BSR/ASHRAE Standard 41.2-2022R

Public Review Draft

Standard Methods for Air Velocity and Airflow Measurements

First Public Review (January 2026)
(Complete Draft for Full Review)

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ASHRAE, 180 Technology Parkway NW, Peachtree Corners, GA 30092

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FOREWORD

ASHRAE Standard 41.2 provides recommended practices for airflow measurements as well as measurement procedures for use in preparation of other ASHRAE standards.

This revision of ANSI/ASHRAE Standard 41.2-2022 includes an update of the steady-state criteria for recording data, an addition that covers airflow mixing devices, an addition that permits the optional use of legacy multiple-nozzle chambers that were specified in the original 1987 version of this standard (reaffirmed in 1992), and changes to make it easier for higher-tier ASHRAE standards to adopt this standard by reference.

This revision of ANSI/ASHRAE Standard 41.2 meets ASHRAE's mandatory language requirements.

1. PURPOSE

This standard prescribes methods for air velocity and airflow measurement, including consideration of density effects.

2. SCOPE

1. This standard applies to air velocity and airflow measurement for testing heating, ventilating, air conditioning, and refrigerating systems and components at pressures within the range of –25 kpa to +25 kpa (–100 in. of water to +100 in. of water) referenced to atmospheric pressure.
2. This standard includes airflow mixing methods to obtain more uniform temperatures and velocities.

3. DEFINITIONS

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

computational fluid dynamics (CFD): the use of applied mathematics, physics, and computational software to visualize how a gas or liquid flows as well as how the gas or liquid affects objects as it flows past.

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

geometrically equivalent diameter: the diameter of a circle having the same area as a non-circular airflow flow area.

hydraulic diameter: four times the airflow area divided by the perimeter of the solid boundary in contact with the air.

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

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

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

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

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

steady-state criteria: the criteria that establish negligible change of air velocity or airflow 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 air velocity or airflow rate is known and has an associated operating tolerance.

test chamber: an airflow-measuring apparatus that has a chamber diameter that is greater than twice the unit under test (UUT) duct diameter or geometrically equivalent diameter.

test duct: an airflow-measuring apparatus that has a constant diameter or geometrically equivalent diameter throughout its length except for transition portions at one or both ends.

test point: a specific set of test operating conditions for recording data where the measured required air velocity or airflow rate is unknown and has an associated operating tolerance.

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

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

unit under test (UUT): equipment that is the subject of air velocity or airflow measurements.

4. CLASSIFICATIONS

4.1 Air Velocity and Airflow Measurement Applications. Air velocity and airflow measurement applications that are within the scope of this standard are classified as one of the following two types:

a. **Laboratory Applications.** Air velocity and airflow measurements under laboratory conditions are engineering development tests or tests to determine product ratings. ***Informative Note:*** Laboratory air velocity and airflow measurements tend to use more accurate instruments than field measurements and tend to meet the instrument manufacturer's installation requirements.

b. **Field Applications.** Air velocity and airflow measurements under field conditions are tests to determine ventilation rates or installed system air velocities and airflows. ***Informative Note:*** Field air velocity and airflow measurements tend to use less accurate instruments than laboratory measurements and often do not meet the instrument manufacturer's installation requirements.

4.2 Airflow Meter Categories

4.2.1 Mass Airflow Meters. Airflow meters in this category perform direct measurement of mass airflow rates.

4.2.2 Volumetric Airflow Meters. Airflow meters in this category perform direct measurement of volumetric airflows. If mass airflow rates are required, each volumetric airflow measurement shall be multiplied by the air density at the flow measurement location to obtain the mass airflow rate measurement.

4.3 Air Velocity Measurement Methods. Methods of air velocity measurement methods that are within the scope of this standard are the methods listed below. These measurement methods are described in Section 7.

a. Pitot-static Tube Air Velocity Measurement Methods
b. Thermal Anemometer
c. Rotating Vane Anemometer
d. Ultrasonic Velocity Flowmeter
e. Drag-Force Velocity Meter
f. Laser Doppler Velocimeter

Informative Note: Any measured average airflow velocity can be multiplied by the area of the duct in the measurement plane to obtain a volumetric airflow rate.

4.4 Airflow Measurement Methods. Methods of airflow measurement that are within the scope of this standard are the methods listed below. These measurement methods are described in Section 9.

a. Pitot-static Tube
b. Single Nozzle Ducts
c. Single- and Multiple-Nozzle Chambers
d. Thermal Dispersion Array
e. Vortex-Shedding Array
f. Capture Hoods
g. Tracer Gas

4.5 Standard Air Density. For the purposes of this standard, standard air density = 1.202 kg/m^3 (0.075 lb_m/ft^3) unless otherwise specified in the test plan in Section 5.1. The conversion error associated with calculating air velocity or airflow measurement uncertainties into I-P units is 0.00004 lb_m/ft^3.

Informative Note: Appendix D provides the derivation of this conversion uncertainty and a description of how this conversion uncertainty is applied to airflow measurement uncertainty calculations.

4.6 Test Apparatus. A test apparatus that is used to measure air velocity or airflow includes instruments, airflow-conditioning elements, and airflow-control elements within a sealed conduit. These are classified as single-nozzle ducts, or single- or multiple-nozzle chambers as defined in Sections 4.6.1 or 4.6.2.

4.6.1 Single-Nozzle Duct. A single-nozzle duct is a test apparatus that has a constant diameter or geometrically equivalent diameter throughout its length except for transition portions at one or both ends.

4.6.2 Single- or Multiple-Nozzle Chamber. A single- or multiple-nozzle chamber is a test apparatus that has a diameter or geometrically equivalent diameter that is greater than twice the UUT duct diameter or geometrically equivalent diameter.

5. REQUIREMENTS

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

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

The test plan shall specify:

a. The minimum value for the accuracy or the maximum value of the measurement uncertainty of the air velocity or airflow measurement system over the full range of operating conditions.
b. The values to be determined and recorded that are selected from this list: air velocity, air velocity pretest uncertainty, air velocity post-test uncertainty, volumetric airflow rate, volumetric airflow pretest uncertainty, volumetric airflow post-test uncertainty, standard volumetric airflow rate, standard volumetric airflow rate pretest uncertainty, standard volumetric airflow rate post-test uncertainty, mass airflow rate, mass airflow pretest uncertainty, and mass airflow post-test uncertainty,
c. Any combination of test points and targeted set points to be performed together with operating tolerances.

5.2 Values to be Determined and Recorded

5.2.1 Values to be Determined and Recorded for Air Velocity Measurements

5.2.1.1 Air velocity if required by the test plan in Section 5.1, m/s (ft/s)

5.2.1.2 If required by the test plan in Section 5.1, the uncertainty in each air velocity measurement shall be estimated as described in Section 10 for each data point or the worst-case uncertainty for all data points shall be estimated and reported for each data point.

5.2.2 Values to be Determined and Recorded for Airflow Measurements

5.2.2.1 Volumetric airflow at the measured density if required by the test plan in Section 5.1, m3/s (cfm).

5.2.2.2 Standard volumetric airflow if required by the test plan in Section 5.1, m^3/s at 1.202 kg/m^3 (scfm at 0.075 lb_m/ft^3)

5.2.2.3 Mass airflow rate if required by the test plan in Section 5.1, kg/s (lb_m/min)

5.2.2.4 If required by the test plan in Section 5.1, the uncertainty in each airflow measurement shall be estimated as described in Section 10 for each data point or the worst-case uncertainty for all data points shall be estimated and reported for each data point.

5.3 Test Requirements

5.3.1. Air Velocity Measurement Requirements

5.3.1.1 Air Velocity Measurement Accuracy or Measurement Uncertainty. A selected air velocity measurement method shall meet or exceed the required air velocity measurement system accuracy or measurement uncertainty over the full range of operating conditions specified in the test plan in Section 5.1.

5.3.1.2 Pretest Air Velocity Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the expected uncertainty for each air velocity test point prior to the conduct of that test in accordance with the pretest uncertainty analysis procedures in ASME PTC 19.1[1].

5.3.1.3 Post-test Air Velocity Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the air velocity measurement uncertainty for each air velocity test point in accordance with the post-test uncertainty analysis procedures in ASME PTC 19.1[1]. Alternatively, if specified in the test plan, the worst-case uncertainty for all test points shall be estimated and reported for each test point.

5.3.1.4 Air Velocity Steady-State Test Criteria. Air velocity test data shall be recorded at steady-state conditions if specified in the test plan in Section 5.1.

5.3.1.4.1 Steady-State Test Criteria Under Laboratory Test Conditions. If the test plan requires air velocity 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 5.3.1.4.3 if the test plan provides test points for air velocity measurement.
b. Apply the steady-state criteria in Section 5.3.1.4.4 if the test plan provides targeted set points for air velocity measurement.

5.3.1.4.2 Steady-State Test Criteria Under Field Test Conditions. If the test plan requires air velocity 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 5.3.1.4.1 are optional.

Informative Note: The steady-state methods in Section 5.3.1.4.1 are likely to be impractical under field test conditions. Under these circumstances, the user may want to select another method to determine the conditions for field test data to be recorded

5.3.1.4.3 Steady-State Air Velocity Criteria for Test Points

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

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

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

Record each sampled air velocity measurement V_i and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the air velocity data trend line using Equation 5-2.

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

Informative Note: It should be noted that the units for the slope in Equation 5-2 are air velocity, m/s (fpm), divided by the units that the user has selected for time.

The mean of the sampled air velocity, $\bar{V}$, is defined by Equation 5-3.

$$\bar{V} = \frac{1}{N}\left[\sum_{i=1}^{N}(V_i)\right], \text{ m/s (fpm)} \tag{5-3}$$

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

$$V_{max} - V_{min} \le \mathrm{V}_L \text{ , m/s (fpm)} \tag{5-4}$$

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

$$|b \times \Delta t| \le 0.5 \times \mathrm{V}_L \text{ , m/s (fpm)} \tag{5-5}$$

$\bar{V}$, as determined by Equation 5-3, represents the steady-state mean air velocity where Equations 5-4 and 5-5 are both satisfied.

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

5.3.1.4.4 Steady-State Air Velocity Criteria for Targeted Set Points

Starting with the time set to zero, sample not less than 30 air velocity measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-6_states the relationship of the test duration to the number of samples and the equal time intervals.

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

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

Record each sampled air velocity measurement V_i and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the air velocity data trend line using Equation 5-7.

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

Informative Note: It should be noted that the units for the slope in Equation 5-7_are air velocity, m/s (fpm), divided by the units that the user has selected for time.

The mean of the sampled air velocities $\bar{V}$ is defined by Equation 5-8.

$$\bar{V} = \frac{1}{N}\left[\sum_{i=1}^{N}(V_i)\right], \text{ m/s (fpm)} \quad (5\text{-}8)$$

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

$$V_{max} - V_{min} \leq V_L \text{ , m/s (fpm)} \quad (5\text{-}9)$$

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

$$|b \times \Delta t| \leq 0.5 \times V_L \text{ , m/s (fpm)} \quad (5\text{-}10)$$

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

$$|V_{SP} - \bar{V}| \leq 0.5 \times V_L \text{ , m/s (fpm)} \quad (5\text{-}11)$$

$\bar{V}$, as determined by Equation 5-8, represents the steady-state mean air velocity where Equations 5-9, 5-10, and 5-11 are all satisfied.

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

5.3.1.5 Unsteady Air Velocity Measurements. If required by the test plan in Section 5.1, air velocity 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, and
d. using instrument response times specified in the test plan.

5.3.1.6 Operating Limits. Operating conditions during air velocity data measurements shall not exceed limits for pressure, pressure differential, temperature, air velocity, or pressure pulsations specified in the test plan in Section 5.1, or the limits prescribed by the air velocity meter manufacturer to achieve the measurement system accuracy required by the test plan.

5.3.2 Airflow Measurement Requirements

5.3.2.1 Airflow Measurement Accuracy or Measurement Uncertainty. A selected airflow measurement method shall meet or exceed the required airflow measurement system accuracy or measurement uncertainty over the full range of operating conditions specified in the test plan in Section 5.1.

5.3.2.2 Pretest Airflow Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the expected uncertainty for each airflow test point prior to the conduct of that test in accordance with the pretest uncertainty analysis procedures in ASME PTC 19.1[1].

5.3.2.3 Post-test Airflow Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the airflow measurement uncertainty for each airflow test point in accordance with the post-test uncertainty analysis procedures in ASME PTC 19.1[1]. Alternatively, if specified in the test plan, the worst-case uncertainty for all test points shall be estimated and reported for each test point.

5.3.2.4 Airflow Leakage Requirements. Unless otherwise specified in the test plan in Section 5.1, measured airflow leakage into or out of the test apparatus shall not be greater than 0.25% of the airflow at the pressure corresponding to the measured airflow specified in the test plan for laboratory measurements and shall not be greater than 1% of the airflow at the pressure corresponding to the measured airflow specified in the test plan for field measurements.

5.3.2.5 Volumetric Airflow Rate Steady State Criteria. Volumetric airflow rate test data shall be recorded at steady-state conditions if required in the test plan in Section 5.1.

5.3.2.5.1 Steady-State Test Criteria Under Laboratory Test Conditions. If the test plan requires volumetric airflow 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 5.3.2.5.3 if the test plan provides test points for volumetric airflow flow rate measurement.
b. Apply the steady-state criteria in Section 5.3.2.5.4 if the test plan provides targeted set points for volumetric airflow flow rate measurement.

5.3.2.5.2 Steady-State Test Criteria Under Field Test Conditions. If the test plan requires volumetric airflow 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 5.3.2.5.1 are optional.

Informative Note: The steady-state methods in Section 5.3.2.5.1 are likely to be impractical under field test conditions. Under these circumstances, the user may want to select another method to determine the conditions for field test data to be recorded.

5.3.2.5.3 Steady-State Volumetric Airflow Flow Rate Criteria for Test Points

Starting with the time set to zero, sample not less than 30 volumetric airflow flow rate measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-12 states the relationship of the test duration to the number of volumetric airflow flow rate samples and the equal time intervals.

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

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

Record each sampled volumetric airflow flow rate measurement Q_i and the corresponding time t_i. Apply the least-squares line method to determine the slope b of the volumetric airflow flow rate data trend line using Equation 5-13.

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

Informative Note: It should be noted that the units for the slope in Equation 5-13_are volumetric airflow flow rate, m^3/s (ft^3/min), divided by the units that the user has selected for time.

The mean of the sampled volumetric airflow flow rates $\bar{Q}$ is defined by Equation 5-14.

$$\bar{Q} = \frac{1}{N}\left[\sum_{i=1}^{N}(Q_i)\right], \text{ m}^3\text{/s (ft}^3\text{/min)} \tag{5-14}$$

The difference between the maximum and minimum sampled values shall be less than or equal to the specified operating tolerance limit as defined in Equation 5-15 where Q_L is the operating tolerance limit.

$$Q_{\max} - Q_{\min} \leq Q_L \text{ , m}^3\text{/s (ft}^3\text{/min)} \tag{5-15}$$

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

$$|b \times \Delta t| \leq 0.5 \times Q_L \text{ , m}^3\text{/s (ft}^3\text{/min)} \tag{5-16}$$

$\bar{Q}$, as determined by Equation 5-14, represents the steady-state mean volumetric airflow rate where Equations 5-15 and 5-16 are both satisfied.

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

5.3.2.5.4 Steady-State Volumetric Airflow Flow Rate Criteria for Targeted Set Points

Starting with the time set to zero, sample not less than 30 volumetric airflow flow rate measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-17_states the relationship of the test duration to the number of samples and the equal time intervals.

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

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 volumetric airflow flow rate fluctuations during operation near the steady-state conditions.

Record each sampled volumetric airflow flow rate measurement Q_i and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the volumetric airflow flow rate data trend line using Equation 5-18.

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

Informative Note: It should be noted that the units for the slope in Equation 5-18 are volumetric airflow flow rate, m^3/s (ft^3/min), divided by the units that the user has selected for time.
The mean of the sampled volumetric airflow flow rates $\bar{Q}$ is defined by Equation 5-19.

$$\bar{Q} = \frac{1}{N}[\sum_{i=1}^{N}(Q_i)], \text{ m}^3\text{/s (ft}^3\text{/min)} \quad (5\text{-}19)$$

The difference between the maximum and minimum sampled values shall be less than or equal to the specified operating tolerance limit as defined in Equation 5-20 where Q_L is the operating tolerance limit.

$$Q_{max} - Q_{min} \leq Q_L \text{ , m}^3\text{/s (ft}^3\text{/min)} \quad (5\text{-}20)$$

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

$$|b \times \Delta t| \leq 0.5 \times Q_L \text{ , m}^3\text{/s (ft}^3\text{/min)} \quad (5\text{-}21)$$

The difference between the test condition and mean of the sampled values shall be less than or equal to half of the specified operating tolerance limit as defined in Equation 5-22 where Q_{SP} is the set point volumetric airflow rate and Q_L is the operating tolerance limit.

$$|Q_{SP} - \bar{Q}| \leq 0.5 \times Q_L \text{ , m}^3\text{/s (ft}^3\text{/min)} \quad (5\text{-}22)$$

$\bar{Q}$, as determined by Equation 5-19, represents the steady-state mean airflow rate where Equation 5-20, 5-21, and Equation 5-22 are all satisfied.

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

5.3.2.6 Unsteady Volumetric Airflow Rate Measurements. If required by the test plan in Section 5.1, volumetric airflow 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, and
d. using instrument response times specified in the test plan.

5.3.2.7 Steady-State Test Criteria for Mass Airflow Rate Measurements. Mass airflow rate test data shall be recorded at steady-state conditions if specified in the test plan in Section 5.1.

5.3.2.7.1 Steady-State Test Criteria Under Laboratory Test Conditions. If the test plan requires mass airflow 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 5.3.2.7.3 if the test plan provides test points for mass airflow rate measurement.
b. Apply the steady-state criteria in Section 5.3.2.7.4 if the test plan provides targeted set points for mass airflow rate measurement.

5.3.2.7.2 Steady-State Test Criteria Under Field Test Conditions. If the test plan requires mass airflow 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 5.3.2.7.1 are optional.

Informative Note: The steady-state methods in Section 5.3.2.7.1 are likely to be impractical under field test conditions. Under these circumstances, the user may want to select another method to determine the conditions for field test data to be recorded.

5.3.2.7.3 Steady-State Mass Airflow Rate Criteria for Test Points

Starting with the time set to zero, sample not less than 30 mass airflow rate measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-23 states the relationship of the test duration to the number of mass airflow rate samples and the equal time intervals.

$$\Delta t = (N-1)\delta t \tag{5-23}$$

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 mass airflow rate fluctuations during operation near the steady-state conditions.

Record each sampled mass airflow rate measurement $\dot{m}_i$ and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the mass airflow rate data trend line using Equation 5-24.

$$b = \left\{\frac{\left[N\left(\sum_{i=1}^{N} t_i \dot{m}_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} \dot{m}_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} {t_i}^2\right) - \left(\sum_{i=1}^{N} t_i\right)^2\right]}\right\} \tag{5-24}$$

***Informative Note*:** It should be noted that the units for the slope in Equation 5-24 are mass airflow rate, kg/s (lb_m/min), divided by the units that the user has selected for time.

The mean of the sampled mass airflow rates $\bar{\dot{m}}$ is defined by Equation 5-25.

$$\bar{\dot{m}} = \frac{1}{N}\left[\sum_{i=1}^{N}(\dot{m}_i)\right], \text{ kg/s (lb}_\text{m}\text{/min)} \tag{5-25}$$

The difference between the maximum and minimum sampled values must be less than or equal to the specified test operating tolerance as defined in Equation 5-26 where $\dot{m}_L$ is the operating tolerance limit.

$$\dot{m}_{max} - \dot{m}_{min} \leq \dot{m}_L \text{ , kg/s (lb}_\text{m}\text{/min)} \tag{5-26}$$

The restriction on the slope of the trend line b is defined in Equation 5-27 where Δt is the sample time interval.

$$|b \times \Delta t| \leq 0.5 \times \dot{m}_L \ , \qquad \text{kg/s (lb}_\text{m}\text{/min)} \tag{5-27}$$

$\bar{\dot{m}}$, as determined by Equation 5-25, represents the steady-state mean mass airflow rate where Equations 5-26 and 5-27 are both satisfied.

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

5.3.2.7.4 Steady-State Mass Airflow Rate Criteria for Targeted Set Points

Starting with the time set to zero, sample not less than 30 mass airflow rate measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-28 states the relationship of the test duration to the number of samples and the equal time intervals.

$$\Delta t = (N - 1)\delta t \tag{5-28}$$

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 mass airflow rate fluctuations during operation near the steady-state conditions.

Record each sampled mass airflow rate measurement $\dot{m}_i$ and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the mass airflow rate data trend line using Equation 5-29.

$$b = \left\{ \frac{\left[N\left(\sum_{i=1}^{N} t_i \dot{m}_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} \dot{m}_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} {t_i}^2\right) - \left(\sum_{i=1}^{N} t_i\right)^2\right]} \right\} \tag{5-29}$$

Informative Note: It should be noted that the units for the slope in Equation 5-29 are mass airflow rate, kg/s (lb_m/min), divided by the units that the user has selected for time.

The mean of the sampled mass airflow rates $\bar{\dot{m}}$ is defined by Equation 5-30.

$$\bar{\dot{m}} = \frac{1}{N}\left[\sum_{i=1}^{N}(\dot{m}_i)\right], \text{ kg/s (lb}_\text{m}\text{/min)} \tag{5-30}$$

The difference between the maximum and minimum sampled values must be less than or equal to the specified test operating tolerance as defined in Equation 5-31 where $\dot{m}_L$ is the operating tolerance limit.

$$\dot{m}_{max} - \dot{m}_{min} \le \dot{m}_L \text{ , kg/s (lb}_\text{m}\text{/min)} \tag{5-31}$$

The restriction on the slope of the trend line *b* is defined in Equation 5-32 where Δt is the sample time interval.

$$|b \times \Delta t| \le 0.5 \times \dot{m}_L \text{ , kg/s (lb}_\text{m}\text{/min)} \tag{5-32}$$

The difference between the test condition and mean of the sampled values shall be less than or equal to half of the specified operating tolerance limit as defined in Equation 5-33 where $\dot{m}_{SP}$ is the set point mass airflow rate and $\dot{m}_L$ is the operating tolerance limit.

$$|\dot{m}_{SP} - \bar{\dot{m}}| \le 0.5 \times \dot{m}_L \text{ , kg/s (lb}_\text{m}\text{/min)} \tag{5-33}$$

$\bar{\dot{m}}$, as determined by Equation 5-18, represents the steady-state mean refrigerant mass flow rate where Equations 5-31, 5-32, and 5-33 are all satisfied.

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

5.3.2.8 Unsteady Mass Airflow Rate Measurements. If required by the test plan in Section 5.1, mass airflow 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, and
d. using instrument response times specified in the test plan.

5.3.2.9 Operating Limits. Operating conditions during airflow data measurements shall not exceed limits for pressure, pressure differential, temperature, air velocity, or pressure pulsations specified in the test plan in Section 5.1, or by the airflow meter manufacturer to achieve the measurement system accuracy required by the test plan.

5.3.2.10 Thermodynamic Properties of Air. The thermodynamic properties of the dry air and moist air shall be obtained from ASHRAE RP-1485[2].

Informative Note: Software based upon ASHRAE RP-1485[A3] is available.

6. INSTRUMENTS

6.1 Instrumentation Requirements for All Measurements

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

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

Informative Note: For further reading, ISO/IEC 17025**,** *General Requirements for the Competence of Testing and Calibration Laboratories*[A3]*,* defines good test laboratory practices.

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

1. Temperature: ANSI/ASHRAE 41.1[3] if temperature measurements are required.
2. Pressure: ANSI/ASHRAE 41.3[4] if pressure measurements are required.
3. Humidity: ANSI/ASHRAE 41.6[5] if humidity measurements are required.
4. Electrical Power or Shaft Power: ANSI/ASHRAE 41.11[6] if electrical power or shaft power measurements are required.

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

a. Temperature measurement system accuracy for both laboratory and field applications shall be within ±0.3°C (±0.5°F).
b. Temperature difference measurement system accuracy for both laboratory and field applications shall be within the greater of ±1% of the measured temperature difference or ±0.1°C (±0.2°F).

6.3 Pressure Measurements

6.3.1 Laboratory Pressure Measurements

6.3.1.1 If laboratory pressure measurements are required by the test plan in Section 5.1, the pressure measurement system accuracy shall be within ±25 Pa (±0.1 in. of water) unless otherwise specified in the test plan. If absolute pressure sensors are not used, the barometric pressure shall be added to obtain absolute pressure values prior to performing uncertainty calculations.

6.3.1.2 If laboratory differential pressure measurements are required by the test plan in Section 5.1, the pressure measurement system accuracy shall be within ±1% of the measured pressure difference, but not more accurate than ±25 Pa (±0.1 in. of water) unless otherwise specified in the test plan. Pressure shall be measured in close proximity to the flowmeter in compliance with the flowmeter manufacturer's specifications.

6.3.2 Field Pressure Measurements

6.3.2.1 If field pressure measurements are required by the test plan in Section 5.1, the pressure measurement system accuracy shall be within 75 Pa (±0.3 in. of water) unless otherwise specified in the test plan. If absolute pressure sensors are not used, the barometric pressure shall be added to obtain absolute pressure values prior to performing uncertainty calculations.

6.3.2.2 If field differential pressure measurements are required by the test plan in Section 5.1, the pressure measurement system accuracy shall be within ±3% of the measured pressure difference but not more accurate than ±75 Pa (±0.3 in. of water) unless otherwise specified in the test plan. Pressure shall be measured in close proximity to the flowmeter in compliance with the flowmeter manufacturer's specifications.

6.4 Power Measurements. If electrical power measurements or shaft power measurements are required by the test plan in Section 5.1, the measurement system accuracy shall be within ±1% of reading.

6.5 Steam-Flow Measurement. If steam-flow rate measurements are required by the test plan in Section 5.1, the measurement system accuracy shall be within ±1% of reading.

6.6 Time Measurements. If time measurements are required by the test plan in Section 5.1, the 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, or (b) a different value for the measurement system accuracy in time measurement is required to be consistent with the required air velocity or airflow measurement accuracy.

7. AIR VELOCITY MEASUREMENT METHODS

7.1 Constraint on All Air Velocity Measurement Methods. A selected air velocity measurement plane shall be greater than 7.5 geometrically equivalent diameters downstream of an obstruction or any change in the airflow direction and shall exceed 3 geometrically equivalent diameters upstream of an obstruction or change in the airflow direction unless otherwise specified by the air velocity measurement instrument manufacturer. For a non-circular duct with an airflow area A, the geometrically equivalent diameter shall be obtained from Equation 7-1. For a round duct, the geometrically equivalent diameter D_E is equal to the interior diameter D.

$$D_E = \sqrt{\frac{4A}{\pi}}, \text{ dimensionless} \qquad (7\text{-}1)$$

where

D_E = geometrically equivalent diameter, m (ft)

A = airflow area, m^2 (ft^2)

7.2 Pitot-Static Tube Air Velocity Measurement Methods. The air velocity measurement methods in this section are based upon Pitot-static tube measurement principles.

7.2.1 Single Pitot-Static Tube Air Velocity Measurement. Figure 7-1 shows an example of Pitot-static tube construction and the tubing connections to manometers or a differential pressure transducer to obtain both velocity and static pressures that are used to determine air velocities at a single measurement point. Pitot-static tubes shall be aligned within ±10 degrees of the airflow direction, and any misalignment shall be included in the uncertainty estimate.

