This is a review of Independent Substantive Changes that were made since the last public review. Text that was removed from the Public Review Draft is provided for reference but is shown in strikeout, and text that has been added is shown with underlines.

Only these changes are open to comment at this time. All other material is provided for context only and is not open for Public Review comment except as it relates to the proposed changes.

Background. The first 41.2-2018R public review (PPR1) that ended on June 14, 2021, had a total of 12 public review comments comprised of 9 substantive public review comments and 3 supportive public review comments. The SSPC 41 voting members voted to accept all proposed responses to substantive public review comments during the SSPC 41 2021 Virtual Annual Meeting on June 22, 2021. The proposed responses to the substantive public review comments were subsequently uploaded into ASHRAE’s Online Comment Database, and then the 2 commenters marked all of proposed responses to substantive public review comments “resolved.” This second 41.2-2018R Independent Substantive Change (ISC) public review draft consists of the responses to the substantive and supportive first public review comments.

Section 3, Definitions: Add the new definition below for clarification.

steady-state criteria: the criteria that establish negligible change of air velocity or airflow with time.

Section 4.5, Standard Air Density: Delete the comma between the SI units and the IP units.

4.5 Standard Air Density. For the purposes of this standard, standard air density = 1.202 kg/m³, (0.075 lbm/ft³) unless otherwise specified in the test plan in Section 5.1. The conversion uncertainty associated with calculating air velocity or airflow measurement uncertainties in I-P units is ±0.00004 lbm/ft³.
5.1 Test Plan. A test plan shall specify the humidity measurement system accuracy and the test points operating conditions to be performed. Additionally, the test plan shall include the test points, targeted set points, and corresponding operating tolerances to be performed. 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.
c. A rating standard.
d. A regulation or code.
e. Any combination of items a. through d.

The test plan shall specify:

a. The air velocity or airflow measurement system accuracy.
b. The values to be determined and recorded that are selected from this list: air velocity, air velocity uncertainty, mass airflow rate, mass airflow uncertainty, volumetric airflow rate, volumetric airflow uncertainty, standard volumetric airflow rate, standard volumetric airflow rate 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 The 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 Standard volumetric airflow if required by the test plan in Section 5.1, standard m³/s at 1.202 kg/m³, (scfm at 0.075 lbm/ft³).

5.2.2.2 Volumetric airflow at the measured density if required by the test plan in Section 5.1, m³/s (cfm).
5.2.2.3 Mass rate of airflow if required by the test plan in Section 5.1, kg/s (lbm/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.

**Section 5.3.1, Air Velocity Measurement: Revise as shown below to separate the steady-state requirements for laboratory operating conditions from the steady-state requirements for field operating conditions.**

### 5.3.1. Air Velocity Measurement Requirements

#### 5.3.1.1 Air Velocity Measurement Accuracy

A selected air velocity measurement method shall meet or exceed the required air velocity measurement system accuracy over the full range of operating conditions specified in the test plan in Section 5.1.

#### 5.3.1.2 Air Velocity Uncertainty

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

#### 5.3.1.3 Air Velocity Steady-State Test Criteria

Air velocity test data shall be recorded at steady-state conditions unless otherwise specified in the test plan in Section 5.1. 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 5.3.1.3.1 if the test plan provides test points for air velocity measurement.

b. Apply the steady-state criteria in Section 5.3.1.3.2 if the test plan provides targeted set points for air velocity measurement.

#### 5.3.1.3.1 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 5.3.1.3.3 if the test plan provides test points for air velocity measurement.

b. Apply the steady-state criteria in Section 5.3.1.3.4 if the test plan provides targeted set points for air velocity measurement.

#### 5.3.1.3.2 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 5.3.1.3.1 are optional.

**Informative Note:** The steady-state methods in Section 5.3.1.3.1 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.

#### 5.3.1.3.3 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 \( \Delta t \) over a test duration \( \Delta t \) where \( \Delta t \) is in time units. Equation 5-1 states the relationship of the test duration to the number of air velocity samples and the equal time intervals.

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

(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 illustrated in Figure 1 using Equation 5-2.

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

(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.

![FIGURE 1: Graphical illustration of the method for determining the steady-state air velocity criteria for test points](image-url)
Determine the mean offset $\mu$ of the sampled data using Equation 5-3, and then calculate the standard deviation $\sigma$ using Equation 5-4.

