute Throat Pressure</td>
<td>( f(p_1, \Delta P) )</td>
<td>( p_1 - \Delta P )</td>
<td>311.05 kPa (45.1 psia)</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Nozzle Inlet Liquid Density</td>
<td>( f(p_1, t_1) )</td>
<td>None: Property Data</td>
<td>998.47 kg/m³ (62.332 lbm/ft³)</td>
</tr>
</tbody>
</table>
### Table B-3. Uncertainty of Each Measured Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal Random Value</th>
<th>Error Origin</th>
<th>Calibration Error</th>
<th>Data Acquisition Error</th>
<th>Data Reduction Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d, \text{ mm (in)} )</td>
<td>20.32 (0.80)</td>
<td>See Note 1 below</td>
<td>0.0305 (0.0012)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( D, \text{ mm (in)} )</td>
<td>49.276 (1.940)</td>
<td>See Note 1 below</td>
<td>0.0508 (0.002)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( t_1, \text{ °C (°F)} )</td>
<td>20 (68)</td>
<td>Calibration</td>
<td>0.194 (0.35)</td>
<td>0.028 (0.05)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ice Reference Junction</td>
<td>0</td>
<td>0</td>
<td>0.133 (0.24)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data Acquisition</td>
<td>0</td>
<td>0</td>
<td>0.167 (0.30)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data Reduction/Curve Fit</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( p_1, \text{ kPa (psia)} )</td>
<td>380 (55.1)</td>
<td>Excitation Voltage</td>
<td>0.0010 (0.00015)</td>
<td>0.0007 (0.0001)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Signal Conditioning</td>
<td>0.0172 (0.0025)</td>
<td>0.0062 (0.0009)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calibration</td>
<td>4.1369 (0.60)</td>
<td>0.0041 (0.0006)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data Acquisition</td>
<td>0</td>
<td>0</td>
<td>0.0276 (0.004)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data Reduction/Curve Fit</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \Delta P, \text{ kPa (psid)} )</td>
<td>68.95 (10.0)</td>
<td>Excitation Voltage</td>
<td>0.0103 (0.0015)</td>
<td>0.0014 (0.0002)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Signal Conditioning</td>
<td>0.0758 (0.011)</td>
<td>0.0048 (0.0007)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calibration</td>
<td>0.4137 (0.06)</td>
<td>0.0138 (0.002)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data Acquisition</td>
<td>0</td>
<td>0</td>
<td>0.0434 (0.0063)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Data Reduction/Curve Fit</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table B-1 shows the uncertainties for each parameter calculated from a ISO17025 lab calibration.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty from an ISO17025 lab calibration</th>
<th>0.0025</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
</table>

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 result 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 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 ASME PTC 19.1-2018 - *Test Uncertainty*, these uncertainties are respectively given as follows:

\[
s_X = \pm \frac{1}{\sqrt{N}} \sqrt{\sum_{k=1}^{K} (s_{X_k})^2}
\]

\[
b_X = \pm \sqrt{\sum_{k=1}^{K} (b_{X_k})^2}
\]

where \( X \) represents a parameter, \( K \) is the total number of elemental uncertainty sources for a given parameter, \( N \) is the number of readings, \( s_{X_k} \) is an elemental random standard uncertainty, and \( b_{X_k} \) is an elemental systematic standard uncertainty. Numerical values of \( s_X \) and \( b_X \) 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 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:

\( s_d = 0.000 \text{ m} \)

\( b_d = 3.050 \times 10^{-5} \text{ m} \)

\( s_D = 0.000 \text{ m} \)

\( b_D = 5.080 \times 10^{-5} \text{ m} \)

\( s_{t_1} = 0.0244 \text{ °C} \)

\( b_{t_1} = 0.295 \text{ °C} \)

\( s_{p_1} = 11.162 \text{ Pa} \)

\( b_{p_1} = 4,137.036 \text{ Pa} \)