***Informative Note*:** Negative values of the 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 air velocity.

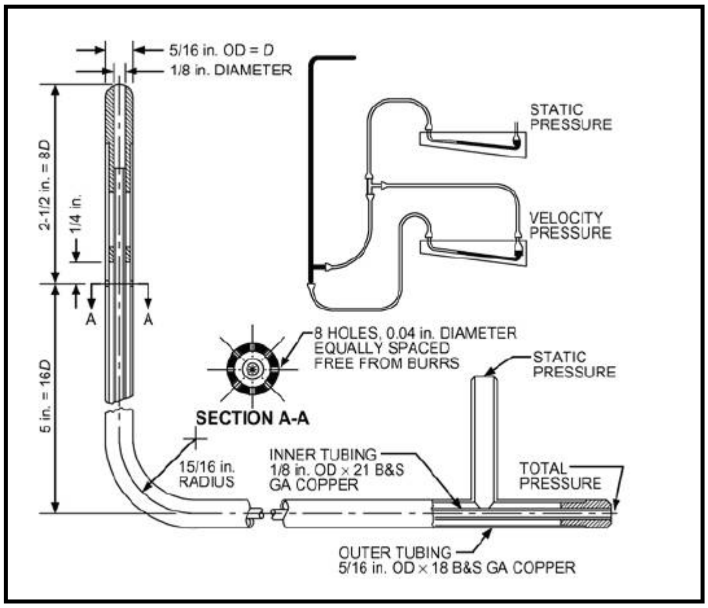


FIGURE 7-1. An example of Pitot-static tube construction and connections

7.2.1.1 Velocity Pressure. The total pressure P_t is the sum of the static pressure P_s and the velocity pressure P_v at the measurement location. The velocity pressure shall be obtained from Equation 7-2.

$$P_v = P_t - P_s, \text{ Pa (in. of water)} \qquad (7\text{-}2)$$

7.2.1.2 Air Velocity. The air velocity at the measurement location shall be obtained from Equation 7-3 in SI units or from Equation 7-4 in I-P units.

In SI units:

$$V = K_1\sqrt{\frac{2P_v}{\rho}} \tag{7-3}$$

where

V = air velocity, m/s
K_1 = calibration coefficient provided by the manufacturer, dimensionless
P_v = velocity pressure, Pa
ρ = air density in the measurement plane, kg/m^3

In I-P units:

$$V = 1097.8K_1\sqrt{\frac{P_v}{\rho}} \qquad \text{at 4 °C (39.2 °F) water temperature} \tag{7-4}$$

where

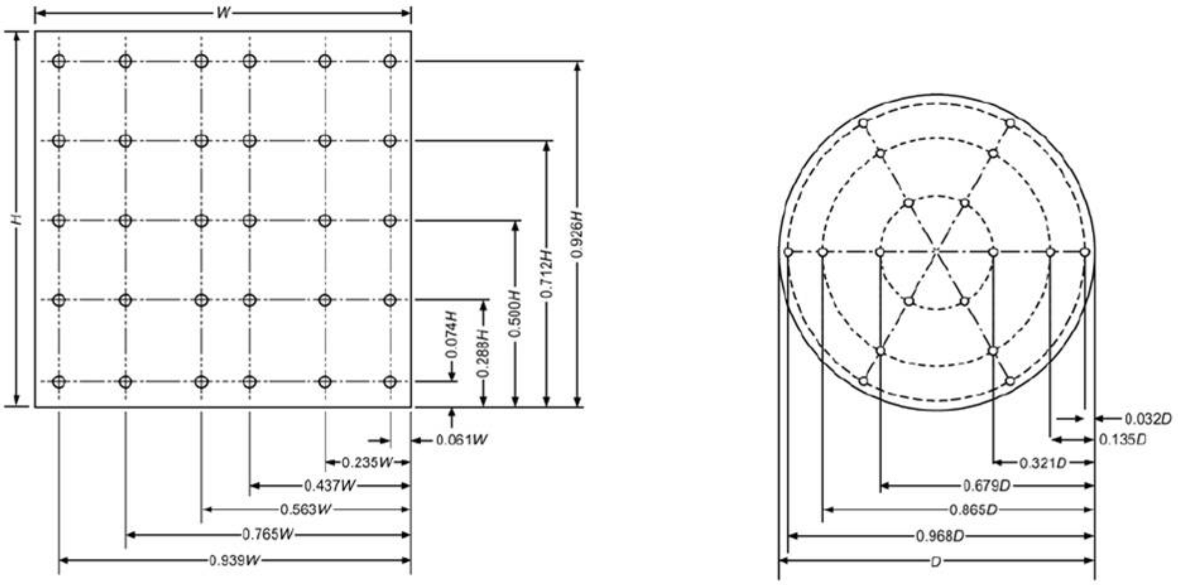
V = average air velocity, ft/min
K_1 = calibration coefficient provided by the manufacturer, dimensionless
P_v = velocity pressure, in. of water
ρ = air density in the measurement plane, lb$_m$/ft^3
1097.8= units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

***Informative Note*:** Refer to Informative Appendix G for the derivation of the units conversion coefficient.

7.2.2 Pitot-Static Tube Traverse Air Velocity Measurement. The process of sequentially positioning a single Pitot-static tube at different measuring points within a measurement plane to measure air velocities is called a Pitot-static tube traverse. Prescribed Pitot-static traverse measuring points within a measurement plane are shown in Figure 7-2 for both rectangular and round ducts. Pitot-static tubes shall be aligned within ±10 degrees of the airflow direction, and any misalignment shall be included in the uncertainty estimate.

Informative Notes:

1. Negative velocity pressure readings, which indicate that the stagnation port pressure is less than the pressure sensed at the static ports, are a clear indication that the Pitot-static tube is not properly aligned with the direction of air velocity.
2. Severe errors are also possible even if negative pressure readings are not observed. It is critical that the flow direction be known and the probe be properly aligned with the flow direction.
3. Traversing techniques have also been applied to other velocity measurement methods, including hot-wire and hot-film anemometers.



Duct Dimensions	No. of Points for Traverse Lines	Position Relative to Inner Wall
18 in. < H, W < 30 in.	5	0.074, 0.288, 0.500, 0.712, 0.926
30 in. ≤ H, W ≤ 36 in.	6	0.061, 0.235, 0.437, 0.563, 0.765, 0.939
H, W > 36 in.	7	0.053, 0.203, 0.366, 0.500, 0.634, 0.797, 0.947

Log-Tchebycheff Rule for Rectangular Ducts

Note: Example duct has 5 × 6 ($H \times W$) measurement pattern, as for rectangular duct of 24 × 30 in.

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

Log-Linear Rule for Circular Ducts

**FIGURE 7-2. Pitot-tube traverse measuring points
for rectangular ducts and round ducts**

7.2.2.1 Velocity Pressure. The total pressure P_{ti} is the sum of the static pressure P_{si} and the velocity pressure P_{vi} at the traverse measurement point. The velocity pressure at each traverse measurement point shall be obtained from Equation 7-5.

$$P_{vi} = P_{ti} - P_{si}, \text{ Pa (in. of water)} \qquad (7\text{-}5)$$

7.2.2.2 Average Velocity Pressure. The average velocity pressure P_{va} shall be obtained from Equation 7-6 where N equals the total number of traverse measurement points.

$$P_{va} = \left(\frac{\sum_{i=1}^{N} \sqrt{P_{vi}}}{N}\right)^2, \text{ Pa (in. of water)} \qquad (7\text{-}6)$$

7.2.2.3 Average Air Velocity. The average air velocity shall be obtained from Equation 7-7 in SI units or from Equation 7-8 in I-P units.

In SI units:

$$V_a = K_2 \sqrt{\frac{2P_{va}}{\rho}} \qquad (7\text{-}7)$$

where

V_{a} = average air velocity, m/s
K_2 = calibration coefficient provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, Pa

ρ = air density in the measurement plane, kg/m^3

In I-P units:

$$V_a = 1097.8\, K_2 \sqrt{\frac{P_{va}}{\rho}} \qquad \text{at 4 °C (39.2 °F) water temperature} \qquad (7\text{-}8)$$

where

V_a = average air velocity, ft/min
K_2 = calibration coefficient provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, in. of water
ρ = air density in the measurement plane, lb$_m$/ft^3
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

***Informative Note*:** Refer to Informative Appendix G for the derivation of the units conversion coefficient.

7.2.3 Self-Averaging Array Air Velocity 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.

7.2.3.1 Average Velocity Pressure. The average velocity pressure shall be obtained from Equation 7-9.

$$P_{va} = P_{ta} - P_{sa}, \text{ Pa (in. of water)} \qquad (7\text{-}9)$$

where

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

7.2.3.2 Average Air Velocity. The average air velocity shall be obtained from Equation 7-10 in SI units or from Equation 7-11 in I-P units.

In SI units:

$$V_a = K_3 \sqrt{\frac{2P_{va}}{\rho}} \qquad (7\text{-}10)$$

where

V_a = average air velocity, m/s
K_3 = calibration coefficient provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, Pa
ρ = air density in the measurement plane, kg/m^3

In I-P units:

$$V_a = 1097.8\, K_3 \sqrt{\frac{P_{va}}{\rho}} \qquad \text{at 4 °C (39.2 °F) water temperature} \qquad (7\text{-}11)$$

where

V_a = average air velocity, ft/min
K_3 = calibration coefficient provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, in. of water
ρ = air density in the measurement plane, lb_m/ft^3
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

***Informative Note*:** Refer to Informative Appendix G for the derivation of the units conversion coefficient.

7.2.4 Self-Averaging Probe Air Velocity 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.

7.2.4.1 Average Velocity Pressure. The average velocity pressure shall be obtained from Equation 7-12.

$$P_{va} = P_{ta} - P_{sa} \qquad (7\text{-}12)$$

where

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

7.2.4.2 Average Air Velocity. The average air velocity shall be obtained from Equation 7-13 in SI units or from Equation 7-14 in I-P units.

In SI units:

$$V_a = K_4 \sqrt{\frac{2P_{va}}{\rho}} \qquad (7\text{-}13)$$

where

V_a = average air velocity, m/s
K_4 = calibration coefficient provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, Pa
ρ = air density in the measurement plane, kg/m^3

In I-P units:

$$V_a = 1097.8 K_4 \sqrt{\frac{P_{va}}{\rho}} \qquad \text{at 4 °C (39.2 °F) water temperature} \qquad (7\text{-}14)$$

where

V_a = average air velocity, ft/min
K_4= calibration coefficient provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, in. of water
ρ = air density in the measurement plane, lb_m/ft^3
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

***Informative Note*:** Refer to Informative Appendix G for the derivation of the units conversion coefficient.

7.3 Thermal Anemometer. The thermal anemometer incorporates one of the following velocity sensors at the sensing end of a probe: (a) a heated resistance temperature device, (b) a thermocouple junction, or (c) a thermistor sensor. Air movement past the electrically-heated velocity sensor cools the sensor in proportion to the speed of the airflow.

Informative Notes:
1. Commercial thermal anemometers normally include associated equipment to collect and average the individual air velocity measurements to provide the resulting measured average air velocity for display or automated data recording.
2. Unlike a Pitot-static probe, which can provide some warning of severe misalignment by giving a negative reading, a thermal anemometer always indicates a positive velocity reading, even if the flow direction is reversed.
3. For user information, see Informative Appendix E Section E6.

7.4 Rotary Vane Anemometers. Rotary vane anemometers provide a direct readout of air velocity based upon the wheel revolution rate. Rotary vane anemometers shall be aligned with the airflow direction within ±10 degrees, and any misalignment shall be included in the uncertainty estimate.

7.5 Ultrasonic Velocity Flowmeters. Ultrasonic flowmeters measure air velocity. Clamp-on ultrasonic flowmeters measure air velocity within a pipe or tube without being inserted into the airflow stream.

Ultrasonic flowmeters use the transit-time method to measure the effect that flow velocity has on bi-directional acoustical signals. An upstream transducer sends a signal to a downstream transducer that then returns a signal. When air is not flowing, the time for the signal to go from one transducer to another, in either direction, is constant. Air 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 airflow velocity.

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

7.6 Drag-Force Velocity Meters. Drag-force flowmeters determine air velocity. Piezoelectric or strain-gage methods are used to sense dynamic drag-force variations. Air velocity shall be obtained from Equation 7-15 in SI units or obtained from Equation 7-16 in I-P units.

Informative Note: For further reading, see Informative Appendix A, Reference A5.

In SI units:

$$V = \sqrt{\frac{2\,f_d}{C_d A \rho}} \qquad (7\text{-}15)$$

where

V = calculated air velocity, m/s
f_d = measured drag force, N
C_d = drag coefficient specified by the meter manufacturer, dimensionless
A = cross-section area, m^2
ρ = air density, kg/m^3

In I-P units:

$$V = \sqrt{\frac{2\,g_c f_d}{C_d A \rho}} \qquad (7\text{-}16)$$

where

V = calculated air velocity, ft/s
f_d = measured drag force, lb_f
C_d = drag coefficient specified by the meter manufacturer, dimensionless
A = cross-section area, ft^2
ρ = air density, lb_m/ft^3
g_c = gravitational constant, 32.174 $(lb_m\text{-}ft)/(lb_f\text{-}s^2)$

7.7 Laser Doppler Velocimeter. A Laser Doppler Velocimeter (LDV) is an optical measurement system that collects scattered light produced by particles that are seeded into the airstream that pass through two intersecting laser beams that have the same light frequency as shown in Figure 7-3.

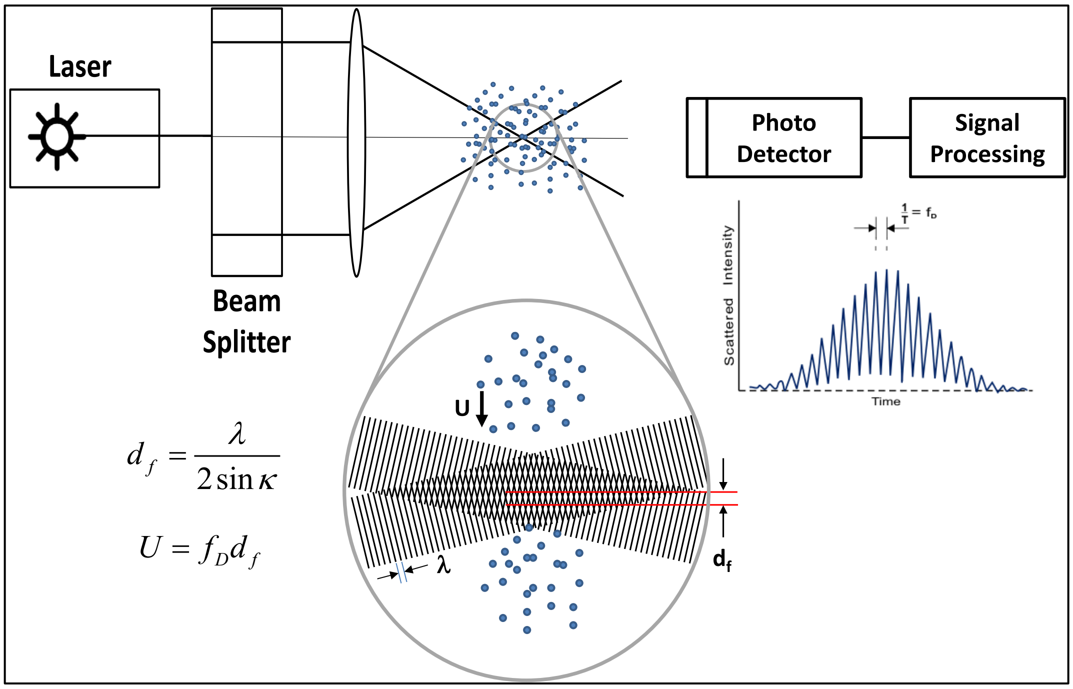


FIGURE 7-3. Laser Doppler Velocimeter (LDV)

The perpendicular air velocity component *U* shall be obtained from Equation 7-17.

$$U = (f_D)(d_f) \tag{7-17}$$

where

U = airflow velocity in direction shown, m/s (fpm)
f_D = measured Doppler burst frequency, Hz
d_f = fringe spacing = $\lambda/[2\sin(\kappa)]$, m (ft)
λ = wavelength of laser light , m (ft)
κ = half of the angle between the two intersecting laser beams, rad (deg)

Informative Note: A variety of Laser Doppler Velocimeters are commercially available.

8. AIRFLOW MEASUREMENT DUCT FEATURES AND COMPONENTS AND AIRSTREAM MIXING COMPONENTS

8.1 Overview. Duct features and components used in the airflow measurement single-nozzle ducts and single- and multiple-nozzle chambers that are described in Section 9 include static pressure taps, piezometer rings, flow straighteners, transition pieces, and variable air supply or exhaust systems.

Additionally, airflow mixing components are applied to single airflow streams or to the junction of two airflow streams to obtain more uniform air temperatures and air velocities.

8.2 Static Pressure Taps. Unless otherwise specified in the test plan in Section 5.1, static pressure taps shall be constructed as defined in Figure 8-1 and shall be located around the duct perimeter in a measurement plane with (a) one pressure tap located on each surface of a rectangular duct and centered within ±10% of the width of the surface, or (b) four pressure taps shall be located with one pressure tap at each 90 degrees of circumference within ±10 degrees.

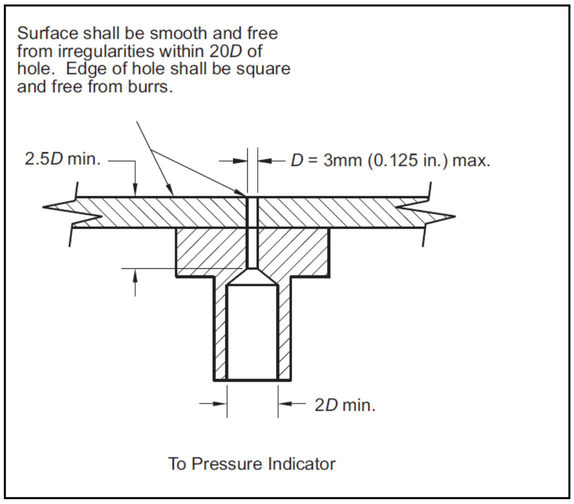


FIGURE 8-1. Static pressure tap construction requirements

8.3 Piezometer Ring

8.3.1 Piezometer Ring Requirements. Piezometer ring is the name given to the static pressure manifolds that provide an average static pressure at a given measurement plane. Unless otherwise specified in the test plan in Section 5.1, piezometer rings shall be installed as illustrated in Figure 8-2 with the following constraints:

a. The four tubing segments (A + B) shall have equal lengths within ±10%.

b. The four tubing segments C shall have equal lengths within ±10%.

c. The tubing segments (D + E) and (F + G) shall have equal lengths within ±10%.

d. The tubing segments (H + J) and (K + L) shall have equal lengths within ±10%.

e. The four tubing segments M shall have equal lengths within ±10%.

f. The four tubing segments N shall have equal lengths within ±10%.

g. Tubing shall be made from metal or plastic with a pressure rating not less than 1480 kPa (200 psig) to pass the installed piezometer ring pressure leak test procedures prescribed in Section 8.3.2.

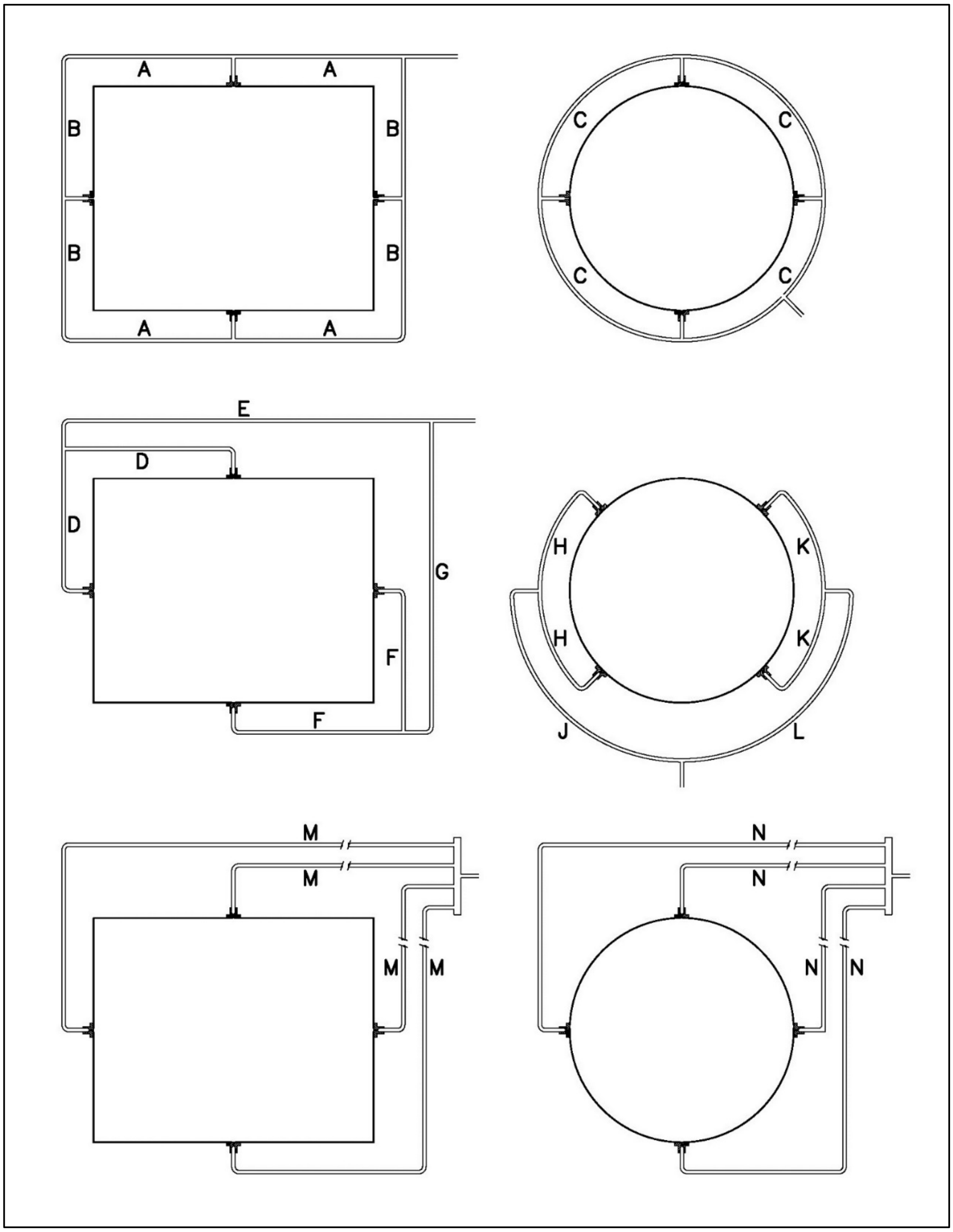


FIGURE 8-2. Piezometer ring connection alternatives

8.3.2 Piezometer Ring Leak Test. Leak test each installed piezometer ring assembly as prescribed in Sections 8.3.2.1, 8.3.2.2, 8.3.2.3, and 8.3.2.4 unless otherwise specified by the test plan in Section 5.1.

8.3.2.1 Disconnect each barometric pressure sensor and each differential pressure sensor in the installed piezometer ring assembly. Use one of the open tube ends to pressurize the assembly in compliance with 8.3.2.2 and 8.3.2.3. Plug the remaining open tube ends.

8.3.2.2 Connect the open end of the tube in to a source of regulated compressed air or compressed nitrogen as illustrated in Figure 8-3 that has (a) an integral pressure gauge at the connection and (b) a dew point temperature no more than -40°C (-40°F) at a pressure not less than 136 kPa (5 psig) and not more than 170 kPa (10 psig).

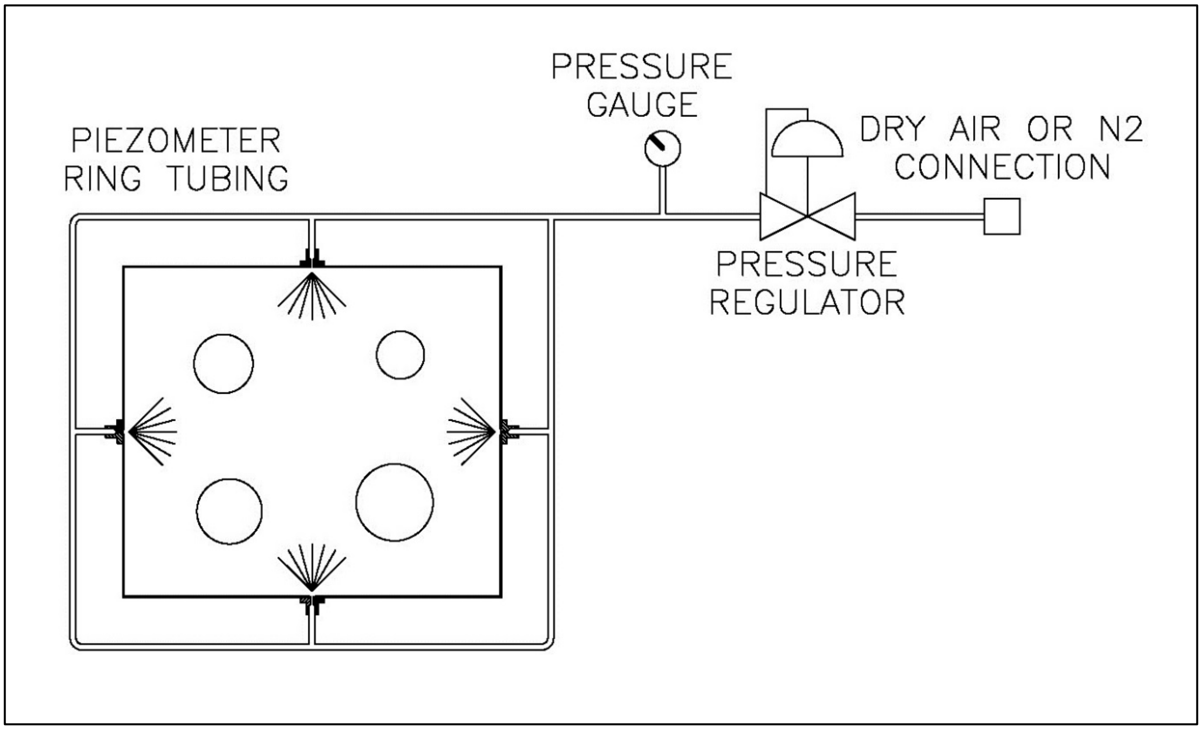


FIGURE 8-3 Piezometer leak test setup illustration

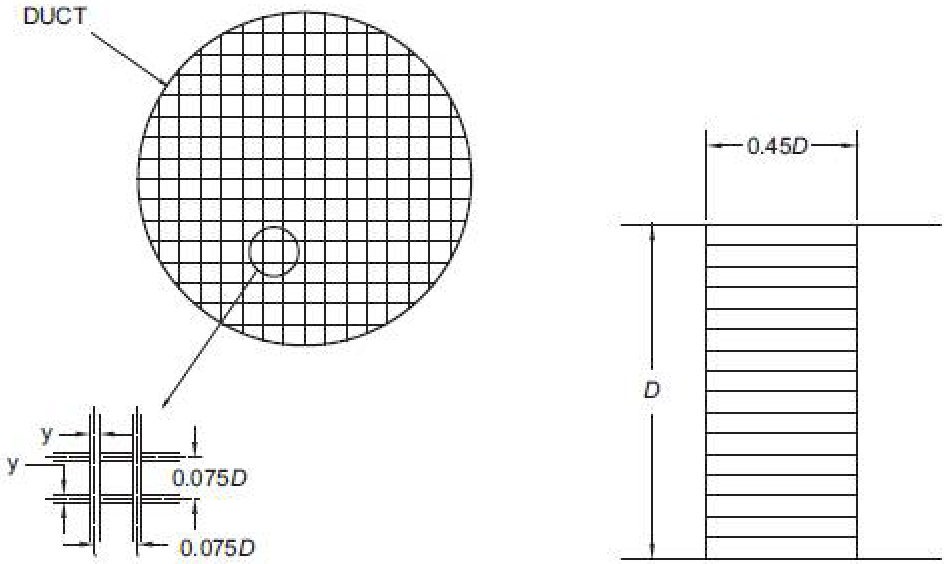
8.3.2.3 Apply a leak test liquid solution to the perimeter of each tubing connection and to the fitting in the installed piezometer assembly. Bubbles in the leak test solution indicate leaks. Repair the installed piezometer assembly to eliminate the leaks that are found using this procedure and repeat this leak test procedure until the installed piezometer ring assembly is leak-free.