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

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

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

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

$\bar{V}$, as determined by Equation 5-5, represents the steady-state mean air velocity provided that one of the following criteria is satisfied:

a. Apply Equation 5-6 if $2\sigma \geq V_L$ where $V_L$ is the specified operating tolerance limit for air velocity, and if Equation 5-6 is satisfied by not less than 95% of the sampled air velocities.

$$|V_i - \mu| \leq 2\sigma, \text{ m/s (fpm)} \quad (5-6)$$

b. Apply Equation 5-7 if $V_L \geq 2\sigma$ where $V_L$ is the specified operating tolerance limit for air velocity, and if Equation 5-7 is satisfied by not less than 95% of the sampled air velocities.

$$|V_i - \mu| \leq V_L, \text{ m/s (fpm)} \quad (5-7)$$

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

5.3.1.3.2 5.3.1.3.4 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 $\delta t$ over a test duration $\Delta t$ where $\Delta t$ is in time units. Equation 5-8 states the relationship of the test duration to the number of samples and the equal time intervals.

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

Informative Notes:

a. The equations in this Section are only valid if the start time for each test duration is zero.

b. 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 illustrated in Figure 2 using Equation 5-9.

$$b = \left\{ \frac{\left[ N\left( \sum_{i=1}^{N} t_i V_i \right) - \left( \sum_{i=1}^{N} t_i \right) \left( \sum_{i=1}^{N} V_i \right) \right]}{N\left( \sum_{i=1}^{N} t_i^2 \right) - \left( \sum_{i=1}^{N} t_i \right)^2} \right\} \quad (5-9)$$

Informative Note: It should be noted that the units for the slope in Equation 5-9 are air velocity, m/s (fpm), divided by the units that the user has selected for time.
Determine the mean offset $\mu$ of the sampled data using Equation 5-10, and then calculate the standard deviation $\sigma$ using Equation 5-11.

$$\mu = \frac{1}{N} \left[ \sum_{i=1}^{N} (V_i - bt_i) \right], \text{ m/s (fpm)} \quad (5-10)$$

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

The mean of the sampled air velocities $\bar{V}$ is defined by Equation 5-12.

$$\bar{V} = \frac{1}{N} \left[ \sum_{i=1}^{N} (V_i) \right], \text{ m/s (fpm)} \quad (5-12)$$

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

$$|\bar{V} - V_{SP}| + |b\Delta t| + 2\sigma \leq V_L, \text{ m/s (fpm)} \quad (5-13)$$
The steady-state condition of the set point air velocity $V_{SP}$ exists (a) where Equation 5-14 is satisfied by not less than 95% of the sampled air velocities where $V_L$ is the operating tolerance limit for velocity.

\[
(V_{SP} - V_L) \leq V_i \leq (V_{SP} + V_L), \text{ m/s (fpm)}
\]  

(5-14)

(b) where

\[-0.50 V_L \leq (V - V_{SP}) \leq 0.50 V_L, \text{ m/s (fpm)}\]

(5-15)

and (c) where

\[
\begin{align*}
\beta \Delta t &\leq 0.50V_L, \text{ m/s (fpm)} \\
|\beta \Delta t| &\leq 0.50V_L, \text{ m/s (fpm)}
\end{align*}
\]

(5-16)

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

Section 5.3.2, Airflow Measurement: Revise as shown below to separate the steady-state requirements for laboratory operating conditions from the steady-state requirements for field operating conditions for volumetric airflow.

5.3.2 Airflow Measurement Requirements

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

5.3.2.2 Airflow Uncertainty. If specified in the test plan in Section 5.1, the uncertainty in each airflow measurement shall be calculated as described in Section 10 for each test point. Alternatively, the worst-case uncertainty for all test points shall be estimated and reported for each test point.

5.3.2.3 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 1% of the airflow at the pressure corresponding to the measured airflow specified in the test plan for field measurements.

5.3.2.4 Volumetric Airflow Rate Steady State Criteria. Volumetric airflow flow rate test data shall be recorded at steady-state conditions if required in the test plan in Section 5.1. If the test plan requires volumetric airflow flow rate test data points to be recorded at steady-state test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, then determine that steady-state test conditions have been achieved using one of the following methods:

a. Apply the steady-state criteria in Section 5.3.2.4.1 if the test plan provides test points for volumetric airflow flow rate measurement.

b. Apply the steady-state criteria in Section 5.3.2.4.2 if the test plan provides targeted set points for volumetric airflow flow rate measurement.