\( s_{\Delta p} = 52.541 \text{ Pa} \)

\( b_{\Delta p} = 435.402 \text{ Pa} \)

\( s_c = 0.000 \text{ Pa} \)

\( b_c = 0.00250 \text{ Pa} \)

**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:
\[ s_d = 0.000 \text{ in.} \quad b_d = 0.00120 \text{ in.} \]
\[ s_D = 0.000 \text{ in.} \quad b_D = 0.00200 \text{ in.} \]
\[ s_t = 0.0439 ^\circ \text{F} \quad b_t = 0.531 ^\circ \text{F} \]
\[ s_{p_1} = 0.00162 \text{ psia} \quad b_{p_1} = 0.600 \text{ psia} \]
\[ s_{p_2} = 0.00762 \text{ psid} \quad b_{p_2} = 0.6031 \text{ psid} \]
\[ s_c = 0.000 \quad b_c = 0.00250 \]

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

The random and systematic standard uncertainties for \( \rho \) 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 \( \rho \). Extremum values of \( t_1 \) and \( p_1 \) within a 95% confidence interval must be calculated to estimate extremum values of \( \rho \), which are then used to estimate the random and systematic standard uncertainties of \( \rho \). 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:

\[
u = \pm \sqrt{(s_x)^2 + (b_x)^2} \quad \text{(B-3)}
\]
\[
U = k \times \nu \quad \text{(B-4)}
\]

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 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 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:

\[ U_{t_1} = 0.592 ^\circ \text{C} \]
\[ U_{p_1} = 8,274.103 \text{ Pa} \]

The extreme values of \( t_1 \) and \( p_1 \) and the corresponding values of \( \rho \) are presented in Table B-4.1.

<table>
<thead>
<tr>
<th>Table B-4.1. Liquid density extreme values – SI units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statement</td>
</tr>
<tr>
<td>( t_1 ) (°C)</td>
</tr>
<tr>
<td>( p_1 ) (kPa)</td>
</tr>
<tr>
<td>( \rho ) (kg/m(^3))</td>
</tr>
</tbody>
</table>

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

\[ s_p = 0.000 \text{ kg/m}^3 \]
\[ b_p = 0.0650 \text{ kg/m}^3 \]
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:

$U_{t_1} = 1.065 \, ^\circ\text{F}$

$U_{p_1} = 1.200 \, \text{psia}$

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

<table>
<thead>
<tr>
<th></th>
<th>Minimum value</th>
<th>Maximum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$ (°F)</td>
<td>66.935</td>
<td>69.065</td>
</tr>
<tr>
<td>$p_1$ (psia)</td>
<td>53.900</td>
<td>56.300</td>
</tr>
<tr>
<td>$\rho$ (lbm/ft³)</td>
<td>62.324</td>
<td>62.340</td>
</tr>
</tbody>
</table>

Based on previous experience, the variations for $\rho$ are assumed to be entirely systematic errors. Using Equation B-4 and defining half the difference between $\rho$ extremums as equal to the expanded uncertainty, the random and systematic standard uncertainties are:

$s_\rho = 0.000 \, \text{lbm/ft}^3$

$b_\rho = 0.00406 \, \text{lbm/ft}^3$

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 39. The random and systematic standard uncertainties of the mass flow rate are respectively given as follows:

\[
s_{\dot{m}} = \pm \sqrt{\sum_{i=1}^{l} \left( \theta_i s_{X_i} \right)^2 + \text{(random correlation terms)}} \tag{B-5}
\]

\[
b_{\dot{m}} = \pm \sqrt{\sum_{i=1}^{l} \left( \theta_i b_{X_i} \right)^2 + \text{(systematic correlation terms)}} \tag{B-6}
\]

where $\theta_i$ is the evaluated partial derivative of $\dot{m}$ with respect to the $i^{th}$ parameter, $l$ is the number of parameters in Equation 7-7, $s_{X_i}$ and $b_{X_i}$ are the corresponding random and systematic standard uncertainties of the $i^{th}$ 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 ASME PTC 19.1-2018 - Test Uncertainty for the methodology. Explicitly, $\theta_i$ is expressed as follows:

\[
\theta_i = \frac{\partial \dot{m}}{\partial X_i} \tag{B-7}
\]

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 $\beta$ 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.