8.3.2.4 Release the leak test pressure, disconnect the source of compressed air or compressed nitrogen, and re-install each barometric pressure sensor and each differential pressure sensor.

8.4 Flow Straighteners. Cell-type flow straighteners shall conform to Figure 8-4 and the thickness dimension, *y*, shall not exceed 0.005 *D*. Star-type flow straighteners shall conform to Figure 8-5.

Informative Notes:

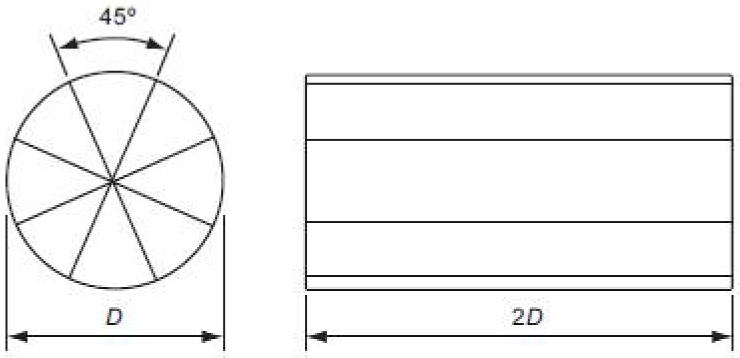
1. Although the term "straightener" is widely used to describe these devices, the replacement term "conditioner" is emerging because "conditioner" more aptly describes the function of these devices.
2. For further reading, see Informative Appendix A citation A5.



Notes:

1. All dimensions shall be within $\pm 0.005D$ except y, which shall not exceed $0.005D$
2. Cell sides shall be flat and straight. Where $y > 3$ mm (0.125 in.), the leading edge of each segment shall have a chamfer of 1.3 mm (0.05 in.) per side. The method of joining cell segments (such as tack welds) shall be kept to the minimum required for mechanical integrity and shall result in minimum protusion into the fluid stream.

FIGURE 8-4. Cell-type flow straightener



The star straightener will be constructed of eight radial blades of length equal to $2D_4$ (with a ±1% tolerance) and of thickness not greater than $0.007D_4$. The blades will be arranged to be equidistant on the circumference with the angular deviation being no greater than 5° between adjacent plates.

FIGURE 8-5. Star-type flow straightener

8.5 Transformation Pieces. Transformation pieces used to connect rectangular units under test (UUTs) to round single-nozzle ducts or single-or multiple-nozzle chambers, or round UUTs to rectangular single-nozzle ducts or single-or multiple-nozzle chambers shall be made in compliance with Figure 8-6.

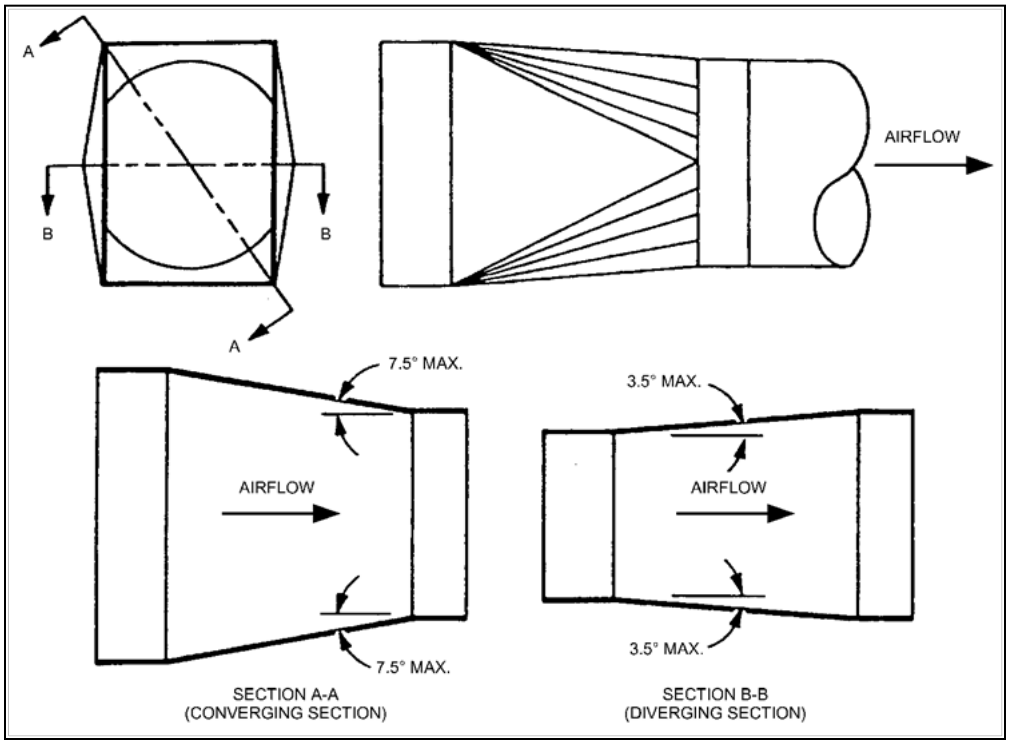


FIGURE 8-6. Transformation pieces

8.6 Airstream Mixing Components

Airstream mixing components are applied to single airflow streams or to the junction of two airflow streams to obtain more uniform air temperatures and air velocities. Figures 8-7, 8-8, and 8-9 are examples of airflow mixing components.

The air mixer portion of ASHRAE Research Project 1733-RP[10] is an example of the application of computational fluid dynamics to visualize the effectiveness of candidate air mixer geometries to create uniform air temperatures and velocities. A summary of the results of that effort is provided in a technical paper authored by Hyunjin Park and Christian K. Bach[11].

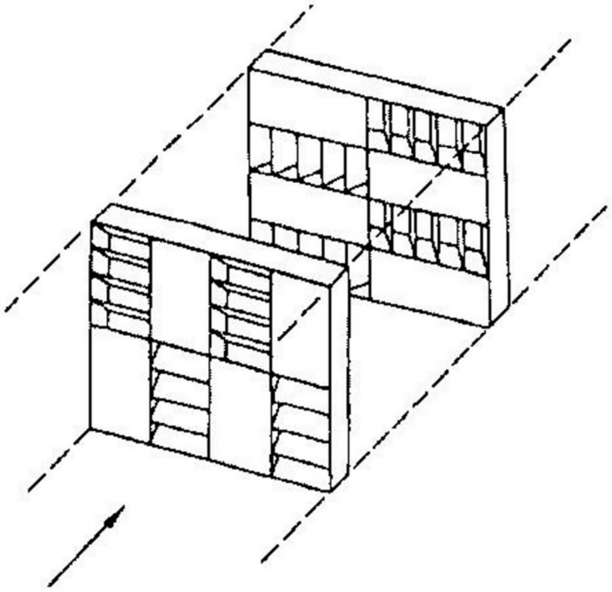


Figure 8-7 Opposing louvers in a rectangular duct

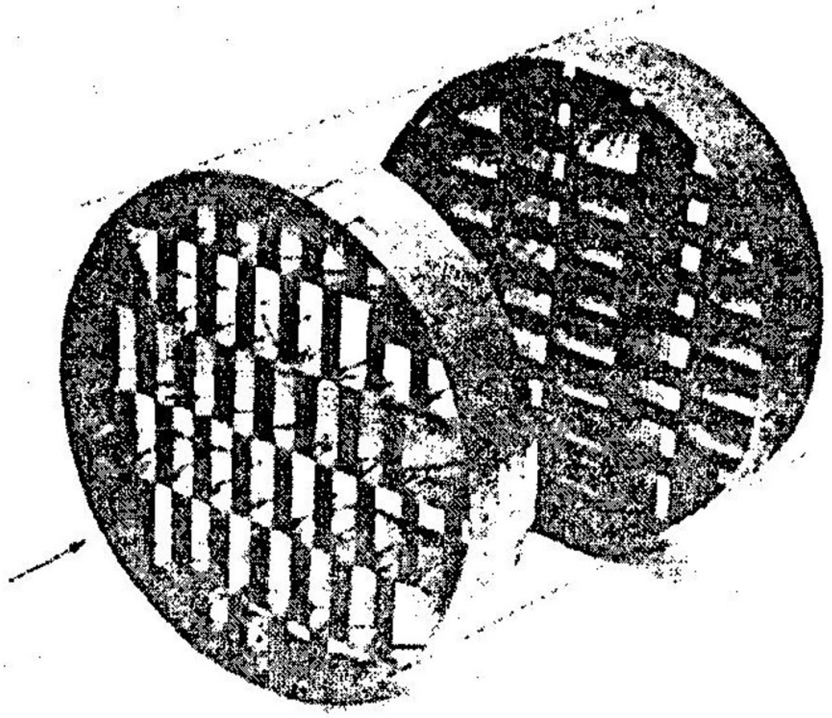


Figure 8-8 Opposing grids in a round duct

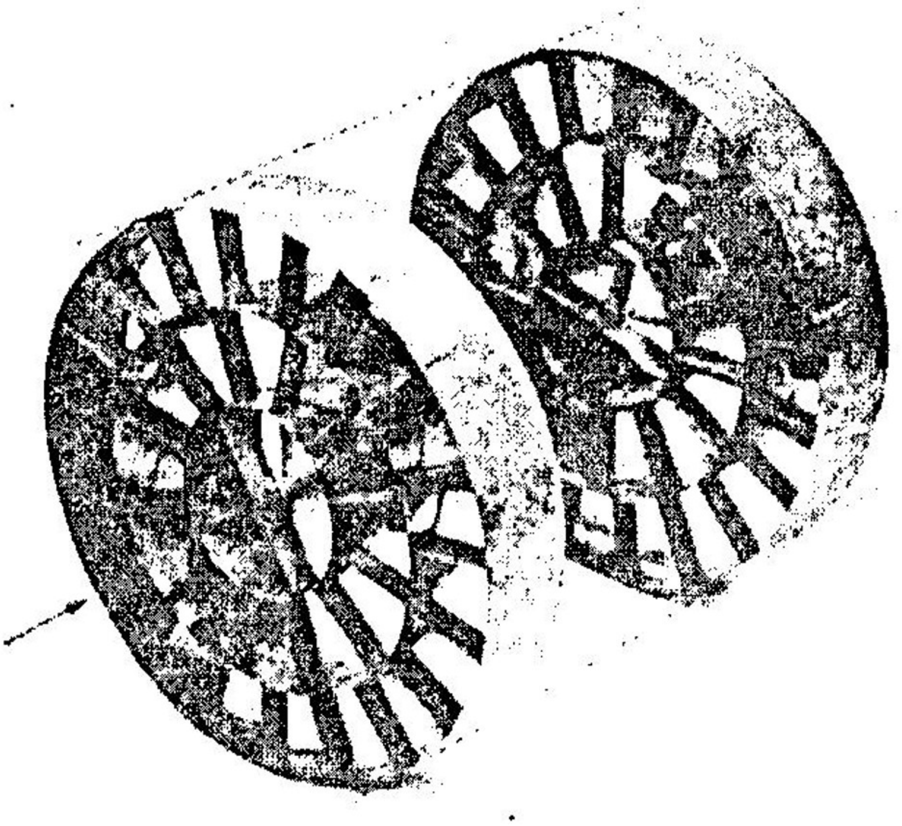


Figure 8-9 Opposing radial segments in a round duct

9. AIRFLOW MEASUREMENT METHODS

9.1 Constraint on All Airflow Measurement Methods Except Nozzle Chambers. Except for single- and multiple-nozzle nozzle chambers, a selected airflow measurement plane shall exceed 7.5 geometrically equivalent diameters downstream of an obstruction or any change in the airflow direction and shall exceed 3 geometrically equivalent diameters upstream of an obstruction or change in the airflow direction unless otherwise specified by the airflow measurement instrument manufacturer. For a non-circular airflow area duct with an airflow area A, the geometrically equivalent diameter shall be obtained from Equation 9-1. For a round duct, the geometrically equivalent diameter D_E is equal to the interior diameter D.

$$D_E = \sqrt{\frac{4A}{\pi}}\text{, dimensionless} \tag{9-1}$$

where
D_E = geometrically equivalent diameter, dimensionless
A = airflow area, m^2 (ft^2)

9.2 Pitot-Static Tube Airflow Measurement Methods. The airflow measurement methods in this section are based upon Pitot-static tube measurement principles.

9.2.1 Pitot-Static Tube Traverse Airflow Measurement. Figure 9-1 shows an example Pitot-static tube construction and the connections to manometers or electronic pressure transducers. Sections 9.2.1, 9.2.2, and 9.2.3 describe three different methods to determine air velocity at measurement points in an airstream by measuring total and static pressures. Pitot-static tubes shall be aligned within ±10 degrees of the airflow direction, and any misalignment shall be included in the uncertainty estimate.

Informative Notes:

1. Negative velocity pressure readings are a clear indication that the Pitot-static tube is not properly aligned with the direction of air velocity.
2. Severe errors are also possible even if negative pressure readings are not observed. It is critical that the flow direction be known, and the probe be properly aligned with the flow direction.
3. Traversing techniques have also been applied to other velocity measurement methods, including hot-wire or hot-film anemometers.

The process of sequentially positioning a single Pitot-static tube at different measuring points within a measurement plane to measure air velocities is called a Pitot-static tube traverse. Prescribed Pitot-static traverse measuring points within a measurement plane are shown in Figure 9-2 for both rectangular and round ducts.

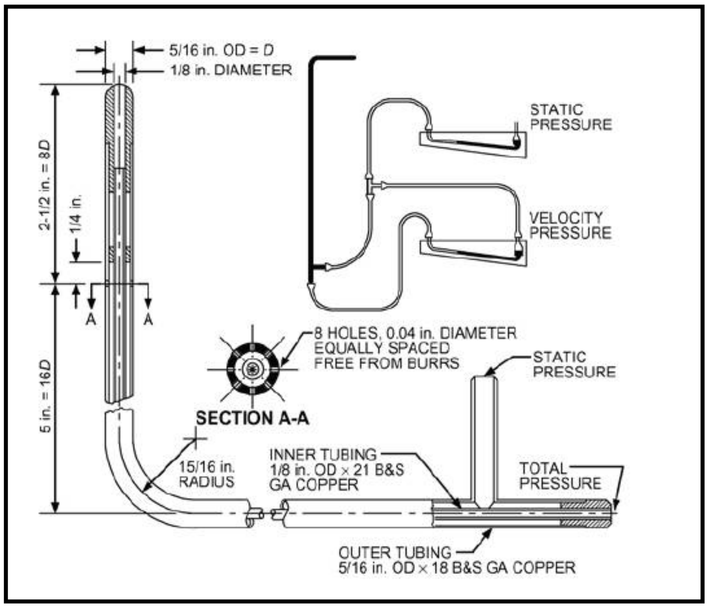
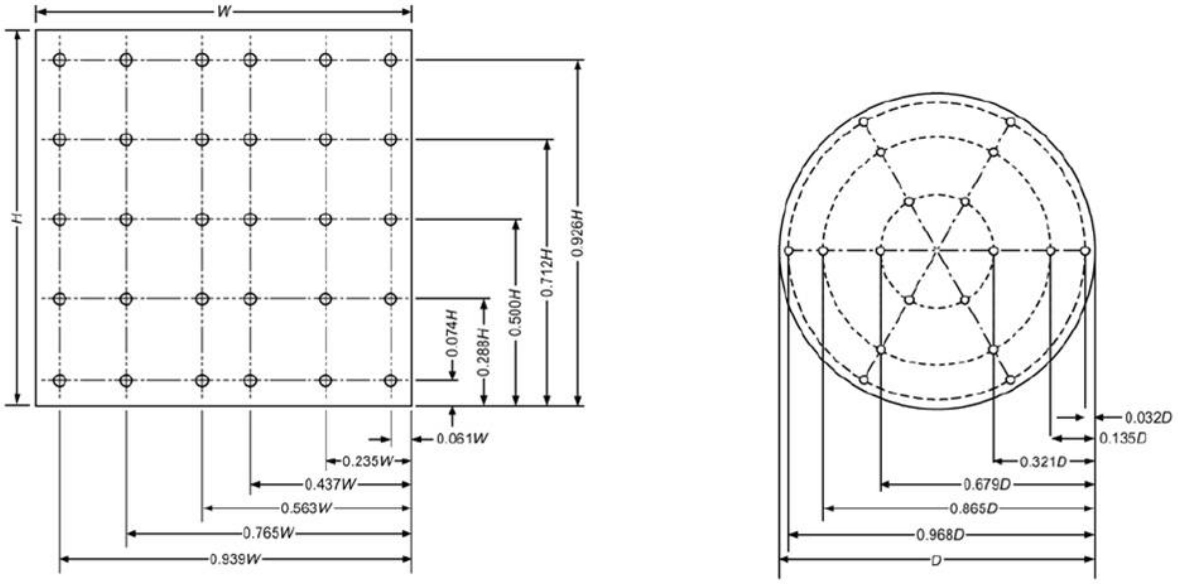


Figure 9-1. An example of Pitot-static tube construction and connections



Duct Dimensions	No. of Points for Traverse Lines	Position Relative to Inner Wall
18 in. < *H*, *W* < 30 in.	5	0.074, 0.288, 0.500, 0.712, 0.926
30 in. ≤ *H*, *W* ≤ 36 in.	6	0.061, 0.235, 0.437, 0.563, 0.765, 0.939
H, *W* > 36 in.	7	0.053, 0.203, 0.366, 0.500, 0.634, 0.797, 0.947

Log-Tchebycheff Rule for Rectangular Ducts

Note: Example duct has 5 × 6 (*H* × *W*) measurement pattern, as for rectangular duct of 24 × 30 in.

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

Log-Linear Rule for Circular Ducts

Figure 9-2. Pitot-tube traverse measuring points for rectangular ducts and round ducts

9.2.1.1 Velocity Pressure. The total pressure P_{ti} is the sum of the static pressure P_{si} and the velocity pressure P_{vi} at each traverse measurement point. The velocity pressure at each measurement location shall be obtained from Equation 9-2.

$$P_{vi} = P_{ti} - P_{si}, \text{ Pa (in. of water)} \tag{9-2}$$

9.2.1.2 Average Velocity Pressure. The average velocity pressure P_{va} shall be obtained from Equation 9-3 where N is the total number of traverse measurement points.

$$P_{va} = \left(\frac{\sum_{i=1}^{N}\sqrt{P_{vi}}}{N}\right)^2, \text{ Pa (in. of water)} \tag{9-3}$$

9.2.1.3 Average Air Velocity. The average air velocity shall be obtained from Equation 9-4 in SI units or from Equation 9-5 in I-P units.

In SI units:

$$V_a = K_5\sqrt{\frac{2P_{va}}{\rho}} \tag{9-4}$$

where

V_a = average air velocity, m/s
K_5 = calibration factor provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, Pa
ρ = air density in the measurement plane, kg/m^3

In I-P units:

$$V_a = 1097.8K_5\sqrt{\frac{P_{va}}{\rho}} \qquad \text{at 4 °C (39.2 °F) water temperature} \qquad (9\text{-}5)$$

where

V_a = average air velocity, ft/min
K_5 = calibration factor provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, in. of water
ρ = air density in the measurement plane, lb_m/ft^3
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

***Informative Note*:** Refer to Informative Appendix G for the derivation of the units conversion coefficient.

9.2.1.4 Volumetric Airflow. The volumetric airflow at the measurement plane shall be obtained from Equation 9-6.

$$Q = V_a A \qquad (9\text{-}6)$$

where

Q = volumetric air flow rate, m^3/s [cfm]
V_a = average air velocity, m/s [ft/min]
A = measurement plane cross section area, m^2 [ft^2]

9.2.2 Self-Averaging Array Airflow 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.

Informative Note: For user information, see Informative Appendix E Section E5.

9.2.2.1 Average Velocity Pressure. The average velocity pressure P_{va} in the measurement plane shall be obtained from Equation 9-7.

$$P_{va} = P_{ta} - P_{sa} \qquad (9\text{-}7)$$

9.2.2.2 Average Air Velocity. The average air velocity shall be obtained from Equation 9-8 in SI units or from Equation 9-9 in I-P units.

In SI units:

$$V_a = K_6\sqrt{\frac{2P_{va}}{\rho}} \qquad (9\text{-}8)$$

where

V_a = average air velocity, m/s
K_6 = calibration factor provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, Pa

ρ = air density in the measurement plane, kg/m^3

In I-P units:

$$V_a = 1097.8K_6\sqrt{\frac{P_{va}}{\rho}} \qquad \text{at 4 °C (39.2 °F) water temperature} \qquad (9\text{-}9)$$

where

V_a = average air velocity, ft/min
K_6 = calibration factor provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, in. of water
ρ = air density in the measurement plane, lb$_m$/ft^3
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

***Informative Note*:** Refer to Informative Appendix G for the derivation of the units conversion coefficient.

9.2.2.3 Volumetric Airflow. The volumetric airflow at the measurement plane shall be obtained from Equation 9-10.

$$Q = V_a A \qquad (9\text{-}10)$$

where

Q = volumetric air flow rate, m^3/s [cfm]
V_a = average air velocity, m/s [ft/min]
A = measurement plane cross section area, m^2 [ft^2]

9.2.3 Self-Averaging Probe Airflow 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.

9.2.3.1 Average Velocity Pressure. The average velocity pressure P_{va} in the measurement plane shall be obtained from Equation 9-11.

$$P_{va} = P_{ta} - P_{sa} \qquad (9\text{-}11)$$

9.2.3.2 Average Air Velocity. The average air velocity shall be obtained from Equation 9-12 in SI units or from Equation 9-13.

In SI units:

$$V_a = K_7\sqrt{\frac{2P_{va}}{\rho}} \qquad (9\text{-}12)$$

where

V_a = average air velocity, m/s

K_7 = calibration factor provided by the manufacturer, dimensionless
P_{va} = average velocity pressure, Pa
ρ = air density, kg/m^3

In I-P units:

$$V_a = 1097.8K_7\sqrt{\frac{P_{va}}{\rho}} \quad \text{at 4 °C (39.2 °F) water temperature} \qquad (9\text{-}13)$$

where

V_a = average air velocity, ft/min
K_7 = calibration factor provided by the manufacturer, dimensionless
P_{va} = pressure, in. of water
ρ = air density in the measurement plane, lb$_m$/ft^3
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

***Informative Note*:** Refer to Informative Appendix G for the derivation of the units conversion coefficient.

9.2.3.3 Volumetric Airflow. The volumetric airflow at the measurement plane shall be obtained from Equation 9-14.

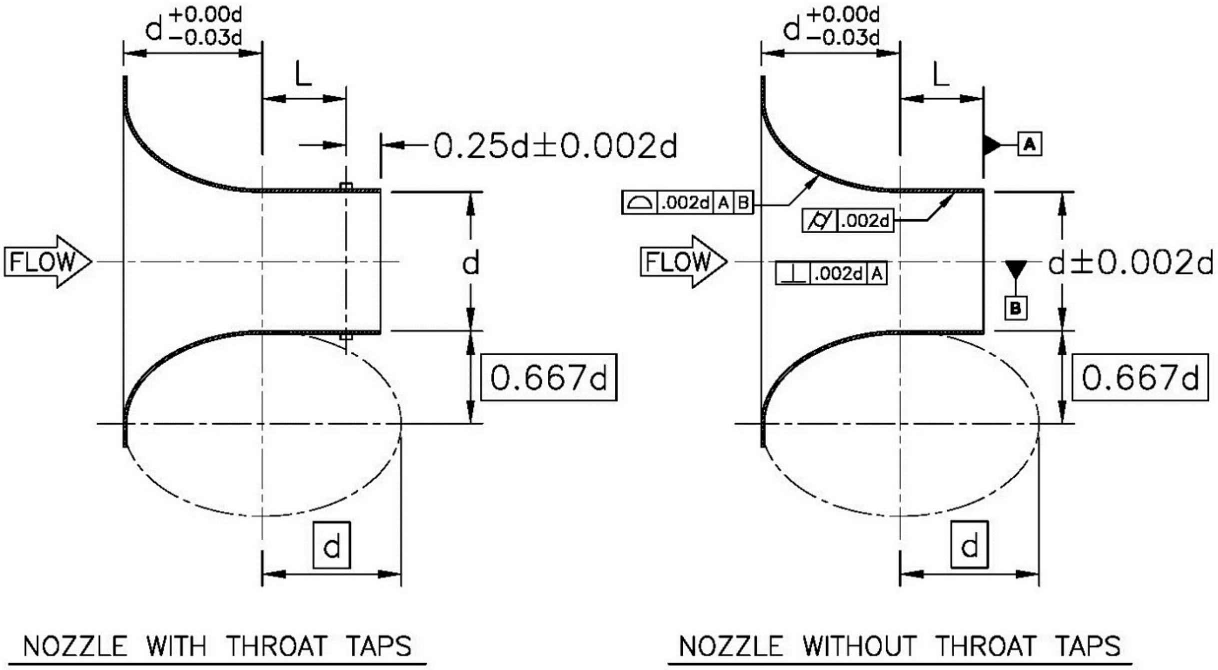
$$Q = V_a A \qquad (9\text{-}14)$$

where

Q = volumetric air flow rate, m^3/s [cfm]
V_a = average air velocity, m/s [ft/min]
A = measurement plane cross section area, m^2 [ft^2]

9.3 Single- and Multiple-Nozzle Airflow Methods

9.3.1 ASHRAE Nozzle Geometry. Figure 9-3 prescribes geometric proportions and specifications for installed nozzles. Nozzles that are constructed in compliance with Figure 9-3 require no calibration[7] unless otherwise specified in the test plan in Section 5.1 if used at a temperature within ±6ºC (±10ºF) of the ambient temperature during the dimensional measurements. Multiple-nozzle chambers use the nozzle version without throat taps.



NOZZLE WITH THROAT TAPS

NOZZLE WITHOUT THROAT TAPS

1. The nozzle shall have a cross-section consisting of an elliptical nozzle and a cylindrical portion as shown. The nozzle throat diameter is d.
2. The dimensions of the elliptical portion are shown.
3. Arcs shall smoothly meet and blend with the cylindrical portion within not more than 0.002d.
4. Nozzle dimension L shall be 0.6d ± 0.005d.
5. Nozzle interior surface roughness shall be not more than ± 0.00002d RMS.
6. ⌭ .002d requires the cylindrical portion to be a cylinder within ±0.002d.
7. ⊥ .002d A requires the nozzle centerline to be perpendicular to the diameter at the nozzle exit within ±0.002d.
8. ⌓ .002d A B requires the surface of the nozzle inlet to be an ellipse with respect to datums A and B within 0.002d.

Figure 9-3. Nozzle geometry

9.3.2 Alternative Nozzle Airflow Measurement Methods and Calculation Procedures.

a. Apply Sections 9.3.3 through 9.6.3.10 to measure airflow using single-nozzle ducts.

   Informative Note: The single-nozzle duct geometry in this standard is the same as it was in Standard 41.2-1997 (RA 2002), but the airflow calculation procedures have been changed to match the ASME MFC-3M[9] airflow calculation procedures.

b. Apply Sections 9.3.3 through 9.3.6.4.12, except the sections that are only for single-nozzle ducts, to measure airflow in single- or multiple-nozzle chambers that are defined in Figure 20.

   Informative Note: ASHRAE Conference Paper ST-16-C031[A7] demonstrates that the measurement post-test uncertainty for a single- or multiple-nozzle chamber that is constructed in compliance with these geometric specifications and using these airflow calculation methods can be as low as ±0.25%.

c. Apply Normative Appendix F to measure airflow using a legacy single- or multiple-nozzle chamber and apply the single- and multiple-nozzle chamber calculation procedures that are defined in Normative Appendix F. This alternative permits the use of legacy single- or multiple-nozzle chambers that are defined in Normative Appendix F without any hardware modifications, but requires the ASME MFC-3M[9] airflow calculation procedures instead of the ASME multiple-nozzle calculation procedures that were current in 1987.

9.3.3 Construction Requirements for Single- and Multiple-Nozzle Chambers and Single-Nozzle Ducts. This section prescribes geometric proportions and specifications for single-nozzle ducts, and for single- and multiple-nozzle chambers. Single-nozzle ducts and single- and multiple-nozzle chambers constructed in compliance with these requirements require no calibration unless otherwise required in the test plan in Section 5.1.