5.3.2.4.1 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 5.3.2.4.3 if the test plan provides test points for air
velocity measurement.

b. Apply the steady-state criteria in Section 5.3.2.4.4 if the test plan provides targeted set points
for air velocity measurement.

5.3.2.4.2 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 5.3.2.4.1 are
optional.

Informative Note: The steady-state methods in Section 5.3.2.4.1 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.

5.3.2.4.3 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 \( \delta t \) over a test duration \( \Delta t \) where \( \Delta t \) is in time units. Equation 5-17 states the
relationship of the test duration to the number of volumetric airflow flow rate 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 illustrated in Figure 3 using Equation 5-18.

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

Informative Note: It should be noted that the units for the slope in Equation 5-2 are volumetric airflow
flow rate, m\(^3\)/s (ft\(^3\)/min), divided by the units that the user has selected for time.
Determine the mean offset $\mu$ of the sampled data using Equation 5-19, and then calculate the standard deviation $\sigma$ using Equation 5-20.

$$
\mu = \frac{1}{N} \left[ \sum_{i=1}^{N} (Q_i - b_t_i) \right], \text{ m}^3/\text{s (ft}^3/\text{min}) \tag{5-19}
$$

$$
\sigma = \left[ \left( \frac{1}{(N-2)} \right) \sum_{i=1}^{N} (Q_i - b_t_i - \mu)^2 \right]^{\frac{1}{2}}, \text{ m}^3/\text{s (ft}^3/\text{min}) \tag{5-20}
$$

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

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

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

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

$$
|Q_i - \mu| \leq 2\sigma, \text{ m}^3/\text{s (ft}^3/\text{min}) \tag{5-22}
$$
b. Apply Equation 5-23 if $Q_L \geq 2\sigma$ where $Q_L$ is the specified operating tolerance limit for volumetric airflow flow rate, and if Equation 5-23 is satisfied by not less than 95% of the sampled volumetric airflow flow rates.

\[ |Q_i - \mu| \leq Q_L, \text{ m}^3/\text{s (ft}^3/\text{min}) \]  

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

### 5.3.2.4.2 5.3.2.4.4 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 $\delta t$ over a test duration $\Delta t$ where $\Delta t$ is in time units. Equation 5-24 states the relationship of the test duration to the number of samples and the equal time intervals.

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

**(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 illustrated in Figure 4 using Equation 5-25.

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

**(Informative Note):** It should be noted that the units for the slope in Equation 5-25 are volumetric airflow flow rate, m$^3$/s (ft$^3$/min), divided by the units that the user has selected for time.
FIGURE 4: Graphical illustration of the method for determining the steady-state volumetric airflow flow rate criteria for targeted set points

Determine the mean offset $\mu$ of the sampled data using Equation 5-26, and then calculate the standard deviation $\sigma$ using Equation 5-27.

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

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

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

\[
\bar{Q} = \frac{1}{N} [\sum_{i=1}^{N} (\bar{m}_i)], \text{ m}^3/\text{s} (\text{ft}^3/\text{min}) \tag{5-28}
\]

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

\[
|\bar{Q} - Q_{SP}| + |b \Delta t| + 2\sigma \leq Q_L, \text{ m}^3/\text{s} (\text{ft}^3/\text{min}) \tag{5-29}
\]

The steady-state condition of the set point volumetric airflow flow rate, $Q_{SP}$, exists (a) where
Equation 5-30 is satisfied by not less than 95% of the sampled volumetric airflow flow rates where \( Q_L \) is the operating tolerance limit for volumetric airflow flow rate

\[
(Q_{SP} - Q_L) \leq Q_I \leq (Q_{SP} + Q_L), \text{ m}^3/\text{s} (\text{ft}^3/\text{min})
\]  

(5-30)

(b) where

\[
-0.50 Q_L \leq (\bar{Q} - Q_{SP}) \leq 0.50 Q_L, \text{ m}^3/\text{s} (\text{ft}^3/\text{min})
\]  

(5-31)

and (c) where

\[
b \Delta t \leq 0.50 Q_L, \text{ m}^3/\text{s} (\text{ft}^3/\text{min})
\]  

(5-32)

In informative Note: For further reading about this method of determining steady-state conditions, refer to Informative Appendix A – Bibliography items A1 and A2.

Section 5.3.2.6, Airflow Measurement: Revise as shown below to separate the steady-state requirements for laboratory operating conditions from the steady-state requirements for field operating conditions for mass airflow measurements.