B3.1 Derivations of the Partial Derivatives in SI Units
B3.1.1 Derive the Partial Derivative $\frac{\partial \dot{m}}{\partial d}$

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

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

\[ \dot{m} = \rho Q \]  

(7-4)

(7-7)

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

\[ \dot{m} = \rho C \left( \frac{\pi d^2}{4} \right) K_1 \sqrt{\frac{2(\Delta P)}{\rho(1-E\beta^4)}} \]

or $\dot{m} = A \times B$  

where

\[ A = C \left( \frac{\pi d^2}{4} \right) K_1 \sqrt{2\Delta P \rho} \quad \text{and} \]

\[ B = \left( 1 - E \left( \frac{d}{D} \right)^4 \right)^{\frac{1}{2}} = \left( 1 - E \frac{d^4}{D^4} \right)^{\frac{1}{2}} \]

(B-10)

(B-11)

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

\[ \frac{\partial \dot{m}}{\partial d} = A \frac{\partial B}{\partial d} + B \frac{\partial A}{\partial d} \]

(B-12)

(B-13)

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

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

(B-14)

\[ \frac{\partial B}{\partial d} = \frac{1}{2} \left( 1 - E \frac{d^4}{D^4} \right)^{-\frac{3}{2}} \left( -4E \frac{d^3}{D^4} \right) \]

(B-15)

Rearranging Equation B-15 yields Equation B-16.

\[ \frac{\partial B}{\partial d} = 2 \left( 1 - E \frac{d^4}{D^4} \right)^{-\frac{3}{2}} \left( E \frac{d^3}{D^4} \right) \]

(B-16)

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

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

(B-17)

Simplifying Equation B-17 yields Equation B-18.

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

(B-18)
The solution to the partial derivative $\frac{\partial m}{\partial d}$ 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.

$$\frac{\partial m}{\partial d} = \frac{1}{2} \left( \sqrt{2} CK_1 d \pi \sqrt{-\frac{\Delta P \rho}{2 \frac{d^4}{d^*}}} \right) + \frac{\sqrt{2} \kappa K_1 \Delta P d^5 \rho \pi}{2D^4 \left( \frac{\Delta P d^4}{d^*} \right) \sqrt{-\frac{\Delta P \rho}{2 \frac{d^4}{d^*}}} \sqrt{\frac{\Delta P d^5 \rho d^*}{2}}}$$  

(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.

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

(B-20)

$$\frac{1}{2} \sqrt{2} CK_1 d \frac{\Delta P \rho}{1 - E \left( \frac{d^4}{d^*} \right)}$$  

(B-21)

$$\frac{1}{2} \sqrt{2} CK_1 d \frac{-\Delta P \rho}{E \left( \frac{d^4}{d^*} \right) - 1}$$  

(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.

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

(B-23)

$$\frac{\sqrt{2} \kappa K_1 \Delta P d^5 \rho \pi}{2D^4 \left( \frac{\Delta P d^4}{d^*} \right) \sqrt{1 - E \left( \frac{d^4}{d^*} \right)} \sqrt{\frac{\Delta P d^5 \rho d^*}{2}}}$$  

(B-24)

$$\frac{\sqrt{2} \kappa K_1 \Delta P d^5 \rho \pi}{2D^4 \left( \frac{\Delta P d^4}{d^*} \right) \sqrt{1 - E \left( \frac{d^4}{d^*} \right)} \sqrt{\frac{\Delta P d^5 \rho d^*}{2}}}$$  