9.3.3.1 Cross Sections of Single- and Multiple-Nozzle Chambers and Single-Nozzle Ducts. The cross section of single- or multiple-nozzle chambers and single-nozzle ducts shall be round or rectangular. Transformation pieces described in Section 8.5 shall be used to connect rectangular units under test (UUTs) to round single- or multiple-nozzle chambers or single-nozzle ducts, or to connect round UUTs to rectangular single- or multiple-nozzle chambers or single-nozzle ducts. For a rectangular single- or multiple-nozzle chamber or single-nozzle duct with interior width and height dimensions equal to *a* and *b* respectively, the geometrically equivalent diameter shall be obtained from Equation 9-15. For a round single- and multiple-nozzle chamber or single-nozzle duct, the geometrically equivalent diameter D_E is equal to the interior diameter *D*.

$$D_E = \sqrt{\frac{4ab}{\pi}} \tag{9-15}$$

where
D_E = geometrically equivalent diameter, dimensionless
a = interior width, m (ft)
b = interior height, m (ft)

9.3.3.2 Nozzle Throat Velocity. The throat velocity of each nozzle shall exceed 3000 fpm (15 m/s).

9.3.3.3 Longitudinal Spacing Requirements. In single- and multiple-nozzle chambers, the minimum distance between the upstream screens and the nozzle inlets shall be the greater of $0.5D_E$ or $1.5d_L$ where d_L is the largest nozzle throat diameter.

9.3.3.4 Radial Spacing Requirement for Adjacent Nozzles. In single- and multiple-nozzle chambers, the centerline-to-centerline distance between adjacent nozzles shall be greater than $3d_L$ where d_L is the largest nozzle throat diameter.

9.3.3.5 Radial Spacing Requirement from Interior Walls. In single- and multiple-nozzle chambers, the distance from the centerline of any nozzle to the nearest interior wall shall be greater than 1.5 times its throat diameter *d*.

9.3.3.6 Single-Nozzle Duct Throat Diameter Limit. The ratio of nozzle throat diameter *d* to the geometrically equivalent diameter of the inlet duct D_E shall not exceed 0.53.

9.3.3.7 Airflow Settling Means Requirements for Single- and Multiple-Nozzle Chambers. An airflow settling means, consisting of at least 3 screens or perforated sheets having open areas of 40% to 65%, shall be installed in single- and multiple-nozzle chambers as indicated on Figure 9-5. Either one of the requirements in Sections 9.3.5.1 or 9.3.5.2 shall be met.

Informative Notes:

1. Where located upstream of the measurement plane, the purpose of the settling means is to provide a uniform flow and pressure field ahead of measurement plane. Where located downstream of the measurement plane, the purpose of the settling means is to absorb and redistribute the kinetic energy to allow expansion to simulate the expansion into an unconfined space.
2. Square mesh round wire screens should be used upstream of the measurement plane and perforated sheets should be used downstream.
3. Three or four screens should be used with decreasing percent of open area in the direction of airflow.

9.3.4 Single-Nozzle Duct Test Setup. Figure 9-4 shows the single-nozzle duct test setup that is within the scope of this standard.

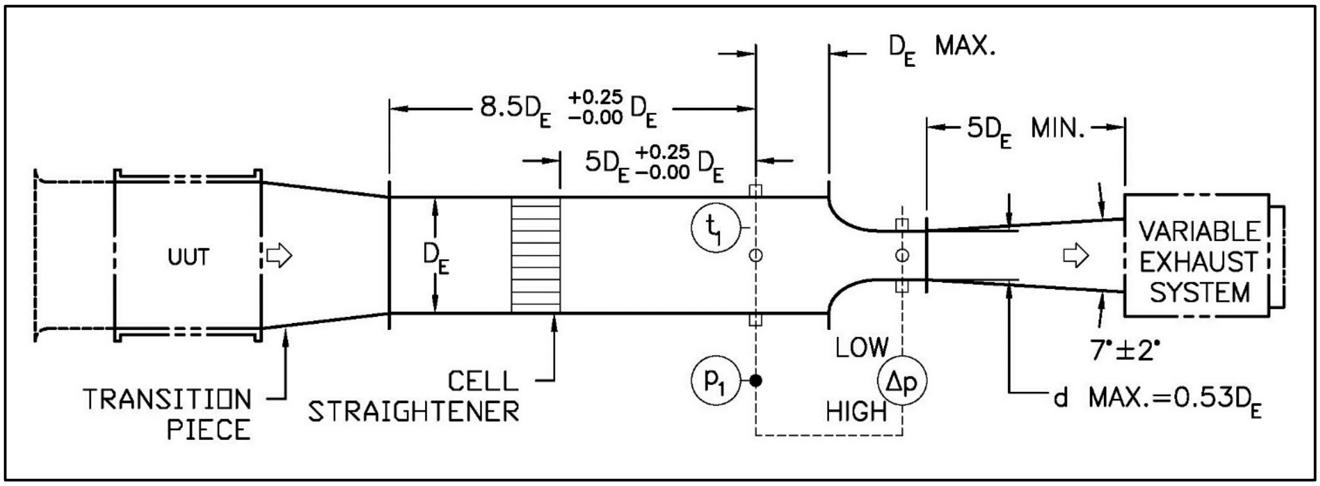


Figure 9-4. Single-nozzle duct test setup

9.3.5 Single- and Multiple-Nozzle Chamber Design. Figure 9-5 shows the construction requirements for a single- or multiple-nozzle chamber. One of the following requirements shall be met for a single-nozzle chamber or a multiple-nozzle chamber:

9.3.5.1 Single- and Multiple-Nozzle Chamber Diameter. The single- or multiple-nozzle_chamber geometrically equivalent diameter shall be sized so that the maximum average air velocity is 2 m/s (400 fpm).

9.3.5.2 Upstream Settling Means Verification Test. The maximum velocity at a distance of 0.1D_E downstream of the upstream settling means shall be measured and shall not exceed the average velocity by more than 20%.

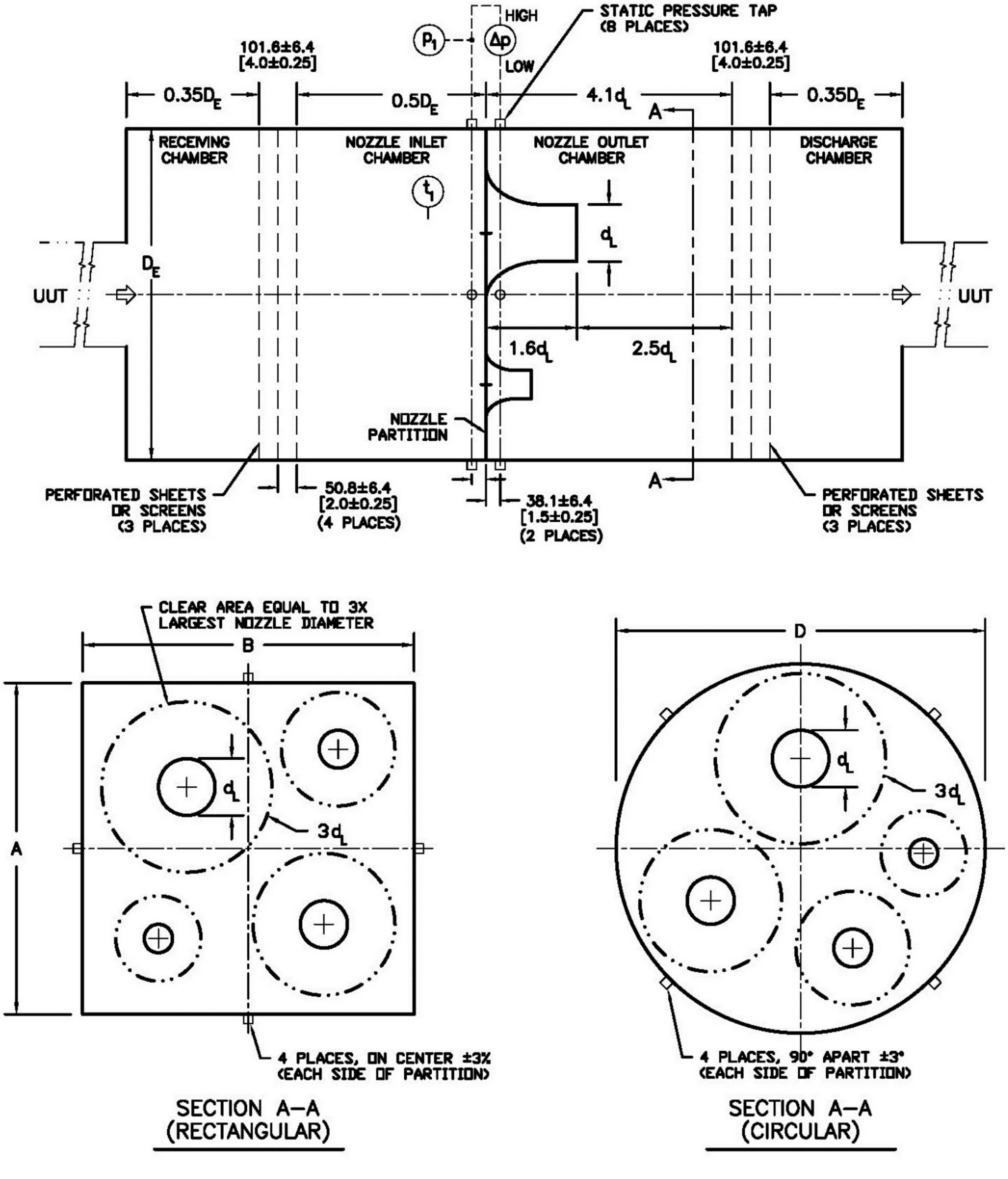


Figure 9-5. Single- or multiple-nozzle chamber construction requirements

9.3.6 Nozzle Airflow Calculations. ASME PTC 19.5[8] and ASME MFC-3M[9] describe measurement of fluid flow in pipes using orifices, flow nozzles, and venturi tubes, including construction proportions and port locations. Single-nozzle duct airflow calculation procedures follow the ASME flow nozzles procedures. Single- and multiple-nozzle chamber airflow calculations follow the ASME flow nozzles procedures, but use a discharge coefficient equation and assertions that are based upon the findings of ASHRAE Technical Paper No. 2334[7].

Calculating a volumetric airflow rate for a single-nozzle duct or a single- or multiple-nozzle chamber requires iteration because the discharge coefficient *C* is a function of the Reynolds number that is a function of the average air velocity, and the average air velocity is not known until the volumetric airflow rate has been determined. ASME PTC 19.5[8] includes an example of this iterative procedure on page 25.

9.3.6.1 Measurements. Measurements required for nozzle airflow calculations are:

a. Inlet duct geometrically equivalent diameter D_E, m (ft)
b. Nozzle throat diameter d, m (ft)
c. Nozzle inlet absolute pressure p_1, Pa (in. of water)
d. Nozzle differential pressure $\Delta p = (p_1 - p_2)$, Pa (in. of water)
e. Nozzle inlet dry-bulb temperature t_1, °C (°F)
f. Nozzle inlet humidity measurement in the form of relative humidity, dew point temperature, or wet bulb temperature in compliance with ANSI/ASHRAE Standard 41.6[4] is required unless dry air is used for the test.

Informative Note: As prescribed in Section 5.3.2.10, obtain nozzle inlet density for dry and moist air from ASHRAE RP-1485 using nozzle inlet absolute pressure, temperature, and humidity.

9.3.6.2 Dynamic Viscosity. Calculate the dynamic viscosity of air behaving as an ideal gas at moderate pressures and temperatures using Equation 9-16 for SI units or Equation 9-17 for IP units.

$$\mu = (17.23 + 0.048\, t_1) \times 10^{-6} \tag{9-16}$$

where

μ = dynamic viscosity, kg/(m-s)

t_1 = nozzle inlet temperature, °C

$$\mu = (11.00 + 0.018\, t_1) \times 10^{-6} \tag{9-17}$$

where

μ = dynamic viscosity, lb_m/(ft-s)

t_1 = nozzle inlet temperature, °F

9.3.6.3 Single-Nozzle Duct Airflow Calculations

9.3.6.3.1 Single-Nozzle Duct Hydraulic Diameter. Single-nozzle inlet duct hydraulic diameter D_h shall be obtained from dimensional measurements. For a round duct D_h is equal to the interior inlet diameter. For a rectangular duct, the hydraulic diameter shall be obtained from Equation 9-18.

$$D_h = \frac{2ab}{(a+b)} \tag{9-18}$$

Where

D_h = hydraulic diameter, dimensionless
a = interior width, m (ft)
b = interior height, m (ft)

9.3.6.3.2 Single-Nozzle Duct Reynolds Number. The single-nozzle duct Reynolds number Re_D shall be obtained from Equation 9-19.

$$Re_D = \frac{\rho_1 V D_h}{\mu_1}, \text{ dimensionless} \tag{9-19}$$

where

ρ_1 = nozzle inlet air density, kg/m^3 (lb$_m$/ft^3)
V = nozzle throat average air velocity, m/s (ft/s)
D_h = hydraulic diameter, m (ft)
μ_1 = nozzle inlet air dynamic viscosity, kg/(m-s) (lb$_m$/(ft-s))

Informative Note: Calculate the dynamic viscosity using Equation 9-16 in SI units or Equation 9-17 in IP units.

9.3.6.3.3 Single-Nozzle Duct Beta Ratio. The beta ratio for the nozzle in a single-nozzle duct shall be obtained from Equation 9-20. If airflow operating temperatures are not within ±6ºC (±10ºF) of the of the ambient temperature during the dimensional measurements, parameters d, D_h, and β shall be corrected to account for thermal expansion in compliance with ASME PTC 19.5[8] Section 3-10.

$$\beta = \left(\frac{d}{D_h}\right), \text{ dimensionless} \tag{9-20}$$

9.3.6.3.4 Volumetric Airflow Rates for a Single-Nozzle Duct. Single-nozzle duct volumetric airflow rates shall be obtained from Equation 9-21 in SI units or Equation 9-22 in I-P units.

In SI units:

$$Q = CA\varepsilon\sqrt{\frac{2(\Delta p)}{\rho_1(1-E\beta^4)}} \tag{9-21}$$

where

Q = nozzle volumetric airflow rate, m^3/s
C = nozzle discharge coefficient, dimensionless
A = nozzle throat area, m^2
ε = nozzle expansibility factor, dimensionless
Δp = nozzle differential pressure, Pa
ρ_1 = nozzle inlet air density for dry or moist air, kg/m^3
E = flow kinetic energy coefficient = 1.043[7]
β = d/D_h, dimensionless

Informative Note: The superscript “7” in “1.043[7]” above is reference number, not an exponent.

In I-P units:

$$Q = 1097.8\, CA\varepsilon \sqrt{\frac{(\Delta p)}{\rho_1(1-E\beta^4)}} \quad \text{at 4 °C (39.2 °F) water temperature} \qquad (9\text{-}22)$$

where

Q = nozzle volumetric airflow rate, cfm
C = nozzle discharge coefficient, dimensionless
A = nozzle throat area, ft^2
ε = nozzle expansibility factor, dimensionless
Δp = nozzle differential pressure, in. of water
ρ_1 = nozzle inlet air density for dry or moist air, lb_m/ft^3
E = flow kinetic energy coefficient = 1.043[7], dimensionless
β = d/D_h, dimensionless
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

Informative Note: The superscript “7” in “1.043[7]” above is reference number, not an exponent.

***Informative Note*:** Refer to Informative Appendix G for the derivation of the units conversion coefficient.

9.3.6.3.5 Nozzle Limits of Use for a Single-Nozzle Duct. The nozzle geometry in Figure 9-3 conforms to ASME’s long radius nozzle type geometry requirements, and the throat velocity requirement in Section 9.3.3.2 confirms that the single-nozzle will be operating within the long radius nozzle limits prescribed by ASME.

9.3.6.3.6 Nozzle Expansibility Factor for a Single-Nozzle Duct. The dimensionless expansibility factor ε for a long radius nozzle shall be obtained from Equation 9-23.

$$\varepsilon = \left[r^{\frac{2}{\gamma}} \left(\frac{\gamma}{\gamma-1}\right)\left(\frac{1-r^{\frac{\gamma-1}{\gamma}}}{1-r}\right)\left(\frac{1-\beta^4}{1-\beta^4 r^{\frac{2}{\gamma}}}\right)\right]^{1/2}, \text{ dimensionless} \qquad (9\text{-}23)$$

where

r = absolute pressure ratio $\left(\frac{p_2}{p_1}\right)$, dimensionless
γ = ratio of specific heat at constant pressure to specific heat at constant volume, dimensionless

9.3.6.3.7 Nozzle Discharge Coefficient for a Single-Nozzle Duct. The dimensionless discharge coefficient C for a long radius nozzle is a function of β and the Reynolds number based upon the nozzle inlet diameter. The discharge coefficient for the nozzle geometry defined in Section 9.3.1 shall be obtained from Equation 9-24.

$$C = 0.99855 - \left[\frac{7.006}{\sqrt{Re_d}}\right] + \left[\frac{134.6}{Re_d}\right], \text{ dimensionless} \qquad (9\text{-}24)$$

9.3.6.3.8 Single-Nozzle Duct Calculation Iteration. An iterative calculation process is required to determine the discharge coefficient. Choose C = 1.0 to begin the iterative calculation procedure. Iteration shall continue until the calculated discharge coefficient C matches the previous discharge coefficient within ±0.005.

9.3.6.3.9 Standard Airflow Rate for a Single-Nozzle Duct. The standard airflow rate for single-nozzle ducts shall be calculated using Equation 9-25 in SI units or Equation 9-26 in I-P units, where ρ_1 is the nozzle inlet air density for dry or moist air, kg/m^3 (lb$_m$/ft^3) and Q is the volumetric airflow rate using Equation 9-25 in SI units or Equation 9-26 in I-P units.

$$\text{Standard cubic meters/second} = \frac{\rho_1 Q}{1.202} \qquad (9\text{-}25)$$

$$\text{Standard cubic feet/minute (scfm)} = \frac{\rho_1 Q}{0.075} \qquad (9\text{-}26)$$

9.3.6.3.10 Mass Airflow Rate for a Single-Nozzle Duct. The mass airflow rate for single nozzles shall be obtained from Equation 9-27, where ρ_1 is the nozzle inlet air density for dry or moist air, kg/m^3 (lb$_m$/ft^3) and Q is the volumetric airflow rate, m^3/s (cfm), using Equation 9-21 in SI units or Equation 9-22 in I-P units.

$$\dot{m} = \rho_1 Q, \text{ kg/s (lb}_m\text{/min)} \qquad (9\text{-}27)$$

9.3.6.4 Single- and Multiple-Nozzle Chamber Airflow Calculations. The single- and multiple-nozzle airflow calculations follow the ASME procedures, but use a discharge coefficient equation and assertions that are based upon the findings of ASHRAE Technical Paper No. 2334.[7]

9.3.6.4.1 Nozzle Throat Diameter in Single- and Multiple-Nozzle Chambers. If airflow operating temperatures are not within ±6ºC (±10ºF) of the temperature when the nozzle dimensional measurements were obtained, the nozzle throat diameter d for each nozzle and the geometrically equivalent diameter of the chamber D_E shall be corrected to account for thermal expansion in compliance with ASME PTC 19.5[9] Section 3-10.

9.3.6.4.2 Reynolds Number for Single- and Multiple-Nozzle Chambers. The Reynolds number Re_D for each nozzle in use shall be obtained from Equation 9-28.

$$Re_d = \frac{\rho_1 V d}{\mu_1}, \text{ dimensionless} \qquad (9\text{-}28)$$

where

ρ_1 = nozzle inlet air density, kg/m^3 (lb$_m$/ft^3)
V = nozzle throat average air velocity, m/s (ft/s)
d = nozzle throat diameter, m (ft)
μ_1 = nozzle inlet dynamic viscosity, kg/(m-s) (lb$_m$/(ft-s))

Informative Note: Calculate the dynamic viscosity using Equation 9-16 in SI units or Equation 9-17 in IP units.

9.3.6.4.3 Beta Ratio for Single- and Multiple-Nozzle Chambers. $\beta = 0$ for single- and multiple-nozzle chambers.[7]

9.3.6.4.4 Nozzle Limits of Use for Single- and Multiple-Nozzle Chambers. The nozzle geometry in Figure 9-3 fits into ASME's long radius nozzle type, and the throat velocity requirement in Section 9.3.2.2 confirms that each nozzle in use will be operating within the long-radius nozzle limits prescribed by ASME.

9.3.6.4.5 Expansibility Factor for Single- and Multiple-Nozzle Chamber Nozzles. The dimensionless expansibility factor ε for a long radius nozzle is shown in Equation 9-29.

$$\varepsilon = \left[r^{\frac{2}{\gamma}} \left(\frac{\gamma}{\gamma-1}\right) \left(\frac{1-r^{\frac{\gamma-1}{\gamma}}}{1-r}\right) \left(\frac{1-\beta^4}{1-\beta^4 r^{\frac{2}{\gamma}}}\right) \right]^{1/2} \text{ dimensionless} \qquad (9\text{-}29)$$

where

r = absolute pressure ratio $\left(\frac{p_2}{p_1}\right)$, dimensionless
γ = ratio of constant pressure to constant volume specific heat, dimensionless

For each nozzle in single- and multiple-nozzle chambers, substitution of $\gamma = 1.4$ and $\beta = 0$ into Equation 9-29 results in Equation 9-30. The expansibility factor for each nozzle shall be obtained from Equation 9-30.

$$\varepsilon = 1 - 0.548(1 - r), \text{ dimensionless} \qquad (9\text{-}30)$$

9.3.6.4.6 Discharge Coefficient for Nozzle Single- and Multiple-Nozzle Chamber Nozzles. Nozzle discharge coefficients shall be calculated for each nozzle in use from Equation 9-31 using the Reynolds number from Equation 9-19.

$$C = 0.99855 - \left[\frac{7.006}{\sqrt{Re_d}}\right] + \left[\frac{134.6}{Re_d}\right], \text{ dimensionless} \qquad (9\text{-}31)$$

An iterative calculation process is required to determine individual nozzle coefficients. Choose $C = 0.98$ to begin the iterative calculation procedure. Iteration shall continue until the calculated discharge coefficient C matches the previous discharge coefficient within ±0.005.

9.3.6.4.7 Volumetric Airflow Rate for Single- and Multiple-Nozzle Chambers. The volumetric airflow rate for single- and multiple-nozzle chambers shall be obtained from Equation 9-32 in SI units or from Equation 9-33 in I-P units where the area is measured at the plane of the throat taps or nozzle exit for nozzles without throat taps.[7] The denominator in these equations includes the term $(1\text{-}E\beta^4)$. However, $\beta = 0$ for single- and multiple-nozzle chambers, so $(1\text{-}E\beta^4) = 1$, and Equations 9-32 and 9-33 become Equations 9-34 and 9-35.

In SI units:

$$Q = \left[\sum_{i=1}^{N} (C_i A_i \varepsilon_i)\right] \sqrt{\frac{2\Delta p}{\rho_1 (1 - E\beta^4)}} \qquad (9\text{-}32)$$

where

Q = volumetric flow rate, m^3/s
N = number of nozzles in use, dimensionless
C = discharge coefficient, dimensionless
A = nozzle throat area, m^2
ε = nozzle expansibility factor, dimensionless
Δp = nozzle differential pressure, Pa
ρ_1 = nozzle inlet air density for dry or moist air, kg/m^3
E = flow kinetic energy coefficient =1.043[7], dimensionless
β = 0

Informative Note: The superscript "7" in "1.043[7]" above is reference number, not an exponent.

In I-P units:

$$Q = 1097.8\,[\sum_{i=1}^{N}(C_i A_i \varepsilon_i)]\sqrt{\frac{\Delta p}{\rho_1(1-E\beta^4)}} \quad \text{at 4 °C (39.2 °F) water temperature} \quad (9\text{-}33)$$

where

Q = nozzle volumetric flow rate, cfm
N = number of nozzles in use, dimensionless
C = discharge coefficient, dimensionless
A = nozzle throat area, ft^2
ε = expansibility factor, dimensionless
Δp = nozzle differential pressure, (in. of water)
ρ_1 = nozzle inlet air density for dry or moist air, lb_m/ft^3
E = flow kinetic energy coefficient =1.043[7], dimensionless
β = 0
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

Informative Note: The superscript "7" in "1.043[7]" above is reference number, not an exponent.

***Informative Note*:** Refer to Informative Appendix G for the derivation of the units conversion coefficient.

In SI units:

$$Q = [\sum_{i=1}^{N}(C_i A_i \varepsilon_i)]\sqrt{\frac{2\Delta p}{\rho_1}} \quad (9\text{-}34)$$

where

Q = volumetric flow rate, m^3/s
N = number of nozzles in use, dimensionless
C = discharge coefficient, dimensionless
A = nozzle throat area, m^2
ε = nozzle expansibility factor, dimensionless

Δp = nozzle differential pressure, Pa
ρ_1 = nozzle inlet air density for dry or moist air, kg/m^3

In I-P units:

$$Q = 1097.8[\sum_{i=1}^{N}(C_i A_i \varepsilon_i)]\sqrt{\frac{\Delta p}{\rho_1}} \quad \text{at 4 °C (39.2 °F) water temperature} \qquad (9\text{-}35)$$

where

Q = nozzle volumetric flow rate, cfm
N = number of nozzles in use, dimensionless
C = discharge coefficient, dimensionless
A = nozzle throat area, ft^2
ε = expansibility factor, dimensionless
Δp = nozzle differential pressure, (in. of water)
ρ_1 = nozzle inlet air density for dry or moist air, lb$_m$/ft^3
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

Informative Note: Refer to Informative Appendix G for the derivation of the units conversion coefficient.

9.3.6.4.8 Standard Airflow Rate for Single- and Multiple-Nozzle Chambers. The standard airflow rate for single- and multiple-nozzle chambers shall be calculated in compliance with Section 4.5 using Equation 9-36 in SI units or Equation 9-37 in I-P units where ρ_1 = air density for dry or moist air.

$$\text{Standard cubic meters/second} = \frac{\rho_1 Q}{1.202} \qquad (9\text{-}36)$$

$$\text{Standard cubic feet/minute (scfm)} = \frac{\rho_1 Q}{0.075} \qquad (9\text{-}37)$$

9.3.6.4.9 Mass Airflow Rate for Single- and Multiple-Nozzle Chambers. The mass airflow rate for single- and multiple-nozzle chambers shall be obtained from Equation9-38, where ρ_1 is the nozzle inlet air density for dry or moist air, kg/m^3 (lb$_m$/ft^3) and Q is the volumetric airflow rate using Equation 9-34 in SI units or Equation 9-35 in I-P units.

$$\dot{m} = \rho_1 Q, \text{ kg/s (lb}_m\text{/min)} \qquad (9\text{-}38)$$

9.4 Thermal Dispersion Arrays. Review Section 9.1. A thermal dispersion sensor measures air velocity at a single point in an airstream by measuring the heat dispersed from the heated sensor into the airstream. Commercial thermal dispersion arrays include (a) multiple thermal dispersion probes comprised of multiple sensors that are equally-spaced along a straight line, and (b) the associated equipment required for collecting and averaging the individual air velocity measurements to provide the resulting measured average air velocity for display or automated data recording.

Install an array of thermal dispersion probes into a measurement plane in either a rectangular duct or a round duct as prescribed in Figure 9-6. In a rectangular duct, X equals the duct height and the tolerance for illustrated dimensions is ±3 mm (±0.12 in.). For a round duct, the tolerance for illustrated positions is ±5 degrees.

Informative Notes:

1. A thermal dispersion array will indicate positive airflow even if the airflow is reversed.
2. For user information, see Informative Appendix E, Section E7.