5.3.2.6 Steady-State Test Criteria for Mass Airflow Rate Measurements. Mass airflow rate test data shall be recorded at steady-state conditions unless otherwise specified in the test plan in Section 5.1. 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 5.3.2.6.1 if the test plan provides test points for mass airflow rate measurement.

b. Apply the steady-state criteria in Section 5.3.2.6.2 if the test plan provides targeted set points for mass airflow rate measurement.

c. Apply the steady-state criteria in Section 5.3.2.6.3 if the test plan provides test points for air velocity measurement.

d. Apply the steady-state criteria in Section 5.3.2.6.4 if the test plan provides targeted set points for air velocity measurement.

5.3.2.6.2 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 5.3.2.4.1 are optional.

**Informative Note:** The steady-state methods in Section 5.3.2.6.1 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.

### 5.3.2.6.1 5.3.2.6.3 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 $\delta t$ over a test duration $\Delta t$ where $\Delta t$ is in time units. Equation 5-33 states the relationship of the test duration to the number of mass airflow rate samples and the equal time intervals.

$$\Delta t = (N - 1) \delta t \quad (5-33)$$

**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 illustrated in Figure 5 using Equation 5-34.

$$b = \left\{ \frac{\left[ N(\sum_{i=1}^{N} t_i \dot{m}_i) - (\sum_{i=1}^{N} t_i)(\sum_{i=1}^{N} \dot{m}_i) \right]}{\left[ N(\sum_{i=1}^{N} t_i^2) - (\sum_{i=1}^{N} t_i)^2 \right]} \right\} \quad (5-34)$$

**Informative Note:** It should be noted that the units for the slope in Equation 5-2 are mass airflow rate, kg/s (lbm/min), divided by the units that the user has selected for time.
Determine the mean offset \( \mu \) of the sampled data using Equation 5-35, and then calculate the standard deviation \( \sigma \) using Equation 5-36.

\[
\mu = \frac{1}{N} \left[ \sum_{i=1}^{N} (\bar{m}_i - b t_i) \right], \text{ kg/s (lbm/min)} \tag{5-35}
\]

\[
\sigma = \sqrt{\left( \frac{1}{N-2} \right) \sum_{i=1}^{N} (\bar{m}_i - b t_i - \mu)^2} \tag{5-36}
\]

The mean of the sampled mass airflow rates \( \bar{m} \) is defined by Equation 5-37.

\[
\bar{m} = \frac{1}{N} \left[ \sum_{i=1}^{N} (\bar{m}_i) \right], \text{ kg/s (lbm/min)} \tag{5-37}
\]

\( \bar{m} \), as determined by Equation 5-37, represents the steady-state mean mass airflow rate provided that one of the following criteria is satisfied:

c. Apply Equation 5-38 if \( 2\sigma \geq \bar{m}_L \) where \( \bar{m}_L \) is the specified operating tolerance limit for mass airflow rate, and if Equation 5-38 is satisfied by not less than 95% of the sampled mass airflow rates.

\[
|m_i - \mu| \leq 2\sigma, \text{ kg/s (lbm/min)} \tag{5-38}
\]
d. Apply Equation 5-39 if \( \bar{m}_L \geq 2\sigma \) where \( \bar{m}_L \) is the specified operating tolerance limit for mass airflow rate, and if Equation 5-38 is satisfied by not less than 95% of the sampled mass airflow rates.

\[
|\bar{m}_i - \mu| \leq \bar{m}_L, \text{ kg/s (lbm/min)} \tag{5-39}
\]

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

### 5.3.2.6.4 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 \( \delta t \) over a test duration \( \Delta t \) where \( \Delta t \) is in time units. Equation 5-40 states the relationship of the test duration to the number of samples and the equal time intervals.

\[
\Delta t = (N - 1)\delta t \tag{5-40}
\]

**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 \( \bar{m}_i \) 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 illustrated in Figure 6 using Equation 5-41.

\[
b = \left\{ \frac{[N(\Sigma_{i=1}^{N} {t_i} \bar{m}_i) - (\Sigma_{i=1}^{N} t_i)(\Sigma_{i=1}^{N} \bar{m}_i)]}{N(\Sigma_{i=1}^{N} {t_i}^2) - (\Sigma_{i=1}^{N} t_i)^2} \right\} \tag{5-41}
\]