(B-25)

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

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

$$\frac{\partial m}{\partial d} = \frac{1}{2} \left( \sqrt{2} CK_1 d \pi \sqrt{-\frac{\Delta P \rho}{2 \frac{d^4}{d^*}}} \right) + \frac{\sqrt{2} \kappa K_1 \Delta P d^5 \rho \pi}{2D^4 \left( \frac{\Delta P d^4}{d^*} \right) \sqrt{-\frac{\Delta P \rho}{2 \frac{d^4}{d^*}}} \sqrt{\frac{\Delta P d^5 \rho d^*}{2}}}$$  

(B-26)

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

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

$$m = \rho \left( \frac{\pi d^2}{4} \right) K_1 \left( \frac{2 \Delta P}{\rho (1 - E \left( \frac{d^4}{d^*} \right))} \right)$$  

(B-27)

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

(B-28)
Because there is no $D$ in $A$ then $\frac{\partial A}{\partial D} = 0$. Therefore, $\frac{\partial m}{\partial D} = A \frac{\partial B}{\partial D}$ (B-29)

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

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

Rearranging Equation B-31 yields Equation B-32.

$$\frac{\partial m}{\partial D} = \frac{-\sqrt{2 \Delta P \rho C E K_1 d^d \pi}}{2 \left[ 1 - E \left( \frac{d^4}{D^4} \right)^2 \right] D^5}$$ (B-32)

Equation B-32 is the solution to the partial derivative $\frac{\partial m}{\partial D}$. 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.

$$\frac{-\sqrt{2 \Delta P \rho C E K_1 d^d \rho \pi}}{2 \left[ 1 - \frac{d^4}{D^4} \right]^2} \times \frac{-\Delta P \rho}{\left[ 1 - \frac{d^4}{D^4} \right]}$$ (B-33)

Multiply Equation B-32 by 2 constants that both = 1 to get Equation B-34.

$$\frac{\partial m}{\partial D} = \frac{-\sqrt{2 \Delta P \rho C E K_1 d^d \pi}}{2 \left[ 1 - E \left( \frac{d^4}{D^4} \right)^2 \right]} \times \sqrt{\frac{-\Delta P \rho}{\left[ 1 - E \left( \frac{d^4}{D^4} \right) \right]}}$$ (B-34)

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

$$\frac{\partial m}{\partial D} = \frac{-\sqrt{2 \Delta P \rho C E K_1 d^d \rho \pi}}{2 \left[ 1 - \frac{d^4}{D^4} \right]^2} \times \frac{-\Delta P \rho}{\sqrt{\left[ 1 - \frac{d^4}{D^4} \right]}}$$ (B-35)

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

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

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

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

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

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

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

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

(B-40)

Isolating the $\rho$ terms in Equation B-40 yields Equation B-41.

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

(B-41)

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

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

(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.

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

(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.

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

(B-44)

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

(B-45)

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

(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.

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

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

(B-48)

\[ \frac{\partial \dot{m}}{\partial \Delta P} = \frac{1}{2} \frac{\sqrt{2\pi d^2 K_1}}{4 \sqrt{\rho \left(1 - E\left(\frac{d}{D}\right)^4\right)}} (\Delta P)^{-\frac{1}{2}} = \frac{\sqrt{2\pi d^2 K_1 (\Delta P)^{-\frac{1}{2}}}}{8 \sqrt{\rho \left(1 - E\left(\frac{d}{D}\right)^4\right)}} \]  

(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.

\[ \frac{\partial \dot{m}}{\partial \Delta P} = \frac{\sqrt{2\pi d^2 K_1 (\Delta P)^{-\frac{1}{2}}}}{8 \sqrt{\rho \left(1 - E\left(\frac{d}{D}\right)^4\right)}} \]  

(B-50)