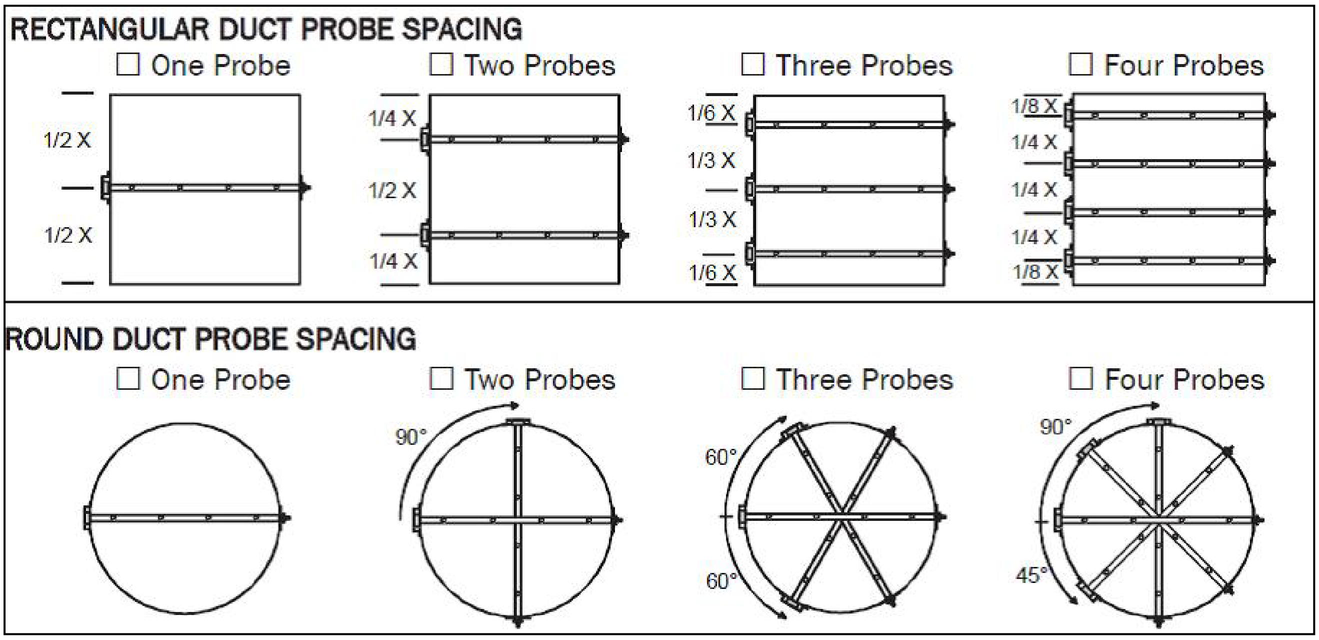


FIGURE 9-6. Thermal dispersion probe locations in rectangular and round ducts

9.5 Vortex-Shedding Arrays. Review Section 9.1. Vortex-shedding arrays are used to determine air 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 airstream passes a blunt-shaped body, the air 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 known relationship between the Strouhal number and the Reynolds number so that the vortex shedding frequency is a known function of the air velocity over a specified flow velocity range.

Informative Note: For further reading, see Informative Appendix A, Reference A5.

9.6 Capture Hoods. Review Section 9.1. Flow capture hoods are portable instruments designed to measure the airflow from diffusers and grilles. A capture hood system consists of a fabric hood and a rigid base assembly that contains the flow sensing equipment. For volumetric airflow measurements, the hood is placed over a diffuser or grille and directs airflow from the outlet or inlet across the flow-sensing manifold in the base of the instrument. The manifold consists of a number of tubes containing upstream and downstream holes in a grid, designed to simultaneously sense and average multiple velocity points across the base of the hood. Airflow from the upstream holes flows through the tubes past a sensor and then exits through the downstream holes.

Informative Notes:

1. Sensors used by different manufacturers include rotating vane anemometers, electronic micromanometers, and thermal anemometers.
2. For user information, see Informative Appendix E, Section E8.

9.7 Tracer Gas Airflow Measurement. Review Section 9.1. Figure 9-7 is a schematic of the tracer gas airflow measurement method. This method uses a tracer gas dilution technique that is based upon the principle of mass conservation. Users shall first check the safety data sheet for the tracer gas to identify health, fire, and explosion hazards for a candidate tracer gas. Tracer gas concentration shall not exceed one tenth of the maximum safe concentration level that is specified in the safety data sheet.

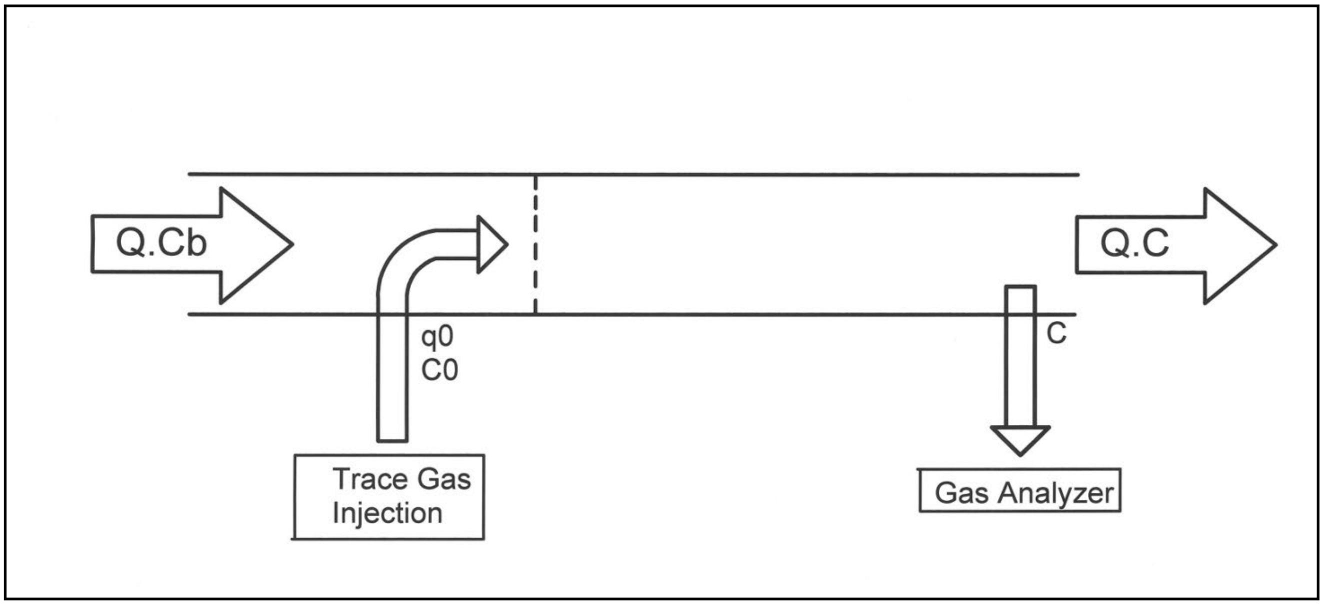


FIGURE 9-7. Tracer gas airflow measurement schematic

Air flows into the tracer gas test section at an unknown volumetric airflow rate Q and a known background concentration C_b of the tracer gas if there is any background concentration present upstream of the tracer gas injection location.

A tracer gas is injected into a duct at a known volumetric flow rate q_0 with known tracer gas concentration C_0 and disperses into the airstream. Preliminary tests shall be conducted to confirm that the variation of the measured concentration across the measurement plane is less than 10% using Equation 9-39.

$$\frac{\sigma_C}{C} < 10\% \qquad (9\text{-}39)$$

where C = the average measured concentration that shall be obtained using Equation 9-40.

$$C = \frac{1}{N}\sum_{i=1}^{N} C_i \qquad (9\text{-}40)$$

where the number of samples, N, shall be not less than 30.

The standard deviation σ_c shall be obtained using Equation 9-41.

$$\sigma_c = \sqrt{\left[\sum_{i=1}^{N} \frac{(C-C_i)^2}{(N-1)}\right]} \qquad (9\text{-}41)$$

If Equation 9-39 is 10% or greater, an airflow straightener in compliance with Section 8.4 shall be added to the duct at least 3 diameters or geometrically equivalent diameters upstream of the tracer gas injection plane to increase tracer gas dispersion to satisfy Equation 9-39.

The volumetric airflow rate Q shall be obtained from Equation 9-42 if there is no tracer gas concentration upstream of the tracer gas injection plane, or from Equation 9-43 if there is a background concentration C_b upstream of the tracer gas injection plane.

$$Q = q_0 \left(\frac{C_0}{C}\right), \text{ m}^3\text{/s (cfm)} \qquad (9\text{-}42)$$

$$Q = q_0 \left(\frac{C_0}{C - C_b}\right), \text{ m}^3\text{/s (cfm)} \qquad (9\text{-}43)$$

10 MEASUREMENT UNCERTAINTY

10.1 Post-Test Uncertainty Analysis. A post-test analysis of the measurement uncertainty, performed in compliance with ASME PTC 19.1,[1] shall accompany each air velocity measurement, volumetric airflow measurement, standard volumetric measurement, and mass airflow 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 estimate for each installation that does not conform to the instrument manufacturer's installation requirements.

Informative Note: This procedure is illustrated in the example uncertainty analysis that is provided in Informative Appendix B.

10.2 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 shown in Equation 10-1:

$$v = \bar{X}_m \pm U_{\bar{X}} \ (P\%) \qquad (10\text{-}1)$$

where:

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

Informative Note: For example: mass airflow = 152.3 kg/s ±0.8 kg/s; 95% [1.209 x 10^6 lb_m/h ± 6300 lb_m/h; 95%] states that the best value for mass airflow is believed to be 152.3 kg/s (1.209 x 10^6 lb_m/h) with a 95% probability that the true value lies within ±0.8 kg/s (6300 lb_m/h) of this value.

11 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 11. Otherwise, Section 11 specifies the test report requirements.

11.1 Test Identification

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

11.2 Unit Under Test Description

a. Model number and serial number.

11.3 Instrument Description

a. 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.

11.4 Measurement System Description

a. Description, model number, and serial number.
b. Operating range.
c. Documentational evidence of measurement system calibration.

11.5 Ambient Conditions

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

11.6 Test Conditions

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

11.7 Test Results. Test results, if required by the test plan in Section 5.1, are:

a. Air velocity, m/s (fpm).
b. Volumetric airflow at a measured density, m^3/s (cfm).
c. Standard volumetric airflow, m^3/s (scfm).
d. Mass rate of airflow, kg/s (lb_m/min).
e. Pretest uncertainty estimate for the air velocity, m/s (fpm).
f. Pretest uncertainty estimate for volumetric airflow at a measured density, m^3/s (cfm)
g. Pretest uncertainty estimate for the standard volumetric airflow, m^3/s (scfm).
h. Pretest uncertainty estimate for the mass rate of airflow, kg/s (lb_m/min).
i. Post-test uncertainty estimate for the air velocity, m/s (fpm).
j. Post-test uncertainty estimate for volumetric airflow at a measured density, m^3/s (cfm)
k. Post-test uncertainty estimate for the standard volumetric airflow, m^3/s (scfm).
l. Post-test uncertainty estimate for the mass rate of airflow, kg/s (lb_m/min).

12 NORMATIVE REFERENCES

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3. ANSI/ASHRAE Standard 41.1- 2024, *Standard Methods for Temperature Measurement*, Atlanta: ASHRAE. See Note 1.

4. ANSI/ASHRAE Standard 41.3- 2022, *Standard Methods for Pressure Measurement*, Atlanta: ASHRAE. See Note 2.
5. ANSI/ASHRAE Standard 41.6-2021 *Standard Methods for Humidity Measurement*, Atlanta: ASHRAE. See Note 3.
6. ANSI/ASHRAE Standard 41.11- 2023 *Standard Methods for Power Measurement*. Atlanta: ASHRAE. See Note 4.
7. Bohanon, H. R., *Fan Single- or multiple-nozzle chamber-Nozzle Coefficients*, *ASHRAE Transactions* No. 2334:104–122. See Note 5.
8. ANSI/ASME PTC 19.5-2004 (R2013)*, Flow Measurement.* ASME, New York, NY. See Note 3. See Note 5.
9. ANSI/ASME MFC-3M-2004 (R2017), *Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi*. ASME, New York, NY. See Note 5.
10. ASHRAE Research Project 1733-RP, *Develop Design Criteria for Psychrometric Air Sampler and Mixer*, Atlanta: ASHRAE.
11. Hyunjin Park and Christian K. Bach, *Performance Characterization of Air Mixing Devices for Square Ducts*, Applied Thermal Engineering 199 (2021) 117495, Science Direct, Accepted 8/22/2021.

Informative Notes:

1: Reference 3 is only required if using temperature measurements.
2: Reference 4 is only required if using pressure measurements.
3: Reference 5 is only required if using humidity measurements.
4: Reference 6 is only required if using power measurements.
5: References 7, 8, and 9 are only required if using nozzle test methods.

(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
INFORMATIVE REFERENCES AND BIBLIOGRAPHY

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

INFORMATIVE APPENDIX B
MULTIPLE-NOZZLE UNCERTAINTY ANALYSIS EXAMPLE

B1. BACKGROUND

In this example, a multiple-nozzle chamber is used to measure the volumetric airflow through a unit under test (UUT), m^3/s (ft^3/m). To minimize numerical errors in the example calculations shown below, all intermediate calculations throughout this appendix have first been processed to more than 5 significant figures and then rounded to about 5 significant figures. Final calculated results have been rounded to 4 significant figures, and the associated uncertainties of the final calculated results have been expressed in no more than 2 significant figures. The multiple nozzle chamber contains one 0.1524 m (6 in.) throat diameter nozzle, one 0.1016 m (4 in.) throat diameter nozzle, one 0.0762 m (3 in.) throat diameter nozzle, and one 0.0508 m (2 in.) throat diameter nozzle. These nozzles are made of aluminum and constructed in compliance with the dimensional requirements in Figure 9-3. The throat diameter of each of these nozzles was measured at 4 locations using an inside micrometer that is NIST-traceable. The ambient temperature during the measurements was 22 4/18 ºC (72 ºF). The measurement results showed that each nozzle is at their nominal size within ±0.0000254 m (±0.001 in.). No out-of-roundness of the throat diameters is detected visually.

During chamber operations, the inlet air to the nozzles had a dry bulb temperature of t_1 = 15 10/18 ºC (60 ºF) with a measurement uncertainty of Δt_1 = 0.014 ºC (0.0252 ºF). The inlet air to the nozzles had a wet bulb temperature of t'_1 = 15 ºC (59 ºF) with a measurement uncertainty of $\Delta t'_1$ = 0.05ºC (0.09 ºF). The measured barometric pressure at the inlet to the nozzle chamber (upstream of the nozzles and downstream of the settling/straightening devices) is p_1 = 101.33 kPa (14.696 psia) with a ±0.01% of reading pressure transducer after a system calibration for a Δp_1 = 0.01/100 x 101.33 kPa = ±0.010133 kPa (Δp_1 = 0.01/100 x 14.696 psia = ±0.0014696 psia).

$$p_2 = p_1 - \Delta P \tag{B1-1}$$

To evaluate the uncertainty in the nozzle discharge coefficient for a multiple nozzle chamber (C), the uncertainty in ΔP is evaluated in SI units in Equations B1-2a through B1-4a and in I-P units in B1-2b through B1-4b.

$$\Delta P = 0.24911\text{kPa with a } \pm 0.14\% \text{ of full scale and a full scale of } 1.2455\text{kPa} \tag{B1-2a}$$

$$\Delta\,(\Delta P) = \pm 0.14/100 \text{ x } 1.2455 = \pm 0.001744 \text{ kPa} \tag{B1-3a}$$

$$p_2 = 101.33 \text{ kPa} - 0.24911 \text{ kPa} = 101.08 \text{ kPa} \tag{B1-4a}$$

$$\Delta P\text{=1 in. of water conventional} = 0.03613 \text{ psia with a } \pm 0.14\% \text{ of full scale and a full scale of 5 in. of water conventional pressure transducer} \tag{B1-2b}$$

$$\Delta\,(\Delta P) = \pm 0.14/100 \text{ x } 5 = \pm 0.007 \text{ in. of water} = \pm 0.000253 \text{ psia} \tag{B1-3b}$$

$$p_2 = 14.696 \text{ psia } - 1 \text{ in. of water conventional} = 14.660 \text{ psia} \tag{B1-4b}$$

(Note: The example is not meant to be evaluated constantly moving between SI and I-P, though instead sticking with one system. Approximate conversions are often used between I-P and SI with the example being first done in I-P and then converted to get SI values. These approximations are used as the exact conversions and can fill the page with decimal places as seen in Appendix C of this document. The conversions used are from B.9 of NIST Special Publication 811[A10].)

The multiple nozzle volumetric airflow rate is defined by Equations 9-34 and 9-35.

$$Q = [\sum_{i=1}^{N}(C_i A_i \varepsilon_i)]\sqrt{\frac{2\Delta p}{\rho_1}} \tag{9-34}$$

$$Q = 1097.8[\sum_{i=1}^{N}(C_i A_i \varepsilon_i)]\sqrt{\frac{\Delta p}{\rho_1}} \tag{9-35}$$

The uncertainty will be evaluated in the following order:

Section B2, “Uncertainty in Areas (A_x)”

Section B3, “Uncertainty in conversion factor of 1097.8 (for I-P only)”

Section B4, “Uncertainty in ε”

Section B5, “Uncertainty in Density (ρ_1)”

Section B6, “Uncertainty in Viscosity”

Section B7, “Uncertainty in Re_x and V_x”

Section B8, “Uncertainty in C”

Section B9, “Uncertainty in $\sum(CA)$”

Section B10, “Uncertainty in Q” (The measurement uncertainty for this multiple nozzle airflow measurement)

B2. UNCERTAINTY IN AREAS (A_x)

The uncertainty in A (nozzle throat area) needs to be evaluated.

$$\text{Area of a circle } A_x = \frac{\pi {D_{Nx}}^2}{4} \tag{B2-1}$$

TABLE B2-1 Nozzle Throat Area

Nozzle Number	Nozzle Throat Diameter	Nozzle Throat Areas	
		SI	I-P
		m^2	ft^2
1	0.1524 m (6 in.)	0.018242	0.19635
2	0.1016 m (4 in.)	0.0081073	0.087267
3	0.0762 m (3 in.)	0.0045604	0.049087
4	0.0508 m (2 in.)	0.0020268	0.021817

$$\Delta A_x = \pm\sqrt{\left(\frac{\partial A_x}{\partial D_{Nx}} \times \Delta D_{Nx}\right)^2} \quad \text{(B2-2)}$$

(Note: While π is not known exactly, the 15 significant digits that are available in commercial software are deemed precise enough not to contribute to the uncertainty of the area. The proof of this is left up to the reader.)

The diameter throat of the nozzle will change with temperature in using Equation B2-3

$$D_{Nxt2} = D_{Nx}\ \mathrm{x}\ \left((t_2 - t_1)\ \mathrm{x}\ \alpha + 1\right) \quad \text{(B2-3)}$$

where α is the thermal expansion coefficient for aluminum 22 x 10^{-6} m/(m-K) [12.3 x 10^{-6} in/in-°F]

TABLE B2-2 D_{Nxt2} Computations

Nozzle Number	Nozzle Throat Diameter	D_{Nxt2}	
		SI	I-P
		m	in
1	0.1524 m (6 in.)	0.15235	5.9991
2	0.1016 m (4 in.)	0.10159	3.9994
3	0.0762 m (3 in.)	0.076189	2.9996
4	0.0508 m (2 in.)	0.050793	1.9997

(Note: For simplification of this example, this correction will not be carried through the example as it would require additional uncertainty calculations for the temperature measurements and thermal expansion coefficients. One can see that for the 0.1524 m (6 in.) throat diameter nozzle the error in diameter is on the same order as the measurement error in the diameter for this relatively small temperature change. For the small nozzle, the change in diameter is approximately one order of magnitude smaller than the measurement error in the diameter.)

Evaluating the derivative of Equation B2-1,

$$\frac{\partial A_1}{\partial D_{N1}} = \frac{\pi D_{N1}}{2} = 0.23939 \text{ m } (9.4248 \text{ in.}) \qquad \text{(B2-4)}$$

TABLE B2-3 Result of $\frac{\partial A_x}{\partial D_{Nx}}$ Computations

Nozzle Number	Nozzle Throat Diameter	$\frac{\partial A_x}{\partial D_{Nx}}$	
		SI	**I-P**
		m	**in.**
1	0.1524 m (6 in.)	0.23939	9.4348
2	0.1016 m (4 in.)	0.15960	6.2832
3	0.0762 m (3 in.)	0.11970	4.7124
4	0.0508 m (2 in.)	0.079797	3.1416

$$\Delta D_{N1} = \Delta D_{N2} = \Delta D_{N3} = \Delta D_{N4} = \pm\, 0.0000254 \text{ m } (\pm\, 0.001 \text{in.}) \qquad \text{(B2-5)}$$

Inserting the values into Table B2-2, yields the results shown in Table B2-4.

TABLE B2-4 Result of ΔA_x Computations

Nozzle Number	Nozzle Throat Diameter	ΔA_x	
		SI	**I-P**
		m^2	**ft^2**
1	0.1524 m (6 in.)	$\pm 6.0805 \times 10^{-6}$	$\pm 6.5450 \times 10^{-5}$
2	0.1016 m (4 in.)	$\pm 4.0537 \times 10^{-6}$	$\pm 4.3633 \times 10^{-5}$
3	0.0762 m (3 in.)	$\pm 3.0402 \times 10^{-6}$	$\pm 3.2725 \times 10^{-5}$
4	0.0508 m (2 in.)	$\pm 2.0268 \times 10^{-6}$	$\pm 2.1817 \times 10^{-5}$

B3. UNCERTAINTY IN CONVERSION FACTOR OF 1097.8 (FOR I-P ONLY)

The uncertainty in conversion factor 1097.8 (I-P only), which shows up in Equation 9-35, needs to be evaluated using Equation 9-34.

From Equation 9-32 we have $Q<m^3/s>$, where units are designated by <units>. Therefore,

$$Q<m^3/s> \; = [\sum(CA)]\varepsilon\sqrt{\frac{2\Delta p}{\rho_1}} \qquad \text{(B3-1)}$$

with $\Delta p <N/m^2>$, and $\rho_1 <kg/m^3>$.

To convert Equation B3-1 to I-P format, with $Q<cfm>$, some conversion factors are required.

1 in. of water conventional = 25.4 mm of water conventional (Exact conversion based on NIST Special Publication 811[A10]).

1 mm of water conventional = 9.80665 Pa (Source BS EN ISO 80000-4:2013[A11]).

1 Pa = psi/6894.8

1 in. of water conventional = 25.4 mm of water conventional x (9.80665 Pa/1 mm of water conventional) x (1 psi/6894.8 Pa) = 0.036127 psi.

1 psi = 1 lb_f/in^2 x $(12\ in/1ft)^2$ =144 lb_f/ft^2

1 in. of water conventional = 0.036127 in. of water x 144 lb_f/ft^2- in. of water = 5.2023 lb_f/ft^2.

Therefore, 1 in. of water conventional = 5.2023 lb_f/ft^2, or written as a conversion factor,

$$\left(\frac{5.2023\ lb_m/ft^2}{1\ in. of\ water}\right) = 1.$$

Also, 1 lb_f = 32.174 lb_m x ft/s^2, or written as a conversion factor

$$\left(\frac{32.174 lb_m\ x\ ft/s^2}{lb_f}\right) = 1.$$

Lastly, 60 sec = 1 min, or written as a conversion factor

$$\left(\frac{60\ s}{min}\right) = 1.$$

Applying these conversion factors in Equation B3-1 above yields Equation B3-2:

$$Q\ < cfm > = [\sum(CA)ft^2]\ \varepsilon\sqrt{\frac{2\Delta p <in.\ of\ water>}{\rho_1 <lb_m/ft^3>}\left(\frac{5.2023\ lb_m/ft^2}{1\ in.\ of\ water}\right)\left(\frac{32.174 lb_m\ x\ ft^2}{s^2\ x\ lb_m}\right)\left(\frac{60s}{min}\right)^2} \qquad \text{(B3-2)}$$

Collecting all the numerical constants yields Equation B3-4a, B3-4b, and 9-35:

$$Q\ < cfm > = \sqrt{2(5.2023)(32.174)(60^2)}\ \lfloor \sum(CA) < ft^2 > \rfloor\ \varepsilon \sqrt{\frac{\Delta p <in.\ of\ water>}{\rho_1 <lb_m/ft^3>}} \quad \text{cfm} \qquad \text{(B3-4a)}$$

$$Q\ < cfm > = 1097.8\ \lfloor \sum(CA) < ft^2 > \rfloor\ \varepsilon \sqrt{\frac{\Delta p <in.\ of\ water>}{\rho_1 <lb_m/ft^3>}} \quad \text{cfm} \qquad \text{(B3-4b)}$$

$$Q\ < cfm > = 1097.8\ \lfloor \sum(CA) < ft^2 > \rfloor\ \varepsilon \sqrt{\frac{\Delta p}{\rho_1}} \quad \text{cfm} \qquad \text{(I-P)} \qquad \text{(9-35)}$$

where it is understood that Q is in the units specified in Table 3-1, $Q< cfm >$, with $A <ft^2>, \Delta P<in.\ of\ water>$, and $\rho_1<lb_m/ft^3>$.

The conversion factor error due to rounding in the above 1097.8 calculated result is +0.0012%. This rounded conversion factor uncertainty is used in Section B10 of this standard.

B4. UNCERTAINTY IN ε

The uncertainty in the multiple nozzle expansibility factor, ε, needs to be evaluated using Equation 9-29 after substituting $\gamma = 1.4$ and $\beta = 0$.

$$\varepsilon = \left[r^{\frac{2}{\gamma}} \left(\frac{\gamma}{\gamma-1}\right) \left(\frac{1-r^{\frac{\gamma-1}{\gamma}}}{1-r}\right) \left(\frac{1-\beta^4}{1-\beta^4 r^{\frac{2}{\gamma}}}\right) \right]^{1/2} \qquad \text{(SI \& I-P)} \qquad \text{(9-29)}$$

$$\Delta\gamma = \pm\sqrt{\left(\frac{\partial\gamma}{\partial p} \times \Delta p\right)^2 + \left(\frac{\partial\gamma}{\partial t} \times \Delta t\right)^2 + \left(\frac{\partial\gamma}{\partial w} \times \Delta w\right)^2} \quad \text{(SI \& I-P)} \qquad \text{(B4-1)}$$

$\frac{\partial\gamma}{\partial p}$ is evaluated numerically using the moist-air properties spreadsheet called LibHuAirProp[A3].

$$\left(\frac{\partial\gamma}{\partial p}\right) = 1.8966 \text{ x } 10^{-5} \text{ x } \frac{1}{\text{kPa}} \qquad \text{(SI)} \qquad \text{(B4-2a)}$$

$$\left(\frac{\partial\gamma}{\partial p}\right) = 0.00013077 \text{ x } \frac{1}{\text{psia}} \qquad \text{(I-P)} \qquad \text{(B4-2b)}$$

For this application (other applications at different altitudes would be different) Δp with respect to p_1=101.325 kPa (14.696 psia) can be assumed to be

Δp = ± 1.4946 kPa

Δp = ±6 in. of water = ±0.21678 psia

$\frac{\partial\gamma}{\partial t}$ is evaluated numerically with LibHuAirProp.

$$\left(\frac{\partial\gamma}{\partial t}\right) = -3.9996 \text{ x } \frac{10^{-5}}{{}^{\text{o}}\text{C}}$$

$$\left(\frac{\partial \gamma}{\partial t}\right) = -2.222 \text{ x } \frac{10^{-5}}{^{o}F}$$

For this application (other applications, say heating mode of a heat pump, would be different), Δt with respect to $22\,\frac{4}{18}$ °C [72 °F] can be assumed to be

$$\Delta t = \pm 6\ \frac{2}{3}\,^{o}C \qquad \text{(SI)} \qquad \text{(B4-3a)}$$

$$\Delta t = \pm 12\ ^{o}F \qquad \text{(I-P)} \qquad \text{(B4-3b)}$$

$\frac{\partial \gamma}{\partial w}$ is evaluated numerically with LibHuAirProp.

$$\left(\frac{\partial \gamma}{\partial w}\right) = -0.135 \qquad \text{(SI \& I-P)} \qquad \text{(B4-4)}$$

For this application (other applications, say heating mode of a heat pump), Δw with respect to dry air can be assumed to be the difference between saturated air at $t_l=15\,\frac{10}{18}$ °C (60 °F) and dry air.

$$\Delta w = \pm 0.0111 \qquad \text{(SI \& I-P)} \qquad \text{(B4-5)}$$

$$\Delta w = \pm 0.0111 \qquad \text{(SI \& I-P)} \qquad \text{(B4-5)}$$

Evaluating Equation B4-1:

$$\Delta\gamma = \pm\sqrt{(1.8966 \text{ x } 10^{-5} \times 1.4946\,)^2 + (-3.9996 \text{ x } 10^{-5} \times 6\ 2/3)^2 + (-0.135 \times 0.0111)^2} \quad \text{(SI)}$$

$$\Delta\gamma = \pm\sqrt{(0.00013077 \times 0.21678)^2 + (-2.222 \text{ x } 10^{-5} \times 12)^2 + (-0.135 \times 0.0111)^2} \quad \text{(I-P)}$$

$$\Delta\gamma = \pm 0.001522 \qquad \text{(SI \& I-P)} \qquad \text{(B4-6)}$$

The largest β would be for DN_1. Assuming that the diameter of the chamber is 0.9144 m (36 in.), then

$$\Delta\beta = \pm 0.167 = \pm 0.1524\ /\ 0.9144 \qquad \text{(SI)} \qquad \text{(B4-7a)}$$

$$\Delta\beta = \pm 0.167 = \pm 6/36 \qquad \text{(I-P)} \qquad \text{(B4-7b)}$$

r = absolute pressure ratio (p_2/p_1), dimensionless:

$$r = \frac{p_1 - \Delta P}{p_1} = \frac{101.08}{101.33} \qquad \text{(SI)}$$

$$r = \frac{p_1 - \Delta P}{p_1} = \frac{14.660}{14.696} \qquad \text{(I-P)}$$

$$r = 0.99755 \qquad \text{(SI \& I-P)} \qquad \text{(B4-8)}$$

$$\Delta r = \pm\sqrt{\left(\frac{\partial r}{\partial p_1} \times \Delta p_1\right)^2 + \left(\frac{\partial r}{\partial \Delta P} \times \Delta(\Delta P)\right)^2} \qquad \text{(B4-9)}$$

$$\frac{\partial r}{\partial p_1} = \frac{\Delta P}{(p_1)^2} = 1.698 \text{ x } 10^{-7} \quad \text{(SI)}$$

$$\frac{\partial r}{\partial \Delta P} = \frac{-1}{p_1} = -9.869 * 10^{-3} \quad \text{(SI)}$$

$$\Delta r = \pm\sqrt{(1.698 * 10^{-7} \times 0.0101325\,)^2 + (-9.869 \text{ x } 10^{-3} \times 0.0017438)^2} \qquad \text{(SI)}$$

$$\frac{\partial r}{\partial p_1} = \frac{\Delta P}{(p_1)^2} = 1.171 \text{ x } 10^{-6} \quad \text{(I-P)}$$

$$\frac{\partial r}{\partial \Delta P} = \frac{-1}{p_1} = -6.805 \text{ x } 10^{-2} \quad \text{(I-P)}$$

$$\Delta r = \pm\sqrt{(1.171 \text{ x } 10^{-6} \times 0.00147)^2 + (-6.805 * 10^{-2} \times 0.000253)^2} \quad \text{(I-P)}$$

$$\Delta r = \pm 1.72 \text{ x } 10^{-5} \qquad \text{(SI \& I-P)} \tag{B4-10}$$

From a numerical evaluation of the derivatives of Equation 9-25

$$\varepsilon = \left[r^{\frac{2}{\gamma}} \left(\frac{\gamma}{\gamma-1}\right) \left(\frac{1-r^{\frac{\gamma-1}{\gamma}}}{1-r}\right) \left(\frac{1-\beta^4}{1-\beta^4 r^{\frac{2}{\gamma}}}\right) \right]^{1/2} \tag{9-29}$$

$$\frac{\partial \varepsilon}{\partial \gamma} \text{ x } \Delta\gamma = \pm 7.41 \text{ x } 10^{-7} \tag{B4-11}$$

$$\frac{\partial \varepsilon}{\partial \beta} \text{ x } \Delta\beta = \pm 1.4 \text{ x } 10^{-6} \tag{B4-12}$$

The error in the Equation 9-29 due to rounding is ±3.1x10^{-5} (turns out this is the dominating error)

$$\varepsilon = 1 - 0.548(1 - r) \tag{9-30}$$

$$\varepsilon = 1 - 0.548(1 - r) = 1 - 0.548(1 - 0.99755) = 0.99866 \tag{B4-13}$$

$$\frac{\partial \varepsilon}{\partial r} = 0.548 \tag{B4-14}$$

$$\Delta\varepsilon = \pm\sqrt{\left(\frac{\partial \varepsilon}{\partial r} \times \Delta r\right)^2 + \left(\frac{\partial \varepsilon}{\partial \beta} \text{ x } \Delta\beta\right)^2 + \left(\frac{\partial \varepsilon}{\partial \gamma} \text{ x } \Delta\gamma\right)^2 + (\text{rounding})^2} \qquad \text{(SI \& I-P)} \tag{B4-15}$$

$$\Delta\varepsilon = \pm\sqrt{(0.548 \times 1.73 * 10^{-5})^2 + (1.4 \text{ x } 10^{-6})^2 + (7.41 \text{ x } 10^{-7})^2 + (3.1 \text{ x } 10^{-5})^2}$$

$$\Delta\varepsilon = \pm 3.2456 \text{ x } 10^{-5} \quad \text{(SI \& IP)} \tag{B4-16}$$

B5. UNCERTAINTY IN DENSITY (ρ_1)

To evaluate the uncertainty in nozzle discharge coefficient for a multi-nozzle chamber (C), the uncertainty in ρ_1 needs to be evaluated.

ρ_1 = 1.2156 kg/m^3 (0.075888 lb$_m$/ft^3) as calculated from LibHuAirProp (B5-1)

$$\Delta\rho_1 = \pm\sqrt{\left(\frac{\partial\rho_1}{\partial t_1} \times \Delta t1\right)^2 + \left(\frac{\partial\rho_1}{\partial W} \times \Delta W\right)^2 + \left(\frac{\partial\rho_1}{\partial p_1} \times \Delta p_1\right)^2 + (\Delta\rho_1\ \text{eqn. uncertainty})^2} \qquad \text{(B5-2)}$$

$$\rho_1 = \rho_{1DA} + \rho_{1W} \qquad \text{(B5-3)}$$

The equations of LibHuAirProp can be seen in ASHRAE RP-1485 Final Report[1]. The density of air comes from Lemmon et al[A10] This document states "In the range from the solidification point to 873 K at pressures to 70 MPa, the estimated uncertainty of density values calculated with the equation of state is ±0.1%."

The density of water comes from the International Association for the Properties of Water and Steam document number IAPWS-95[A11] which, in Figure 1, states that the uncertainty in water vapor density is ±0.001% (or even over a tight range ±0.0001%).

Thus a total estimate of uncertainty in the moist air density can be ±0.1%.

$$\Delta\rho_1\ \text{eqn. uncertainty} = \pm\frac{0.1}{100}\ \text{x}\ 1.2156 = \pm 1.2156\ \text{x}\ 10^{-3}\ \text{kg/m}^3 \qquad \text{(SI)} \qquad \text{(B5-4)}$$

$$\Delta\rho_1\ \text{eqn. uncertainty} = \pm\frac{0.1}{100}\ \text{x}\ 0.075888 = \pm 7.5888 * 10^{-5}\ \text{lb}_m/\text{ft}^3 \qquad \text{(B5-5)}$$

$$W = 0.010462\ \text{as calculated by LibHuAirProp} \qquad \text{(B5-6)}$$

$\Delta W = \frac{1}{100}\ \text{x}\ 0.010462 = 0.00010462$ based on Appendix C of ASHRAE 41.6-2014[4] and taking a middle uncertainty of ±1% between the two points offered in the last paragraph. For a detailed uncertainty, not just an example as offered in this Appendix B, one would need to calculate ΔW based on the example in Appendix C of ASHRAE 41.6-2014[4] of the actual operating or worse-case conditions.

For the purpose of coming up with the quantities $\frac{\partial\rho_1}{\partial t_1}$, $\frac{\partial\rho_1}{\partial W}$, and $\frac{\partial\rho_1}{\partial p_1}$, equation 28 of 2013 *ASHRAE Handbook – Fundamentals* [A12] Chapter 36, Equation 28 can be used as a close approximation.

In SI units,

$$\frac{1}{\rho_1} = 0.28704\ \text{x}\ (\ t_1 + 273.15)\ \text{x}\ (1 + 1.6079\ \text{x}\ W)/\ p_1$$

$$\rho_1 = \frac{p_1}{0.28704\ \text{x}\ (\ t_1 + 273.15)\ \text{x}\ (1 + 1.6079\ \text{x}\ W)}$$

$$\frac{\partial\rho_1}{\partial t_1} = -\frac{p_1}{0.28704\ \text{x}\ (t_1 + 273.15)^2\ \text{x}\ (1 + 1.6079\ \text{x}\ W)} = -0.004165$$

$$\frac{\partial\rho_1}{\partial W} = -\frac{1.6079 * p_1}{0.28704\ \text{x}\ (t_1 + 273.15)\ \text{x}\ (1 + 1.6079\ \text{x}\ W)^2} = -1.9014$$

$$\frac{\partial\rho_1}{\partial p_1} = \frac{1}{0.28704\ \text{x}\ (\ t_1 + 273.15)\ \text{x}\ (1 + 1.6079\ \text{x}\ W)} = 0.011867$$

In I-P units,

$$\frac{1}{\rho_1} = 0.37049\ \text{x}\ (\ t_1 + 459.67)\ \text{x}\ (1 + 1.6079\ \text{x}\ W)/\ p_1$$

$$\rho_1 = \frac{p_1}{0.37049\ \text{x}\ (\ t_1 + 459.67) * (1 + 1.6079 * W)}$$

$$\frac{\partial\rho_1}{\partial t_1} = -\frac{p_1}{0.37049 * (t_1 + 459.67)^2\ \text{x}\ (1 + 1.6079\ \text{x}\ W)} = -0.00014445$$

$$\frac{\partial \rho_1}{\partial W} = -\frac{1.6079 \text{ x } p_1}{0.37049 \text{ x } (t_1+459.67) \text{ x } (1+1.6079 \text{ x } W)^2} = -0.1187$$

$$\frac{\partial \rho_1}{\partial p_1} = \frac{1}{0.37049 \text{ x } (\, t_1+459.67) \text{ x } (1+1.6079 \text{ x } W)} = 0.005108$$

Substituting the above values into Equation B5-2 results in:

$$\Delta\rho_1 = \pm 0.0012390 \text{ kg/m}^3 \text{ (SI)} \qquad \text{(B5-7a)}$$

$$\Delta\rho_1 = \pm 7.7349 \text{ x } 10^{-5} \text{ lb}_\text{m}/\text{ft}^3 \text{ (I-P)} \qquad \text{(B5-7b)}$$

B6. UNCERTAINTY IN VISCOSITY

The air viscosity is μ_1 = 1.7899x10^{-5} Ns/m^2 or Pa∗s (1.2028x10^{-5} lb_m/ft-s) as calculated by LibHuAirProp. The equation sources of LibHuAirProp can be seen in the User's Guide for the LibHuAirProp software. The viscosity of dry air comes from Lemmon and Jacobson[A13] with an uncertainty of ±1%. Properties of water were based on the *International Association for the Properties of Water and Steam (IAPWS) Formulation 2008 for the Viscosity of Ordinary Water Substance*[A14] with an uncertainty of ±0.17%.

A detailed comparison could be accomplished using mixing rules to determine the total uncertainty of the moist air viscosity, though given that moist air is mostly air, the uncertainty of the air viscosity is dominating, and there is some uncertainty in the mixing rules, a conservative approach of the following is used:

$$\Delta\mu_1 \text{ eqn. uncertainty} = \pm\sqrt{(1\%)^2 + (0.17\%)^2} = \pm 1.01\%$$

$$\Delta\mu_1 \text{ eqn. uncertainty} = \pm\sqrt{(1\%)^2 + (0.17\%)^2} = \frac{1.01}{100} \text{ x } 1.7899 \text{ x } 10^{-5} = 1.808 \text{ x } 10^{-7} \text{ Pa} * \text{s (SI)}$$

$$\Delta\mu_1 \text{ eqn. uncertainty} = \pm\sqrt{(1\%)^2 + (0.17\%)^2} = \frac{1.01}{100} \text{ x } 1.2028 \text{ x } 10^{-5} = 1.215 \text{ x } 10^{-7} \text{ lb}_\text{m}/(\text{ft} * \text{s) (I-P)}$$

$$\Delta\mu_1 = \pm\sqrt{\left(\frac{\partial\mu_1}{\partial t_1} \times \Delta t1\right)^2 + \left(\frac{\partial\mu_1}{\partial W} \times \Delta W\right)^2 + \left(\frac{\partial\mu_1}{\partial p_1} \times \Delta p_1\right)^2 + (\Delta\mu_1 \text{ eqn. uncertainty})^2} \qquad \text{(B6-1)}$$

$\frac{\partial\mu_1}{\partial t_1}$ is evaluated numerically with LibHuAirProp.

$$\frac{\partial\mu_1}{\partial t_1} = 4.720 \text{ x } 10^{-11} \text{ Pa-s/}^\circ\text{C}$$

$$\frac{\partial\mu_1}{\partial t_1} = 1.762 \text{ x } 10^{-11} \text{ lb}_\text{m}\text{/ft-s-}^\circ\text{F}$$

$\frac{\partial\mu_1}{\partial W}$ is evaluated numerically with LibHuAirProp.

$$\frac{\partial \mu_1}{\partial W} = -8.255 \times 10^{-9} \text{ Pa-s}$$

$$\frac{\partial \mu_1}{\partial W} = -5.547 \times 10^{-9} \text{ lb}_m\text{/ft-s}$$

$\frac{\partial \mu_1}{\partial p_1}$ is evaluated numerically with LibHuAirProp.

$$\frac{\partial \mu_1}{\partial p_1} = 1.132 \times 10^{-16} \text{ s}$$

$$\frac{\partial \mu_1}{\partial p_1} = 5.248 \times 10^{-13} \text{ lb}_m\text{/ft-s- psia}$$

Substituting values into Equation B6-1 results in:

$$\Delta\mu_1 = \pm 1.808 \times 10^{-7} \quad \text{Pa-s} \quad \text{(SI)} \qquad \text{(B6-2a)}$$

$$\Delta\mu_1 = \pm 1.215 \times 10^{-7} \text{ lb}_m\text{/ft-s} \quad \text{(I-P)} \qquad \text{(B6-2b)}$$

B7. UNCERTAINTY IN Rex AND Vx

$$Re_{dx} = \frac{\rho_1 V_x d_x}{\mu_1} \quad \text{(SI \& I-P)} \qquad \text{(9-28)}$$

where

ρ_1= nozzle inlet air density, kg/m^3 (lb$_m$/ft^3)
V_x =nozzle throat average air velocity, m/s (ft/s)
d_x =nozzle throat diameter, m (ft)
μ_1 =nozzle inlet dynamic viscosity, kg/(m-s) (lb$_m$/(ft-s))

TABLE B7-1 Reynolds Number Computations

Nozzle Number	Nozzle Throat Diameter	Re_{dx}	
		SI	I-P
		dimensionless	dimensionless
1	0.1524 m (6 in.)	2.0586×10^5	2.0586×10^5
2	0.1016 m (4 in.)	1.3679×10^5	1.3679×10^5
3	0.0762 m (3 in.)	1.0232×10^5	1.0232×10^5
4	0.0508 m (2 in.)	6.7913×10^4	6.7913×10^4

$$\frac{\partial C_1}{\partial Re_{d1}} = \frac{3.503}{Re_{d1}^{3/2}} - \frac{134.6}{Re_{d1}^{2}} \quad \text{(SI \& I-P)} \qquad \text{(B7-1)}$$

TABLE B7-2 Results of $\frac{\partial C_x}{\partial Re_{dx}}$ Computations

Nozzle Number	Nozzle Throat Diameter	$\frac{\partial C_x}{\partial Re_{dx}}$	
		SI	I-P
		dimensionless	dimensionless
1	0.1524 m (6 in.)	3.4329×10^{-8}	3.4329×10^{-8}
2	0.1016 m (4 in.)	6.0244×10^{-8}	6.0244×10^{-8}
3	0.0762 m (3 in.)	9.4171×10^{-8}	9.4171×10^{-8}
4	0.0508 m (2 in.)	1.6845×10^{-8}	1.6845×10^{-8}

$$\Delta Re_{dx} = \pm\sqrt{\left(\frac{\partial Re_{dx}}{\partial \rho_1} \times \Delta\rho_1\right)^2 + \left(\frac{\partial Re_{dx}}{\partial V_x} \times \Delta V_x\right)^2 + \left(\frac{\partial Re_{dx}}{\partial d_x} \times \Delta d_x\right)^2 + \left(\frac{\partial Re_{dx}}{\partial \mu_1} \times \Delta\mu_1\right)^2} \quad \text{(B7-2)}$$

$$\frac{\partial Re_{dx}}{\partial \rho_1} = \frac{V_x d_x}{\mu_1} \quad \text{(SI \& I-P)} \quad \text{(B7-3)}$$

TABLE B7-3 Results of $\frac{\partial Re_{dx}}{\partial \rho_x}$ Computations

Nozzle Number	Nozzle Throat Diameter	$\frac{\partial Re_{dx}}{\partial \rho_x}$	
		SI	I-P
		m^3/kg	ft^3/lb_m
1	0.1524 m (6 in.)	1.6934×10^{5}	2.7126×10^{6}
2	0.1016 m (4 in.)	1.1253×10^{5}	1.8026×10^{6}
3	0.0762 m (3 in.)	8.4172×10^{4}	1.3483×10^{6}
4	0.0508 m (2 in.)	5.5867×10^{4}	8.9490×10^{5}

$$\frac{\partial Re_{dx}}{\partial d_x} = \frac{\rho_1 V_x}{\mu_1} \quad \text{(SI \& I-P)} \quad \text{(B7-4)}$$

TABLE B7-4 Results of $\frac{\partial \mathrm{Re}_{dx}}{\partial d_x}$ Computations

Nozzle Number	Nozzle Throat Diameter	$\frac{\partial \mathrm{Re}_{dx}}{\partial d_x}$	
		SI	I-P
		1/m	1/ft
1	0.1524 m (6 in.)	1.3508×10^6	4.1171×10^5
2	0.1016 m (4 in.)	1.3464×10^6	4.1038×10^5
3	0.0762 m (3 in.)	1.3428×10^6	4.0928×10^5
4	0.0508 m (2 in.)	1.3369×10^6	4.0748×10^5

$$\frac{\partial \mathrm{Re}_{dx}}{\partial \mu_1} = \frac{-d_x \rho_1 V_x}{\mu_1^2} \qquad \text{(SI \& I-P)} \qquad \text{(B7-5)}$$

TABLE B7-5 Results of $\frac{\partial \mathrm{Re}_{dx}}{\partial \mu_1}$ Computations

Nozzle Number	Nozzle Throat Diameter	$\frac{\partial \mathrm{Re}_{dx}}{\partial \mu_1}$	
		SI	I-P
		m^2/Ns	ft-s/lb_m
1	0.1524 m (6 in.)	-1.1501×10^{10}	-1.7115×10^{10}
2	0.1016 m (4 in.)	-7.6424×10^9	-1.1373×10^{10}
3	0.0762 m (3 in.)	-5.7165×10^9	-8.5070×10^9
4	0.0508 m (2 in.)	-3.7942×10^9	-5.6463×10^9

$$\frac{\partial \mathrm{Re}_{dx}}{\partial V_x} = \frac{\rho_1 d_x}{\mu_1} \quad \text{(SI \& I-P)} \qquad \text{(B7-6)}$$

TABLE B7-6 Results $\frac{\partial Re_{dx}}{\partial V_x}$ Computations

Nozzle Number	Nozzle Throat Diameter	$\frac{\partial Re_{dx}}{\partial V_x}$	
		SI	I-P
		s/m	s/ft
1	0.1524 m (6 in.)	10350	3174.7
2	0.1016 m (4 in.)	6900.1	2103.1
3	0.0762 m (3 in.)	5175.1	1577.4
4	0.0508 m (2 in.)	3450.0	1051.6

where

V_x = nozzle throat average air velocity, m/s (ft/s) of nozzle x.

In SI units,

$$V_x = \frac{Q_x}{A_x} = C_x \varepsilon \sqrt{\frac{2\Delta p}{\rho_1}} = \left(0.99855 - \left[\frac{7.006}{\sqrt{Re_{dx}}}\right] + \left[\frac{134.6}{Re_{dx}}\right]\right) \text{ x } \varepsilon \sqrt{\frac{2\Delta p}{\rho_1}} \quad \text{m/s} \qquad \text{(B7-7a)}$$

In I-P units,

$$V_x = \frac{Q_x}{A_x} = \frac{1097.8}{60} \text{ x } C_x \varepsilon \sqrt{\frac{\Delta p}{\rho_1}} = \frac{1097.8}{60\left(0.99855 - \left[\frac{7.006}{\sqrt{Re_{dx}}}\right] + \left[\frac{134.6}{Re_{dx}}\right]\right)} \text{ x } \varepsilon \sqrt{\frac{\Delta p}{\rho_1}} \quad \text{ft/s} \qquad \text{(B7-7b)}$$

The above equation for V_x is circular and of course requires iteration. Note that Section 9.3.6.4.6 recommends iteration until C matches the previous discharge coefficient within 0.5%. Note this could become a dominating error.

In both SI and I-P units,

$$\Delta V_x = \pm\sqrt{\left(\frac{\partial V_x}{\partial Re_{dx}} \times \Delta Re_{dx}\right)^2 + \left(\frac{\partial V_x}{\partial \varepsilon} \text{ x } \Delta\varepsilon\right)^2 + \left(\frac{\partial V_x}{\partial \Delta p} \text{ x } \Delta(\Delta p)\right)^2 + \left(\frac{\partial V_x}{\partial \rho_1} \text{ x } \Delta\rho_1\right)^2} \qquad \text{(B7-8)}$$

$$\frac{\partial V_x}{\partial Re_{dx}} = \varepsilon \sqrt{\frac{2\Delta p}{\rho_1}} \text{ x } \left(\frac{3.503}{Re_{dx}^{3/2}} - \frac{134.6}{Re_{dx}^2}\right) \quad \text{(SI)} \qquad \text{(B7-9a)}$$

$$\frac{\partial V_x}{\partial Re_{dx}} = \frac{1097.8}{60} \text{ x } \varepsilon \sqrt{\frac{\Delta p}{\rho_1}} \text{ x } \left(\frac{3.503}{Re_{dx}^{3/2}} - \frac{134.6}{Re_{dx}^2}\right) \quad \text{(I-P)} \qquad \text{(B7-9b)}$$

TABLE B7-7 Results of $\frac{\partial V_x}{\partial Re_{dx}}$ Computations

Nozzle Number	Nozzle Throat Diameter	$\frac{\partial V_x}{\partial Re_{dx}}$	
		SI	I-P
		m/s	ft/s
1	0.1524 m (6 in.)	6.9405×10^{-7}	2.2770×10^{-6}
2	0.1016 m (4 in.)	1.2544×10^{-6}	4.1153×10^{-6}
3	0.0762 m (3 in.)	1.9039×10^{-6}	6.2462×10^{-6}
4	0.0508 m (2 in.)	3.4116×10^{-6}	1.1196×10^{-6}

$$\frac{\partial V_x}{\partial \varepsilon} = \sqrt{\frac{2\Delta p}{\rho_1}} \text{ x } \left(0.99855 - \left[\frac{7.006}{\sqrt{Re_{dx}}}\right] + \left[\frac{134.6}{Re_{dx}}\right]\right) \qquad \text{(SI)} \qquad \text{(B7-10a)}$$

$$\frac{\partial V_x}{\partial \varepsilon} = \frac{1097.8}{60} \text{ x } \sqrt{\frac{\Delta p}{\rho_1}} \text{ x } \left(0.99855 - \left[\frac{7.006}{\sqrt{Re_{dx}}}\right] + \left[\frac{134.6}{Re_{dx}}\right]\right) \qquad \text{(I-P)} \qquad \text{(B7-10b)}$$

TABLE B7-8 Results of $\frac{\partial V_x}{\partial \varepsilon}$ Computations

Nozzle Number	**Nozzle Throat Diameter**	$\frac{\partial V_x}{\partial \varepsilon}$	
		SI	**I-P**
		m/s	**ft/s**
1	0.1524 m (6 in.)	19.916	65.340
2	0.1016 m (4 in.)	19.852	65.129
3	0.0762 m (3 in.)	19.799	64.954
4	0.0508 m (2 in.)	19.711	64.668

$$\frac{\partial V_x}{\partial \Delta p} = \frac{\varepsilon\sqrt{2}\left(0.99855-\left[\frac{7.006}{\sqrt{Re_{dx}}}\right]+\left[\frac{134.6}{Re_{dx}}\right]\right)}{\sqrt{\Delta p}\ x\ 2\sqrt{\rho_1}} \qquad \text{(SI)} \qquad \text{(B7-11a)}$$

$$\frac{\partial V_x}{\partial \Delta p} = \frac{\frac{1097.8}{60\ x\ 2}\ x\ \varepsilon\left(0.99855-\left[\frac{7.006}{\sqrt{Re_{dx}}}\right]+\left[\frac{134.6}{Re_{dx}}\right]\right)}{\sqrt{\Delta p}\ x\ \sqrt{\rho_1}} \qquad \text{(I-P)} \qquad \text{(B7-11b)}$$

TABLE B7-9 Results of $\frac{\partial V_x}{\partial \Delta p}$ Computations

Nozzle Number	**Nozzle Throat Diameter**	$\frac{\partial V_x}{\partial \Delta p}$	
		SI	**I-P**
		m^2-s/kg	**ft/(s-in. of water)**
1	0.1524 m (6 in.)	0.039921	32.626
2	0.1016 m (4 in.)	0.039792	32.521
3	0.0762 m (3 in.)	0.039686	32.433
4	0.0508 m (2 in.)	0.039511	32.290

$$\frac{\partial V_x}{\partial \rho_1} = \frac{\varepsilon\Delta p\left(0.99855-\left[\frac{7.006}{\sqrt{Re_{dx}}}\right]+\left[\frac{134.6}{Re_{dx}}\right]\right)}{\sqrt{\frac{2\Delta p}{\rho_1}}\ x\ (\rho_1)^2} \qquad \text{(SI)} \qquad \text{(B7-12a)}$$

$$\frac{\partial V_x}{\partial \rho_1} = -1097.8/60 * \frac{\varepsilon\sqrt{\Delta p}\left(0.99855-\left[\frac{7.006}{\sqrt{Re_{dx}}}\right]+\left[\frac{134.6}{Re_{dx}}\right]\right)}{2(\rho_1)^{1.5}} \qquad \text{(I-P)} \qquad \text{(B7-12b)}$$

TABLE B7-10 Result of $\frac{\partial V_x}{\partial \rho_1}$ Computations

Nozzle Number	Nozzle Throat Diameter	$\frac{\partial V_x}{\partial \rho_1}$	
		SI	**I-P**
		m^4(kg-s)	**ft^4(lb_m-s)**
1	0.1524 m (6 in.)	8.1807	429.92
2	0.1016 m (4 in.)	8.1544	428.53
3	0.0762 m (3 in.)	8.1325	427.38
4	0.0508 m (2 in.)	8.0966	425.50

Note: For the remainder of Section B7, the focus will be on Nozzle 1 in I-P units to illustrate the calculations required. The calculations for Nozzle 1 in SI units and the other nozzles in both SI, and I-P units were also performed, but the details are not included here.