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

\[ \frac{\partial \dot{m}}{\partial \Delta P} = \frac{-\sqrt{2\pi d^2 K_1 (\Delta P)^{-\frac{1}{2}}}}{8 \left(\frac{E d^4}{D^4 - 1}\right) \sqrt{\left(\frac{-E d^4}{D^4 - 1}\right) \frac{-\Delta P \rho}{Ed^4}}} \]  

(B-51)

B3.2 Evaluation of Partial Derivatives in SI Units

\[ \frac{\partial \dot{m}}{\partial d} = \frac{1}{2} \left( \sqrt{2CK_1 d \pi} \sqrt{\frac{-\Delta P \rho}{Ed^4 - 1}} + \frac{\sqrt{2CEK_1 \Delta P d^2 \rho \pi}}{2D^4 \left(\frac{Ed^4}{D^4 - 1}\right)^2 \times \sqrt{\left(\frac{-\Delta P \rho}{Ed^4 - 1}\right)}} \right) \]  

(B-52)

\[ \frac{\partial \dot{m}}{\partial d} = 405.008 \text{ kg/(m-s)} \]  

(B-53)

\[ \frac{\partial \dot{m}}{\partial D} = \frac{-\sqrt{2CEK_1 \Delta P d^4 \rho \pi}}{2D^4 \left(\frac{Ed^4}{D^4 - 1}\right)^2 \times \sqrt{\left(\frac{-\Delta P \rho}{Ed^4 - 1}\right)}} \]  

(B-54)

\[ \frac{\partial \dot{m}}{\partial D} = -5.037 \text{ kg/(m-s)} \]  

(B-55)

\[ \frac{\partial \dot{m}}{\partial C} = \sqrt{2CK_1 d^2 \pi} \sqrt{\frac{-\Delta P \rho}{Ed^4 - 1}} \]  

(B-56)

\[ \frac{\partial \dot{m}}{\partial C} = 4.011 \text{ kg/s} \]  

(B-57)

\[ \frac{\partial \dot{m}}{\partial \rho} = \frac{\sqrt{2CEK_1 \Delta P d^2 \pi}}{\left(8 \left(\frac{Ed^4}{D^4 - 1}\right) \times \sqrt{\left(\frac{-\Delta P \rho}{Ed^4 - 1}\right)}\right)} \]  

(B-58)

\[ \frac{\partial \dot{m}}{\partial \rho} = 0.00200 \text{ m}^3/\text{s} \]  

(B-59)
\[
\frac{\partial \dot{m}}{\partial \Delta \rho} = \frac{-\sqrt{2CK_1\rho d^2\pi}}{8(\frac{E\pi^4}{D^4}-1) \times \left(\frac{\Delta \rho}{E\pi^4} - 1\right)} \quad (B-60)
\]

\[
\frac{\partial \dot{m}}{\partial \Delta \rho} = 2.89 \times 10^{-5} \text{ kg/(Pa-s)} \quad (B-61)
\]

**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.

\[
\frac{\partial \dot{m}}{\partial d} = 22.679 \text{ lbm/(in-s)} \quad (B-62)
\]

\[
\frac{\partial \dot{m}}{\partial \rho} = -0.282 \text{ lbm/(in-s)} \quad (B-63)
\]

\[
\frac{\partial \dot{m}}{\partial c} = 8.842 \text{ lbm/s} \quad (B-64)
\]

\[
\frac{\partial \dot{m}}{\partial p} = 0.0706 \text{ ft}^3/\text{s} \quad (B-65)
\]

\[
\frac{\partial \dot{m}}{\partial \Delta \rho} = 0.440 \text{ lbm/(psid-s)} \quad (B-66)
\]

**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**

\[
s_{\dot{m}} = 0.00152 \text{ kg/s} \quad (B-67)
\]

\[
b_{\dot{m}} = 0.0203 \text{ kg/s} \quad (B-68)
\]