Substituting results into Equation B7-8 for Nozzle 1 in I-P units:

$$\Delta V_1 = \pm\sqrt{(2.2770 \text{ x } 10^{-6} \times \Delta Re_{d1})^2 + 5.3268 \text{ x } 10^{-2}} \tag{B7-13}$$

Substituting results into Equation B7-2 for Nozzle 1 in I-P units:

$$\Delta Re_{d1} = \pm\sqrt{(3154.7 \times \Delta V_1)^2 + (4.3677 \text{ x } 10^6} \tag{B7-14}$$

By solving the two equations, B7-13 and B7-14, for the two unknowns leads to the results shown in Equations B7-15 and B7-16 for Nozzle 1 in IP units:

$$\Delta Re_{d1} = \pm 2213.2 \tag{B7-15}$$

$$\Delta V_1 = \pm 0.23085 \text{ ft/s} \tag{B7-16}$$

Table B7-11 shows the comparable results for all four of the nozzles in both SI and I-P units.

TABLE B7-11 Results of $\Delta \mathrm{Re}_{dx}$ and $\Delta \mathrm{V}_{x}$ Computations

Nozzle Number	Nozzle Throat Diameter	$\Delta \mathrm{Re}_{dx}$	$\Delta \mathrm{V}_{x}$	
		SI and I-P	SI	I-P
		dimensionless	m/s	ft/s
1	0.1524 m (6 in.)	2213.1	±0.070366	±0.23065
2	0.1016 m (4 in.)	1470.8	±0.070146	±0.22773
3	0.0762 m (3 in.)	1100.4	±0.069967	±0.22715
4	0.0508 m (2 in.)	730.83	±0.069671	±0.22619

B8 UNCERTAINTY IN C

The uncertainty in nozzle discharge coefficient for a multiple nozzle chamber *C* needs to be evaluated.

$$\mathrm{C}_{x} = 0.99855 - \left[\frac{7.006}{\sqrt{\mathrm{Re_d}}}\right] + \left[\frac{134.6}{\mathrm{Re_d}}\right] \qquad (9\text{-}31)$$

TABLE B8-1 Nozzle Discharge Coefficients

Nozzle Number	Nozzle Throat Diameter	C_{x}
		SI and I-P
		dimensionless
1	0.1524 m (6 in.)	0.98376
2	0.1016 m (4 in.)	0.98059
3	0.0762 m (3 in.)	0.97796
4	0.0508 m (2 in.)	0.97365

$$\Delta \mathrm{C_x} = \pm\sqrt{\left(\frac{\partial \mathrm{C_x}}{\partial \mathrm{Re_{dx}}} \times \Delta \mathrm{Re_{dx}}\right)^2 + (\Delta \mathrm{C\ Eqn..\,Uncertainty})^2 + (\Delta \mathrm{C\ convergence})^2} \qquad (\mathrm{B8\text{-}1})$$

The nominal value for convergence uncertainty is taken to be $\Delta \mathrm{C\ convergence} = \pm 0.5\%$, though a stricter limit could be used.

The empirically derived nozzle discharge coefficient corrects the theoretical flow equation to the actual flow. Leutheusser[A15] provides a derivation of *C* purely based on fundamental equations for nozzles with a $\beta = 0$ over a small Re_d range ($10^3 < Re_d < 10^6$).

$$C = 1 - 6.528/Re_d^{0.5} \qquad \text{(B8-2)}$$

Using this C and comparing to the C_x ε of this standard, the largest difference is found on the largest nozzle, which also is outside the Re_{dx} range ($Re_{dx} = 2x10^6$). This difference is on the order of 0.3%, and, as such, a conservative 0.35% uncertainty will be prescribed.

$$\Delta \mathrm{C\ Eqn..Uncertainty} = 0.35\% \qquad \text{(B8-3)}$$

$$\frac{\partial C_x}{\partial Re_{dx}} = \frac{3.503}{Re_{dx}^{3/2}} - \frac{134.6}{Re_{dx}^2} \qquad \text{(B8-4)}$$

TABLE B8-2 Results of ΔC_x Computations

Nozzle Number	Nozzle Throat Diameter	ΔC_x
		SI and I-P
		dimensionless
1	0.1524 m (6 in.)	±0.006005
2	0.1016 m (4 in.)	±0.006005
3	0.0762 m (3 in.)	±0.006005
4	0.0508 m (2 in.)	±0.003004

(Note: $\Delta C_x = \pm 0.00348$ if the convergence criterion for C is changed from 0.5% to 0.05%. This may require one or two more iterations.)

B9 UNCERTAINTY IN $\sum(\mathrm{CA})$

$$\sum(\mathrm{CA}) = C_1A_1 + C_2A_2 + C_3A_3 + C_4A_4 \quad \text{(SI \& I-P)} \qquad \text{(B9-1)}$$

$$\sum(\mathrm{CA}) = 0.032329\ \mathrm{m}^2 \quad \text{(SI)} \qquad \text{(B9-2a)}$$

$$\sum(\mathrm{CA}) = 0.34798\ \mathrm{ft}^2 \quad \text{(I-P)} \qquad \text{(B9-2b)}$$

$$\Delta \sum CA = \pm\sqrt{\sum_{i=1}^{4}\left(\frac{\partial \sum CA}{\partial C_i} * \Delta C_i\right)^2} \quad \text{(SI and I-P)} \qquad \text{(B9-3)}$$

$$\frac{\partial \sum(\mathrm{CA})}{\partial C_i} = A_i \quad \text{(SI and I-P)} \qquad \text{(B9-4)}$$

$$\frac{\partial \sum(\mathrm{CA})}{\partial A_i} = C_i \quad \text{(SI and I-P)} \qquad \text{(B9-5)}$$

Plugging the known values into Equation B9-4 leads to the results in Equation B9-6a in SI units and Equation B9-6b in I-P units.

$$\Delta\sum(\mathrm{CA}) = \pm 0.00012382\ \mathrm{m}^2 \qquad \text{(SI)} \qquad \text{(B9-6a)}$$

(Note: $\Delta\sum(\mathrm{CA}) = \pm 0.00007203$ m^2 if the convergence criterion for C is changed to 0.05% from 0.5% which may require one or two more iterations.)

$$\Delta\sum(CA) = \pm 0.0013328\ \mathrm{ft}^2 \qquad \text{(I-P)} \qquad \text{(B9-6b)}$$

(Note: $\Delta\sum(CA) = \pm 0.00077536$ ft^2 if the convergence criterion for C is changed to 0.05% from 0.5% which may require one or two more iterations.)

B.10 UNCERTAINTY IN Q

The uncertainty in volumetric airflow rate Q needs to be evaluated.

$$Q = [\sum(CA)]\ \varepsilon\sqrt{\frac{2\Delta p}{\rho_1}}\ \mathrm{m}^3/\mathrm{s} \qquad \text{(9-34)}$$

$$Q = 1097.8\ [\sum(CA)]\ \varepsilon\sqrt{\frac{\Delta p}{\rho_1}}\ \mathrm{cfm} \qquad \text{(9-35)}$$

In SI units,

$$\Delta Q = \pm\sqrt{\left(\frac{\partial Q}{\partial\sum(CA)} \times \Delta\sum(CA)\right)^2 + \left(\frac{\partial Q}{\partial\varepsilon} \times \Delta\varepsilon\right)^2 + \left(\frac{\partial Q}{\partial\Delta p} \times \Delta(\Delta p)\right)^2 + \left(\frac{\partial Q}{\partial\rho_1} \times \Delta\rho_1\right)^2} \qquad \text{(B10-1a)}$$

In I-P units,

$$\Delta Q = \pm\sqrt{\left(\frac{\partial Q}{\partial\sum(CA)} \times \Delta\sum(CA)\right)^2 + \left(\frac{\partial Q}{\partial\varepsilon} x\ \Delta\varepsilon\right)^2 + \left(\frac{\partial Q}{\partial\Delta p} x\ \Delta(\Delta p)\right)^2 + \left(\frac{\partial Q}{\partial\rho_1} x\ \Delta\rho_1\right)^2 + (Conversion\ Factor)^2} \qquad \text{(B10-1b)}$$

$$\frac{\partial Q}{\partial\sum(CA)} = \varepsilon\sqrt{\frac{2\Delta p}{\rho_1}} = 20.2175 \qquad \text{(SI)} \qquad \text{(B10-2a)}$$

$$\frac{\partial Q}{\partial\sum(CA)} = 1097.8\varepsilon\sqrt{\frac{\Delta p}{\rho_1}} = 3979.72 \qquad \text{(I-P)} \qquad \text{(B10-2b)}$$

$$\frac{\partial Q}{\partial\varepsilon} = \sum(CA)\sqrt{\frac{2\Delta p}{\rho_1}} = 0.65448 \quad \mathrm{m}^3/\mathrm{s} \qquad \text{(SI)} \qquad \text{(B10-3a)}$$

$$\frac{\partial Q}{\partial\varepsilon} = 1097.8\sum(CA)\sqrt{\frac{\Delta p}{\rho_1}} = 1386.7\ \mathrm{cfm} \qquad \text{(I-P)} \qquad \text{(B10-3b)}$$

$$\frac{\partial Q}{\partial\Delta p} = \frac{\sum(CA)\ \varepsilon}{\rho_1\sqrt{\frac{2\Delta p}{\rho_1}}} = 0.001312\ \mathrm{m}^3/\mathrm{s\text{-}Pa} \qquad \text{(SI)} \qquad \text{(B10-4a)}$$

$$\frac{\partial Q}{\partial \Delta p} = \frac{1097.8 \sum(CA)\ \varepsilon}{2 * \rho_1 * \sqrt{\frac{\Delta p}{\rho_1}}} = 692.435 \text{ ft}^3\text{/(min-in. of water Conventional)} \quad \text{(I-P)} \qquad \text{(B10-4b)}$$

$$\frac{\partial Q}{\partial \rho_1} = \frac{-\sum(CA)\ \varepsilon\ \Delta p}{(\rho_1)^2 \sqrt{\frac{2\Delta p}{\rho_1}}} = -0.26884 \qquad \text{(SI)} \qquad \text{(B10-5a)}$$

$$\frac{\partial Q}{\partial \rho_1} = \frac{-1097.8 \sum(CA)\ \varepsilon\ \Delta p}{2(\rho_1)^2 \sqrt{\frac{\Delta p}{\rho_1}}} = -9124.4 \quad \text{(I-P)} \qquad \text{(B10-5b)}$$

Substituting values into Equations B10-1 and Equation 9-34 in SI units results in Equation B10-6 and B10-7, and substituting values into Equations B10-1 and Equation 9-35 in I-P units results in Equation B10-8 and B10-9.

$$\Delta Q = \pm\ 0.003408 \text{ m}^3\text{/s} \qquad \text{(B10-6)}$$

(Note: $\Delta Q = \pm 0.002732$ m^3/s if the convergence criterion for C is changed to 0.05% from 0.5% which may require one or two more iterations.)

$$Q = 0.6536 \text{ m}^3\text{/s} \qquad \text{(B10-7)}$$

$$\Delta Q = \pm\ 7.2149 \text{ cfm} \qquad \text{(B10-8)}$$

(Note: $\Delta Q = \pm 5.7893$ cfm if the convergence criterion for C is changed to 0.05% from 0.5% which may require one or two more iterations.)

$$Q = 1384.9 \text{ ft}^3\text{/min} \qquad \text{(B10-9)}$$

Summarizing the results and expressing both the calculated result and its associated uncertainty in a reasonable number of significant figures yields for SI units:

$$Q = 0.6536 \text{ m}^3\text{/s} \pm 0.0034 \text{ m}^3\text{/s} \qquad \text{(B10-10a)}$$

and for IP units:

$$Q = 1385 \text{ cfm} \pm 7 \text{ cfm} \qquad \text{(B10-10b)}$$

(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
VELOCITY UNCERTAINTY ANALYSIS EXAMPLE USING PITOT-STATIC TUBE

The air velocity measured using a Pitot-static tube depends on the separate independent measurements of velocity pressure, atmospheric pressure, dry-bulb temperature, and wet-bulb temperature. The velocity measured using a Pitot-static tube is given in Equation C-1 in SI units and in Equation C-2 in I-P units.

$$V = \sqrt{\frac{2P_v}{\rho}} \text{ m/s (SI)} \tag{C-1}$$

$$V = 1097.8\sqrt{\frac{P_v}{\rho}} \text{ ft/min (I-P)} \tag{C-2}$$

The density can be determined from equations in ASHRAE RP-1485[2] that depend upon the atmospheric pressure, the dry-bulb temperature, and the wet-bulb temperature. For this analysis, the parameter values are shown in SI in Table C-1 for SI units and Table C-2 for I-P units. Additionally, the analysis is shown in exact values for IP values with the SI values being approximate.

Parameter	Average	Absolute Uncertainty	Units
Patm	98.2	±0.0220	kPa
Pv	99.6	±0.249	Pa
Twb	19.4	±0.28	ºC
Tdb	26.7	±0.28	ºC

TABLE C-1 Assumed parameter values (SI)

Parameter	Average	Absolute Uncertainty	Units
Patm	29.0	±0.0065	in. Hg
Pv	0.400	±0.001	in. of water
Twb	67.0	±0.5	ºF
Tdb	80.0	±0.5	ºF

TABLE C-2 Assumed parameter values (I-P)

Using the parameter values to obtain the density from ASHRAE RP-1485, the following values are calculated:

$$\rho_o = 1.136 \text{ kg/m}^3 \text{ (SI)} \tag{C-3}$$

$$\rho_o = 0.07074 \text{ lb}_m\text{/ft}^3 \text{ (I-P)} \tag{C-4}$$

$$V = \sqrt{\frac{2P_v}{\rho_o}} = 13.24 \text{ m/s (SI)} \tag{C-5}$$

$$V = 1097.8\sqrt{\frac{P_v}{\rho_o}} = 2610 \text{ ft/min (I-P)} \tag{C-6}$$

The total uncertainty associated with the air velocity measurement can be determined using Equation C-7.

$$\sigma_{total}{}^2 = \sigma_{T_{db}}{}^2 + \sigma_{T_{wb}}{}^2 + \sigma_{P_{atm}}{}^2 + \sigma_{P_v}{}^2 + \sigma_\theta{}^2 \tag{C-7}$$

Each uncertainty can be determined using Equation C-8.

$$\sigma_x{}^2 = \left(\frac{1}{\bar{y}}\frac{\partial y}{\partial x}u_x\right)^2 \tag{C-8}$$

Where Equation C-8 is the instrument manufacturer's stated accuracy for the measured quantity under evaluation. When the above equation is solved for each input parameter the calculated uncertainty is 0.1%, which should be expressed as Equation C-9a in SI units and Equation C-9b in I-P units.

$$13.24 \pm 0.02 \text{ m/s (SI)} \tag{C-9a}$$

$$2610 \pm 3.5 \text{ ft/min (I-P)} \tag{C-9b}$$

Parameter	**Absolute Uncertainty $\partial y/\partial x\ u_x$**	**Relative Uncertainty $1/\bar{y}\ \partial y/\partial x\ u_x$**	**Contribution**
P_{atm}	0.001	0.01%	0.72%
P_v	0.017	0.13%	88.14%
T_{wb}	0.001	0.01%	0.67%
T_{db}	0.006	0.04%	10.46%

TABLE C-3 Uncertainty associated with each measured parameter (SI)

Parameter	Absolute Uncertainty $\partial y/\partial x\ u_x$	Relative Uncertainty $1/\bar{y}\ \partial y/\partial x\ u_x$	Contribution
P_{atm}	0.295	0.01%	0.72%
P_v	3.262	0.12%	88.14%
T_{wb}	0.285	0.01%	0.67%
T_{db}	1.124	0.04%	10.46%

TABLE C-4 Uncertainty associated with each measured parameter (I-P)

(Note: The above analysis is only applicable when the Pitot-static tube is oriented in the airflow. Experimental measurements of the Pitot-static tube in Figure C-1 shows the effect of misalignment on the accuracy of the velocity measurement – this is why there is a ±10 degree alignment restriction in this standard. Moreover, this dependence is defined by a coefficient of pressure, C_p, which is defined by Equation C-11 and plotted in Figure C-1 [See Appendix A Section A5 for more detailed information].)

$$C_P = \frac{P_V}{\frac{1}{2}\rho V^2} \tag{C-10}$$

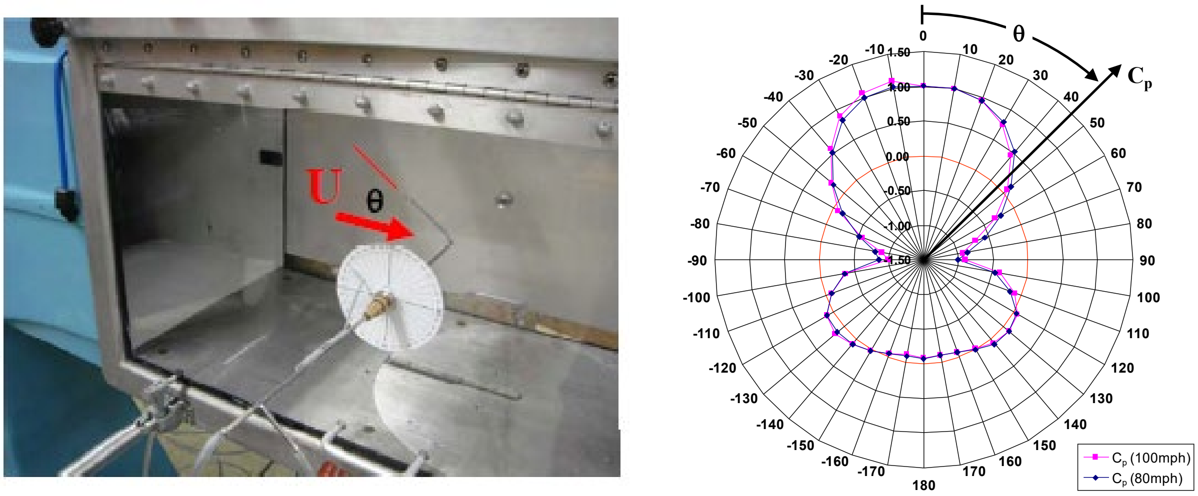

FIGURE C-1 Experimental Test Set Up (left) to Determine the Dependence of the Angle of Attack on the Coefficient of Pressure (right).

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INFORMATIVE APPENDIX D
SUPPLEMENTARY UNCERTAINTY CALCULATION PROCEDURES

D1. EXACT CONVERSION of 1.202 kg/m^3 to lb$_m$/ft^3

D1.1 Exact Conversions. When conversions between different systems of units are made, uncertainty needs to be accounted for if exact conversions are not used. Exact conversions often can be obtained with no added uncertainty as one system of units is often defined as a certain quality of the SI equivalent. NIST Special Publication 1038[A16] is a good source of conversion factors, though note only the conversion factors in bold in this document are exact.

D1.2 Exact conversion of m to ft. The conversion from m to ft can be found on page 8 of NIST Special Publication 1038[A9] and is reproduced below.

$$1 \text{ ft} = 0.3048 \text{ m (exact)} \tag{D-1}$$

D1.3 Exact conversion of kg to lb$_m$. The conversion from kg to lb$_m$ can be found on page 11 of NIST Special Publication 1038[A8] and is reproduced below.

$$1 \text{ lb}_m\text{=}0.45359237 \text{ kg (exact)} \tag{D-2}$$

D1.4 Exact conversion of 1.202 kg/m^3 to lb$_m$/ft^3. The conversion from 1.202 kg/m^3 to lb$_m$/ft^{3}can be found by mathematical functions from the conversions in Equations D-3, D-4, and D-5.

$$1.202 \text{ kg/m}^3 \text{ x } (1 \text{ lb}_m)/(0.45359237 \text{ kg}) \text{ x } (0.3048 \text{ m})^3/(1 \text{ ft})^3 \tag{D-3}$$

$$=$$

$$1.202 \text{ lb}_m/\text{ft}^3/(0.45359237) \text{ x } (0.3048)^3 \tag{D-4}$$

$$=$$

$$0.0750384086125258 \text{ lb}_m/\text{ft}^3 \text{ (exact)} \tag{D-5}$$

D1.5 Approximation of 1.202 kg/m^3 to lb$_m$/ft^3. The conversion from 1.202 kg/m^3 to lb$_m$/ft^{3}can be approximated as 0.075 lb$_m$/ft^3 with an associated error not more than +0.00004 lb$_m$/ft^3. The convention in uncertainty analysis is to lump errors in with all other unknowns and report a ± value. Thus, the conversion from 1.202 kg/m^3 to lb$_m$/ft^3 can be approximated as 0.075 lb$_m$/ft^3 with an associated uncertainty due to the approximation during conversion of ±0.00004 lb$_m$/ft^3.

(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 E
USER INFORMATION

E1. INTRODUCTION. The content of this Appendix is intended to provide advice and commentary to augment the information presented within the body of the standard. Note that the advice and commentary in this Appendix is not necessarily supported by peer-reviewed references. If this Appendix contains any information that is contrary to the information presented in the body of the standard, disregard the information in this Appendix.

E2. COMPARISON OF AIRFLOW MEASUREMENTS. Table E-1 provides general information and commentary regarding the airflow measurement methods that are included in this standard.

TABLE E-1 Summary of Airflow Measurement Methods

Section	Method	Typical Airflow or Air Velocity Range	Typical Accuracy (percent of reading)	Applications	Comments
9.2	Pitot-static Tube: • Single Pitot-tubes • Pitot-static Tube Traverse • Self-Averaging Arrays • Self-Averaging Probes	4-50 m/s (800-10,000 fpm)	±2% to ±10%	Hand-held instruments used for field measurement; fixed position in laboratories.	Alignment with airstream direction is critical
9.3	Single and Multiple Airflow Nozzles	Throat velocity ≥ 3000 fpm (15 m/s)	±0.5% to ±2%	Widely used for laboratory and field measurements.	No comment
9.4	Thermal Dispersion Array	(10-10,000 fpm)	±1% to ±10%	Often used for inlet measurements. Low velocity capabilities.	Some thermistors are not designed for repeated heating and cooling cycles.
9.5	Vortex Shedding Arrays	No comment	No comment	No comment	No comment

9.6	Capture Hoods	17 - 4250 m^3/h (10 -2500 cfm)	±3%	Measure airflow rates into/out of system air delivery vents and diffusers.	Correction factors may be required as needed by diffuser type.
9.7	Tracer Gas	No comment	No comment	No comment	Used to measure building air change rates and for calibrating other airflow meters.

E3. COMPARISON OF AIR VELOCITY MEASUREMENT METHODS. Table E-2 provides general information and commentary regarding the air velocity measurement methods that are included in this standard.

TABLE E-2 Summary of Air Velocity Measurement Methods

Section	**Air Velocity Measurement Method**	**Typical Air Velocity Range**	**Typical Accuracy**	**Comments**
7.2.	Pitot-Static Tube	3-50 m/s (600-10,000 fpm)	±2% to ±5%	Adversely affected by misalignment with the airstream.[A13]
7.3	Thermal Anemometer	0.1-50 m/s (10-10,000 fpm)	±2% to ±10%	Adversely affected by thermal plume at low airflows.
7.4	Rotary Vane Anemometer	0.03-30 m/s (60-6000 fpm)	±2% to ±5%	Adversely affected by turbulence intensity.
7.5	Drag-Force Velocity Meter	0.1-50 m/s (10-10,000 fpm)	±2%	No comment
7.6	Laser Doppler Velocimeter	0.005-50 m/s (1-10,000 fpm)	±1% to 3%	Requires optical access. High cost.

E4. SELF-AVERAGING ARRAYS. Both Pitot-static tube traverse method and self-averaging array devices use the difference between total and static pressures to provide velocity pressure and therefore a means from which velocity can be calculated. Pitot-static tube has been used since 1732. It is reliable, but with limits.

Self-averaging arrays are not portable but are intended for permanent and fixed installations. They were developed for and have been used in Heating, Ventilation, Air-Conditioning, and Refrigeration (HVAC&R) systems since the 1960s. Their use grew together with that of Variable Air Volume (VAV) air distribution designs.

Also known as a ‘self-averaging array,’ the Pitot Array can be described as a bifurcated tube with two sets of segregated collection holes, with each set connected to a collection manifold: One set for total pressure and another set for static pressure. The difference between these pressures (ΔP) equals velocity pressure by definition, which can be mathematically converted to air velocity at actual or standard conditions. Although these devices can be equivalent in some laboratory environments or under excellent field conditions (Equation E-1), they are most often misapplied in conditions unsuited for the technology and thereby producing very poor results. The basic formula for velocity governing both the traverse and the array is:

$$V = K\sqrt{\frac{2\Delta P}{\rho_x}} \qquad \text{(E-1)}$$

A minimum “straight run” of 10 equivalent duct diameters was required for “acceptable” measurement accuracy. In many cases, a flow-straightening honeycomb was required to minimize the averaging error due to the single pressure outputs from the manifolds, interconnected with the sampling ports.

Self-averaging arrays using a single calibration coefficient (K-factor) will result in measurement error as the airflow varies to under approximately 5.08 m/s (1,000 ft/min). Use of a single K-factor is common for commercial HVAC&R devices. Nonetheless, Pitot arrays can demonstrate accuracies of ±2% (not including errors from the pressure transducer), when compared to laboratory test tunnels having very “flat” velocity profiles with sufficiently high Reynolds numbers (i.e., for V >3.05 m/s (600 ft/min)).

In most cases, the pressure transducer is the greatest source of velocity pressure measurement error, especially at lower flows. Because the relationship of airflow-to-differential pressure is a square root function, the uncertainty of the pressure transducer results in significantly greater “per cent of reading” errors as the airflow is turned down. These uncertainties do not include the contributions from the in-duct device, which may result from turbulence or skewed velocity profiles.

Self-averaging arrays try to equalize non-uniform velocity pressure profiles by sampling from multiple pickup points and to produce an average of total or static pressures across the plane of measurement. Self-averaging arrays produce averaging errors that exceed those of devices using independent sensors, even when the number of pickup points far exceeds the later. As a direct result, the self-averaging array does not have the capabilities or properties of a Pitot-static tube traverse or any measurement method or device using individual velocity determinations.

The two methods cannot be equated and any comparison or implied equivalency is superficial. Some have exploited the similarities. For example, some have made reference to the number of sampling ports (holes) that have been termed “sensors” or “sensing points” and suggested that the number and location of these sampling positions should comply with the positions of velocity determination used in a standard duct traverse with a Pitot-static probe.
When explained, anyone can understand that they are not comparable. ISO 3966 explains the many sources of Pitot-static tube errors, as do the instructions included in ASHRAE Standard 111 and the guidelines of Testing, Adjusting, and Balancing (TAB) national associations.

Pitot traverse and Pitot arrays can be used effectively, but knowledge of their duct position and velocity limitations are needed to ensure optimal performance.

E5. THERMAL ANEMOMETERS. The thermal (or hot-wire, or hot-film) anemometer consists of a heated resistance temperature device (RTD), thermocouple junction, or thermistor sensor constructed at the end of a probe. It is designed to provide a direct, simple method of determining air velocity at a point in the flow field. The probe is placed into an airstream, and air movement past the electrically heated velocity sensor tends to cool the sensor in proportion to the speed of the airflow. The electronics and sensor are commonly combined into a portable, hand-held device that interprets the sensor signal and provides a direct reading of air velocity in either analog or digital display format. Often, the sensor probe also incorporates an ambient temperature-sensing RTD or thermistor, in which case the indicated air velocity is temperature compensated to standard air density conditions.

Thermal anemometers have long been used in fluid flow research. Research anemometer sensors have been constructed using very fine wires in configurations that allow characterization of fluid flows in one, two, and three dimensions, with sensor/electronics response rates up to several hundred kilohertz. This technology has been incorporated into more ruggedized sensors suitable for measurements in the HVAC&R field, primarily for unidirectional airflow measurement. Omni-directional sensing instruments suitable for thermal comfort studies are also available.

The principal advantages of thermal anemometers are their wide dynamic range and their ability to sense extremely low velocities. Commercially available portable instruments often have a typical accuracy (including repeatability) of 2% to 5% of reading over the entire velocity range. Accuracies of ±2% of reading or better are obtainable from microcontroller (microprocessor)-based thermistor and RTD sensor assemblies, some of which can be factory calibrated to known reference standards (e.g., National Institute of Standards (NIST) air speed tunnels). An integrated microcontroller also allows an array of sensor assemblies to be combined in one duct or opening, providing independently derived velocity and temperature measurements at each point.

Limitations of thermistor-based velocity measuring devices depend on sensor configuration, specific thermistor type used, and the application. At low velocities, thermal anemometers can be significantly affected by their own thermal plumes (from self-heating). Products using this technology can be classified as hand-held instruments or permanently mounted probes and arrays, and as those with analog electronic transmitters and those that are microcontroller-based. Limitations of hand-held and analog electronic thermal anemometers include the following: (1) the unidirectional sensor must be carefully aligned in the airstream (typically to within ±20° rotation) to achieve accurate results; (2) the velocity sensor must be kept clean because contaminant build-up can change the calibration (which may change accuracy performance); and (3) because of the inherent high speed of response of thermal anemometers, measurements in turbulent flows can yield fluctuating velocity measurements.

Electronically controlled time-integrated functions are now available in many digital air velocity meters to help smooth these turbulent flow measurements. Microcontroller-based thermal dispersion devices are typically configured as unidirectional instruments but may have multiple velocity-sensing elements capable of detecting flow direction. These devices can be used to measure a “bleed” air velocity between two spaces or across a fixed orifice. With mathematical conversion, these measured velocities can closely approximate equivalents in differential pressure down to five decimal places (inches of water). They can be used for space pressure control, to identify minute changes in flow direction, or for estimating volumetric flow rates across a fixed orifice by equating to velocity pressure.

In the HVAC&R field, thermal anemometers are suitable for a variety of applications. They are particularly well-suited to the low velocities associated with outside air intake measurement and control, return or relief fan tracking for pressurization in VAV systems, VAV terminal box measurement, unit ventilator and packaged equipment intake measurement, space pressurization for medical isolation, and laboratory fume hood face velocity measurements, typically in the 0.25 m/s (50 fpm) to 0.1 m/s (200 fpm) range. Thermal anemometers can also take multipoint traverse measurements in ventilation ductwork.

E6. THERMAL DISPERSION ARRAYS. Energy dissipated from a heated thermistor is directly related to velocity and mass velocity. This is one application of the definition of 'thermal dispersion' based on the known physical relationship between power and a number of variables in a mathematical expression which includes velocity or mass velocity and the temperature difference between a heated source and ambient temperature.

Several methods are used for determining airflow, which is proportional to the rate of heat loss from a temperature dependent resistor device. There are also as many ways as there are manufacturers to use thermal devices as airflow meters. No two are known to be the same and few generalities apply to all. Thermal Dispersion Arrays can only be compared by their measured performance ability and long term reliability.

Some manufacturers use King's Law or some form of it to determine the rate of heat-loss to a fluid, which is proportional to flow. One common approach is to measure the power required to keep the device at a constant temperature, which is a measurement of its rate of heat loss. This method requires measuring the voltage across the device at a known resistance. An analog to digital converter is usually required to measure the voltage. Since the power drop across the device is proportional to the square of the voltage, a very precise analog to digital converter is required to measure the voltage to achieve an acceptable power measurement. Since power dissipation is proportional to the square of the voltage, an error in the voltage measurement results in a magnified error in the calculation of the heat loss rate. For example, a voltage measurement error of 5% leads to a 10% error in the heat loss rate measurement calculation.

In another approach, the voltage across the device with a constant current running through it is measured. In this example, the power dissipated can be measured as the product of the voltage and current through the device. However, the temperature of the device, which is an important parameter in determining air flow, varies with the power dissipated and hence the device temperature must be determined independently. Moreover, even this method requires an expensive and precise analog to digital converter.

For industrial applications with higher temperatures and/or corrosive environments, platinum or stainless RTDs are preferred but are not popular in the HVAC&R community. Within HVAC&R comfort applications, thermistors are the sensor of choice because of their relative cost advantage, size, and performance capabilities. For thermistors, the correct industry name is needed for component identification and comparison to manufacturer name.

The specific thermistor types being used for thermal dispersion airflow measurement devices in the current HVAC market are:

1. Bead-in-Glass (Probe thermistor);
2. Several types of Chip thermistors
    a. Chip-in-Glass;
    b. Epoxy Coated and
    c. Diode Case.

Although originally designed to provide greater interchangeability, consistent temperature performance and mass production for uses such as wall stats and surface mounted to electronics, most thermistors do not have all of the qualities needed for suitability in airflow measurement application. Characteristics important for airflow measurement in HVAC&R conditions are stability or long-term drift, response time or sensitivity to changes, lead conduction, and resistance to external sources of corrosion. A deficiency in any of these areas for a sensor used in an airflow measurement assembly would provide a meter that would not perform satisfactorily and/or is likely to fail prematurely.

The nature of the thermistor-sensors' raw output and visible requirement for microprocessor-based electronics led some manufacturers to factory calibration. Some of these designs would not be viable without calibration. Other designs have chosen to leave output adjustment to contractors in the field without any formal calibration process, similar to adjustment methods used by velocity pressure devices. This requires assumptions about the validity of the basic design, sensor, and electronics performance. With proper selection of the components, attention to detail, and a robust design, thermal dispersion devices have demonstrated superior precision, reliability, and a wide performance range for over 30 years.

E7. AIRFLOW HOODS. Flow-measuring hoods are portable instruments designed to measure supply or exhaust airflow through diffusers and grilles in HVAC&R systems. The assembly typically consists of a fabric hood section, a plastic or metal base, an airflow-measuring manifold, ammeter, and handles for carrying and holding the hood in place.

For volumetric airflow measurements, the flow-measuring hood is placed over a diffuser or grille. The fabric hood captures and directs airflow from the outlet or inlet across the flow-sensing manifold in the base of the instrument. The manifold consists of a number of tubes containing upstream and downstream holes in a grid, designed to simultaneously sense and average multiple velocity points across the base of the hood. Air from the upstream holes flows through the tubes past a sensor and then exits through the downstream holes. Sensors used by different manufacturers include swinging vane anemometers, electronic micromanometers, and thermal anemometers. In electronic micromanometers, air does not actually flow through the manifold, but the airtight sensor senses the pressure differential from the upstream to downstream series of holes. The meter on the base of the hood interprets the signal from the sensor and provides a direct reading of volumetric flow in either an analog or digital display format.

As a performance check in the field, the indicated flow of a measuring hood can be compared to a duct traverse flow measurement (using a Pitot-static tube or thermal anemometer). All flow-measuring hoods induce some back pressure on the air-handling system because the hood restricts flow out of the diffuser. This added resistance alters the true amount of air coming out of the diffuser. In most cases, this error is negligible and is less than the accuracy of the instrument. For proportional balancing, this error need not be taken into account because all similar diffusers have about the same amount of back pressure. To determine whether back pressure is significant, a velocity traverse can be made in the duct ahead of the diffuser with and without the hood in place. The difference in average velocity of the traverse indicates the degree of back-pressure compensation required on similar diffusers in the system. For example, if the average velocity is 4.06 m/s (800 fpm) with the hood in place and 4.17 m/s (820 fpm) without the hood, the indicated flow reading can be multiplied by 1.025 on similar diffusers in the system (820/800 = 1.025). As an alternative, the designer of the air-handling system can predict the head-induced airflow reduction by using a curve supplied by the hood manufacturer. This curve indicates the pressure drop through the hood for different flow rates.

NORMATIVE APPENDIX F
LEGACY SINGLE- AND MULTIPLE-NOZZLE CHAMBER REQUIREMENTS

F1. Construction Requirements for Single- and Multiple-Nozzle Chambers. This section prescribes geometric proportions and specifications for legacy single- and multiple-nozzle chambers.

F1.1 Cross Sections of Single- and Multiple-Nozzle Chambers. The cross section of single- or multiple-nozzle chambers shall be round or rectangular. Transformation pieces described in Section 8.5 shall be used to connect rectangular units under test (UUTs) to round single- and multiple-nozzle chambers, or to connect round UUTs to rectangular single- or multiple-nozzle chambers. For a rectangular single- and multiple-nozzle chambers with interior width and height dimensions equal to a and b respectively, the geometrically equivalent diameter shall be obtained from Equation F-1. For a round single- and multiple-nozzle chambers or single-nozzle duct, the geometrically equivalent diameter m is equal to the interior diameter.

$$m = \sqrt{\frac{4ab}{\pi}} \tag{F-1}$$

F1.2 Nozzle Throat Velocity. The throat velocity of each nozzle shall exceed 3000 fpm (15 m/s).

F1.2 Longitudinal Spacing Requirements. In single- and multiple-nozzle chambers, the minimum distance between the upstream screens and the nozzle inlets shall be the greater of $0.5m$ or $1.5d_L$ where d_L is the largest nozzle throat diameter.

F1.3 Airflow Settling Means Requirements for Single- and Multiple-Nozzle Chambers. An airflow settling means, consisting of screens or perforated sheets having open areas of 50% to 60%, shall be installed in single- and multiple-nozzle chambers as indicated on Figures F-1 and F-2. Either one of the requirements in Sections F2.1 or F2.2 shall be met.

Informative Notes:

1. Where located upstream of the measurement plane, the purpose of the settling means is to provide a uniform flow and pressure field ahead of measurement plane. Where located downstream of the measurement plane, the purpose of the settling means is to absorb and redistribute the kinetic energy to allow expansion to simulate the expansion into an unconfined space.
2. Square mesh round wire screens should be used upstream of the measurement plane and perforated sheets should be used downstream.

F2. Single- and Multiple-Nozzle Chamber Design. Figures F-1 and F-2 show the construction requirements for a single- or multiple-nozzle chamber. One of the following requirements shall be met for a single- or multiple-nozzle chamber:

F2.1 Single- or Multiple-Nozzle Chamber Diameter. The single- or multiple-nozzle chamber geometrically equivalent diameter m shall be sized so that the maximum average air velocity is 2 m/s (400 fpm).

F2.2 Upstream Settling Means Verification Test. The maximum velocity at a distance of $0.1m$ downstream of the upstream settling means shall be measured and shall not exceed the average velocity by more than 20%.

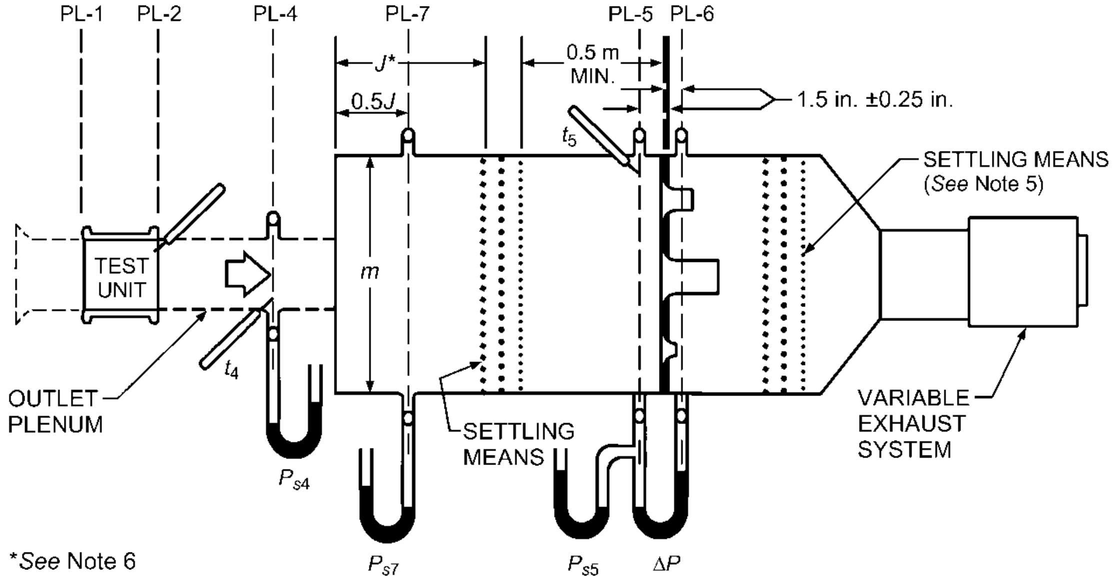

FIGURE F-1: Outlet single- and multiple-nozzle chamber setup

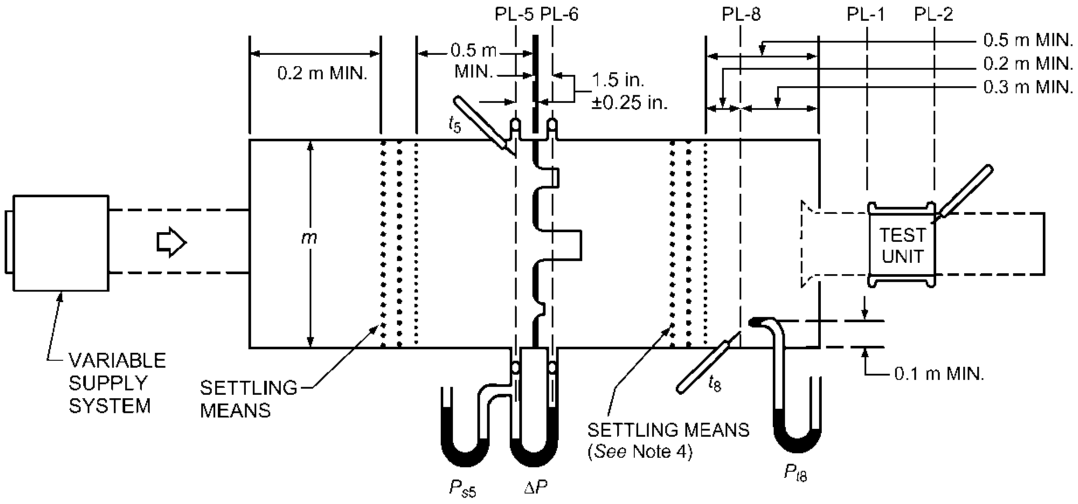

FIGURE F-2: Inlet single- or multiple-nozzle chamber setup

F3. Nozzle Airflow Calculations. ASME PTC 19.5[8] and ASME MFC-3M[9] describe measurement of fluid flow in pipes using orifices, flow nozzles, and venturi tubes, including construction proportions and port locations. Single- or multiple-nozzle chamber airflow calculations follow the ASME flow nozzles procedures, but use a discharge coefficient equation and assertions that are based upon the findings of ASHRAE RP-2334[7].

Calculating a volumetric airflow rate for a single- or multiple-nozzle chamber requires iteration because the discharge coefficient *C* is a function of the Reynolds number that is a function of the average air velocity, and the average air velocity is not known until the volumetric airflow rate has been determined. ASME PTC 19.5[8] includes an example of this iterative procedure on page 25.

F3.1 Measurements. Measurements required for nozzle airflow calculations are:

g. Inlet duct geometrically equivalent diameter D_E, m (ft)
h. Throat diameter d, m (ft)
i. Inlet absolute pressure p_1, Pa (in. of water)
j. Differential pressure $\Delta p = (p_1 - p_2)$, (in. of water)
k. Inlet dry-bulb temperature, t_1 °C (°F)
l. Inlet humidity measurement in the form of relative humidity, dew point, or wet bulb temperature in compliance with ASHRAE Standard 41.6[5] is required unless dry air is used for the test.

F3.2 Thermodynamic Properties of Air. Nozzle inlet density for dry and moist air shall be obtained from ASHRAE RP-1485[2] using nozzle inlet absolute pressure, temperature, and humidity.

Informative Note: Software based upon ASHRAE RP-1485 is available[A3].

F3.3 Dynamic Viscosity. Calculate the dynamic viscosity of air behaving as an ideal gas at moderate pressures and temperatures using Equation F-2 for SI units or Equation F-3 for IP units.

$$\mu = (17.23 + 0.048\, t_1) \times 10^{-6} \tag{F-2}$$

where

μ = dynamic viscosity, kg/(m-s)

t_1 = nozzle inlet temperature, °C

$$\mu = (11.00 + 0.018\, t_1) \times 10^{-6} \tag{F-3}$$

where

μ = dynamic viscosity, lb_m/(ft-s)

t_1 = nozzle inlet temperature, °F

F4. Single- and Multiple-Nozzle Airflow Calculations. The single- and multiple-nozzle airflow calculations follow the ASME procedures, but use a discharge coefficient equation and assertions that are based upon the findings of ASHRAE Technical Paper-2334.[7]

F4.1 Nozzle Throat Diameter for Single- or Multiple-Nozzle Chambers. If airflow operating temperatures are not within ±6ºC (±10ºF) of the temperature when the nozzle dimensional measurements were obtained, the nozzle throat diameter d for each nozzle and the geometrically equivalent diameter of the chamber m shall be corrected to account for thermal expansion in compliance with ASME PTC 19.5[8] Section 3-10.

F4.2 Reynolds Number for Single- and Multiple-Nozzle Chambers. The Reynolds number Re_d for each nozzle in use shall be obtained from Equation F-4.

$$Re_d = \frac{\rho_1 V d}{\mu_1}, \text{ dimensionless} \tag{F-4}$$

where

ρ_1 = nozzle inlet air density, kg/m^3 (lb$_m$/ft^3)
V = nozzle throat average air velocity, m/s (ft/s)
d = nozzle throat diameter, m (ft)
μ_1 = nozzle inlet dynamic viscosity, kg/(m-s) (lb$_m$/(ft-s))

Informative Note: Calculate the dynamic viscosity using Equation F-2 in SI units or Equation F-3 in IP units.

F4.3 Single- and Multiple-Nozzle Beta Ratio. $\beta = 0$ for single- and multiple-nozzle chambers.[7]

F4.4 Nozzle Limits of Use for Single- and Multiple- Nozzle Chambers. The nozzle geometry in Figure 9-3 fits into ASME's long radius nozzle type, and the throat velocity requirement in Section 9.3.3.2 confirms that that each nozzle in use will be operating within the long-radius nozzle limits prescribed by ASME.

F4.5 Expansibility Factor for Single- and Multiple-Nozzle Chamber Nozzles. The dimensionless expansibility factor ε for a long radius nozzle is shown in Equation F-5.

$$\varepsilon = \left[r^{\frac{2}{\gamma}} \left(\frac{\gamma}{\gamma - 1} \right) \left(\frac{1 - r^{\frac{\gamma-1}{\gamma}}}{1 - r} \right) \left(\frac{1 - \beta^4}{1 - \beta^4 r^{\frac{2}{\gamma}}} \right) \right]^{1/2}, \text{ dimensionless} \tag{F-5}$$

where

r = absolute pressure ratio $\left(\frac{p_2}{p_1}\right)$, dimensionless
γ = ratio of constant pressure to constant volume specific heat

For each single- and multiple-nozzle chambers, the substitution of γ =1.4 and β = 0 into Equation F-5 results in Equation F-6. The single- and multiple-nozzle expansibility factor for each nozzle shall be obtained from Equation F-6.

$$\varepsilon = 1 - 0.548(1 - r) \tag{F-6}$$

F4.6 Discharge Coefficient for Nozzle Single- and Multiple-Nozzle Chamber Nozzles. Nozzle discharge coefficients shall be calculated for each nozzle in use from Equation F-7 using the Reynolds number from Equation F-4.

$$C = 0.99855 - \left[\frac{7.006}{\sqrt{Re_d}} \right] + \left[\frac{134.6}{Re_d} \right] \tag{F-7}$$

An iterative calculation process is required to determine individual nozzle coefficients. Choose C = 0.98 to begin the iterative calculation procedure. Iteration shall continue until the calculated discharge coefficient C matches the previous discharge coefficient within ±0.005.

F4.7 Volumetric Airflow Rate for Single- and Multiple-Nozzle Chambers. The volumetric airflow rate for single- or multiple-nozzle chambers shall be obtained from Equation F-8 in SI units or from Equation F-9 in I-P units where the area is measured at the plane of the throat taps or nozzle exit for nozzles without throat taps.[7] The denominator in these equations includes the term (1-$E\beta^4$). However, β = 0 for single- and multiple-nozzle chambers, so (1-$E\beta^4$) = 1, and Equations F-8 and F-9 become Equations F-10 and F-11.

$$Q = [\sum_{i=1}^{N}(C_i A_i \varepsilon_i)]\sqrt{\frac{2\Delta p}{\rho_1(1-E\beta^4)}}\ \text{m}^3/\text{s} \qquad \text{(F-8)}$$

where

Q = volumetric flow rate, m^3/s
N = number of nozzles in use, dimensionless
C = discharge coefficient, dimensionless
A = nozzle throat area, m^2
ε = nozzle expansibility factor, dimensionless
Δp = nozzle differential pressure, Pa
ρ_1 = nozzle inlet air density for dry or moist air, kg/m^3
E = flow kinetic energy coefficient = 1.043[7] , dimensionless
β = 0

Informative Note: The superscript "7" in "1.043[7]" above is reference number, not an exponent.

$$Q = 1097.8[\sum_{i=1}^{N}(C_i A_i \varepsilon_i)]\sqrt{\frac{\Delta p}{\rho_1(1-E\beta^4)}}\quad \text{cfm} \quad \text{at 4 °C (39.2 °F) water temperature} \qquad \text{(F-9)}$$

where

Q = nozzle volumetric flow rate, cfm
N = number of nozzles in use, dimensionless
C = discharge coefficient, dimensionless
A = nozzle throat area, ft^2
ε = expansibility factor, dimensionless
Δp = nozzle differential pressure, (in. of water)
ρ_1 = nozzle inlet air density for dry or moist air, lb_m/ft^3
E = flow kinetic energy coefficient = 1.043[7], dimensionless
β = 0
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

Informative Note: The superscript "7" in "1.043[7]" above is reference number, not an exponent.

$$Q = [[\sum_{i=1}^{N}(C_i A_i \varepsilon_i)]]\sqrt{\frac{2\Delta p}{\rho_1}} \qquad \text{m}^3/\text{s} \qquad \text{(F-10)}$$

where

Q = volumetric flow rate, m^3/s
N = number of nozzles in use, dimensionless

C = discharge coefficient, dimensionless
A = nozzle throat area, m^2
ε = nozzle expansibility factor, dimensionless
Δp = nozzle differential pressure, Pa
ρ_1 = nozzle inlet air density for dry or moist air, kg/m^3

$$Q = 1097.8[\sum_{i=1}^{N}(C_i A_i \varepsilon_i)]\sqrt{\frac{\Delta p}{\rho_1}} \quad \text{cfm} \qquad \text{at 4 °C (39.2 °F) water temperature} \qquad \text{(F-11)}$$

where

Q = nozzle volumetric flow rate, cfm
N = number of nozzles in use, dimensionless
C = discharge coefficient, dimensionless
A = nozzle throat area, ft^2
ε = expansibility factor, dimensionless
Δp = nozzle differential pressure, (in. of water)
ρ_1 = nozzle inlet air density for dry or moist air, lb$_m$/ft^3
1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

F4.8 Multiple-Nozzle Standard Airflow Rate. The standard airflow rate shall be calculated in compliance with Section 4.5 using Equation F-12 in SI units or Equation F-13 in SI units.

$$\text{Standard cubic meters/second} = \frac{\rho_1 Q}{1.202} \qquad \text{(F-12)}$$

$$\text{Standard cubic feet/minute (scfm)} = \frac{\rho_1 Q}{0.075} \qquad \text{(F-13)}$$

F4.9 Mass Airflow Rate for Single- and Multiple-Nozzle Chambers. The mass airflow rate for multiple-nozzle chambers shall be obtained from Equation F-14 where $\rho_1$is the nozzle inlet air density for dry or moist air in SI units or IP units, and Q is the volumetric airflow rate in SI units in Equation F-10 in SI units or F-11 in IP units.

$$\dot{m} = \rho_1 Q \qquad \text{kg/s (lb}_m\text{/min)} \qquad \text{(F-14)}$$

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 G
DERIVATION OF I-P UNITS CONVERSION COEFFICENT 1097.8

In Section 7.2.1.2, the air velocity at the Pitot-static tube measurement location shall be obtained from Equation 7-3 in SI units.

In SI units:

$$V = K_1\sqrt{\frac{2P_v}{\rho}} \tag{7-3}$$

where

V = air velocity, m/s
K_1 = calibration coefficient provided by the manufacturer, dimensionless
P_v = velocity pressure, Pa
ρ = air density in the measurement plane, kg/m^3

It follows that the I-P units conversion coefficient can be derived from Equation G-1.

$$P_v = \frac{1}{2(K_1^2)} \times \left(\frac{\rho V^2}{g_c}\right) \tag{G-1}$$

where

P_v is the velocity pressure in (*in. of water*)

ρ is the air density in the measurement plane in $\left(\frac{lb_m}{ft^3}\right)$

V is the air velocity in $\left(\frac{ft}{min}\right)$ and

g_c is the gravitational constant $= 32.174\ \frac{lb_m - ft}{lb_f - s^2}$

Therefore, the I-P units conversion coefficient can be determined using Equations G-2, G-3, and G-4:

$$P_v = \frac{1}{2}\left(\rho \times \frac{lb_m}{ft^3}\right)\left(V \times \frac{ft}{min}\right)^2\left(\frac{1}{60}\right)^2\left(\frac{min}{s}\right)^2\left(\frac{1}{32.174}\ \frac{lb_f - s^2}{lb_m \times ft}\right)\left(\frac{1\ in.of\ water - ft^2}{5.2023 lb_f}\right) \tag{G-2}$$

$$P_v = \left(\frac{\rho V}{1097.8K_1}\right)^2 \tag{G-3}$$

$$V = 1097.8K_1\sqrt{\left(\frac{P_v}{\rho}\right)} \qquad \text{at 4 °C (39.2 °F) water temperature} \qquad \text{(G-4)}$$

The conversion coefficient (1097.8) has units of $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

Notes:

1. The water temperature of 4°C (39.2°F) was selected for this application because pure water reaches its maximum density of approximately 1000 kg/m³ or 1 g/cm³ at this temperature.
2. The conversions used are from NIST Special Publication 811[A8], Appendix B.9.

The same logic can be applied to yield the same units conversion coefficient for volumetric airflow equations for single- and multiple nozzle chambers. For example,

In SI units:

$$Q = \left[\sum_{i=1}^{N}(C_i A_i \varepsilon_i)\right]\sqrt{\frac{2\Delta p}{\rho_1(1-E\beta^4)}} \qquad \text{(9-32)}$$

where

Q = volumetric flow rate, m³/s
N = number of nozzles in use, dimensionless
C = discharge coefficient, dimensionless
A = nozzle throat area, m²
ε = nozzle expansibility factor, dimensionless
Δp = nozzle differential pressure, Pa
ρ_1 = nozzle inlet air density for dry or moist air, kg/m³
E = flow kinetic energy coefficient =1.043[7], dimensionless
β = 0

Informative Note: The superscript "7" in "1.043[7]" above is a reference number, not an exponent.

In I-P units:

$$Q = 1097.8\left[\sum_{i=1}^{N}(C_i A_i \varepsilon_i)\right]\sqrt{\frac{\Delta p}{\rho_1(1-E\beta^4)}} \qquad \text{at 4 °C (39.2 °F) water temperature} \qquad \text{(9-33)}$$

where

Q = nozzle volumetric flow rate, cfm
N = number of nozzles in use, dimensionless
C = discharge coefficient, dimensionless
A = nozzle throat area, ft²
ε = expansibility factor, dimensionless
Δp = nozzle differential pressure, (in. of water)
ρ_1 = nozzle inlet air density for dry or moist air, lb_m/ft^3
E = flow kinetic energy coefficient =1.043[7], dimensionless
β = 0

1097.8 = units conversion coefficient, $\left(\frac{1}{min}\sqrt{\frac{lb_m}{in.\ of\ water - ft}}\right)$

Informative Note: The superscript “7” in “1.043[7]” above is a reference number, not an exponent.

Notes:

1. The water temperature of 4°C (39.2°F) was selected for this application because pure water reaches its maximum density of approximately 1000 kg/m³ or 1 g/cm³ at this temperature.
2. The conversions used are from NIST Special Publication 811[A8], Appendix B.9.