**B4.2 I-P Units**

\[
s_{\dot{m}} = 0.00335 \text{ lbm/s} \quad (B-69)
\]

\[
b_{\dot{m}} = 0.0447 \text{ lbm/s} \quad (B-70)
\]

**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**

\[
u_{\dot{m}} = 0.0204 \text{ kg/s} \quad (B-71)
\]

\[
U_{\dot{m}} = 0.0407 \text{ kg/s} \quad (B-72)
\]

The mass flow rate, at 95% confidence level, is:

\[
\dot{m} = 3.9908 \pm 0.0407 \text{ kg/s} \quad (B-73)
\]

**B5.2 I-P Units**

\[
u_{\dot{m}} = 0.0449 \text{ lbm/s} \quad (B-74)
\]

\[
U_{\dot{m}} = 0.0897 \text{ lbm/s} \quad (B-75)
\]

The mass flow rate, at 95% confidence level, is:

\[
\dot{m} = 8.7981 \pm 0.0897 \text{ lbm/s} \quad (B-76)
\]
(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:
INFORMATION REGARDING LIQUID FLOW MEASUREMENT
UNCERTAINTIES FOR INSTALLATIONS THAT DO NOT MEET
THE FLOWMETER MANUFACTURER’S REQUIREMENTS

C1. 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 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-2000 (R2011) titled, Method for Establishing Installation Effects on Flowmeters, defines laboratory test methods for measuring velocity profiles with multiple piping configurations (installation effects). These tests are not routinely done 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 appendix provides brief descriptions of the work that was performed and the corresponding web sites for the reports and/or technical papers.

New research work is needed to first assess what has been done previously, and then 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 appendix points the user to existing research reports and technical papers, but this committee has not done a technical assessment of these documents. Web searches found other studies conducted by manufacturers, but ASHRAE’s non-commercial policy prevents listing links to those sites.

C2. Previous Research Results and Technical Papers

C2.1 Technical Paper: Flowmeter Installation Effects – Wild Claims, Bright Ideas, and Stark Realities. The authors of this 1995 paper describe an 8-year project sponsored by a NIST-industry consortium that addressed the pipe flow distortions produced by selected piping configurations.
C2.2 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.


C2.4 Pipe Elbow Effects on the V-Cone Flowmeter. This 1993 paper presents installation effects on a special type of flow meter with baseline comparisons to orifice plate differential pressure flow meters.
(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 D**

**FLOWMETER ACCURACY COMPARISONS**

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

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

<table>
<thead>
<tr>
<th>Liquid Flow Measurement Method</th>
<th>Liquid Flow Measurement Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coriolis Flowmeters</td>
<td>±0.05% of reading</td>
</tr>
<tr>
<td>Thermal Flowmeters</td>
<td>±1% of reading</td>
</tr>
<tr>
<td>Orifice Meters</td>
<td>±0.5% of reading</td>
</tr>
<tr>
<td>Flow Nozzles</td>
<td>±0.5% of reading</td>
</tr>
<tr>
<td>Venturi Tubes</td>
<td>±0.5% of reading</td>
</tr>
<tr>
<td>Turbine Flowmeters</td>
<td>±0.25% of reading</td>
</tr>
<tr>
<td>Variable-Area Flowmeters</td>
<td>±2% of reading</td>
</tr>
<tr>
<td>Ultrasonic Flowmeters</td>
<td>±1% of reading</td>
</tr>
<tr>
<td>Vortex-Shedding Flowmeters</td>
<td>±0.75% of reading</td>
</tr>
<tr>
<td>Drag-Force Flowmeters</td>
<td>±2% of reading</td>
</tr>
<tr>
<td>Magnetic Flowmeters</td>
<td>±0.5% of reading</td>
</tr>
<tr>
<td>Positive Displacement Flowmeters</td>
<td>±0.5% of reading</td>
</tr>
<tr>
<td>Pitot-static Tube Methods</td>
<td>±10% of full scale</td>
</tr>
</tbody>
</table>