**Informative Note:** It should be noted that the units for the slope in Equation 5-41 are mass airflow rate, kg/s (lbm/min), divided by the units that the user has selected for time.
Determine the mean offset $\mu$ of the sampled data using Equation 5-42, then calculate the standard deviation $\sigma$ using Equation 5-43.

\[
\mu = \frac{1}{N} \left[ \sum_{i=1}^{N} (\bar{m}_i - b t_i) \right], \text{ kg/s (lbm/min)} \tag{5-42}
\]
\[
\sigma = \left[ \left( \frac{1}{N-2} \right) \sum_{i=1}^{N} (\bar{m}_i - b t_i - \mu)^2 \right]^{\frac{1}{2}}, \text{ kg/s (lbm/min)} \tag{5-43}
\]

The mean of the sampled mass airflow rates $\bar{m}$ is defined by Equation 5-44.

\[
\bar{m} = \frac{1}{N} \left[ \sum_{i=1}^{N} (\bar{m}_i) \right], \text{ kg/s (lbm/min)} \tag{5-44}
\]

A tolerance on the fluctuations about the trend line represents a limit on the fluctuation level relative to the trend line of the sampled data. If the tolerance of fluctuations about the trend line is not specified in the test plan, the bounds for a 95% confidence limit for the fluctuations about the trend line shall then be determined according to Equation 5-42.

\[
|\bar{m} - \bar{m}_{SP}| + |b \Delta t| + 2 \sigma \leq \bar{m}_L, \text{ kg/s (lbm/min)} \tag{5-45}
\]
The steady-state condition of the set point mass airflow rate $\dot{m}_{SP}$ exists (a) where Equation 5-46 is satisfied by not less than 95% of the sampled mass airflow rates where $\dot{m}_L$ is the operating tolerance limit for mass airflow rate

$$\left( \dot{m}_{SP} - \dot{m}_L \right) \leq \dot{m} \leq \left( \dot{m}_{SP} + \dot{m}_L \right) \text{, kg/s (lbm/min)} \quad (5-46)$$

(b) where

$$-0.50 \dot{m}_L \leq (\bar{\dot{m}} - \dot{m}_{SP}) \leq 0.50 \dot{m}_L \text{, kg/s (lbm/min)} \quad (5-47)$$

and (c) where

$$b\Delta t \leq 0.50\dot{m}_L \text{, kg/s (lbm/min)} \quad (5-48)$$

$$|b\Delta t| \leq 0.50\dot{m}_L \text{, kg/s (lbm/min)} \quad (5-48)$$

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

### Section 9.1, Constraint for All Airflow Measurement Methods: Correct this section as shown below.

#### 9.1 Constraint on All Airflow Measurement Methods Except for 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 rectangular duct with interior width and height dimensions equal to $a$ and $b$ respectively, 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 $D$.

$$D_E = \frac{\sqrt{4ab}}{\pi} \quad (9-1)$$

where

$D_E =$ geometrically equivalent diameter, dimensionless

$a =$ interior width, m (ft)

$b =$ interior height, m (ft)

### Section 9.3.3, Nozzle Airflow Test Setup Construction Requirements: Revise as shown below to

(a) clarify the intent of this section, (b) eliminate duplicate Thermodynamic Properties of Air, and (c) add Section 9.3.6.2, Dynamic Viscosity, and renumber the subsequent equations.
9.3.3 Construction Requirements for Single- and Multiple-Nozzle Chambers Nozzle Airflow Test Setup Construction Requirements. 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 Test Single- and Multiple-Nozzle Chambers and Test Ducts. The cross section of test chambers and test 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 test single- and multiple-nozzle chambers or test ducts, or to connect round UUTs to rectangular test single- and multiple-nozzle chambers or test ducts. For a rectangular test single- and multiple-nozzle chamber or test 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 test single- and multiple-nozzle chamber or test duct, the geometrically equivalent diameter \(D_E\) is equal to the interior diameter \(D\).

\[
D_E = \sqrt{\frac{4ab}{\pi}}
\]  

(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 multiple-nozzle chambers, the centerline-to-centerline distance between adjacent nozzles shall exceed \(3d_L\) 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 exceed 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 Nozzle 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 where indicated on Figure 20. Either one of the requirements in Sections 9.3.5.1 or 9.3.5.2 shall be met.

Informative Note:

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 19 shows the single-nozzle duct test setup that is within the scope of this standard.

![FIGURE 19 Single-Nozzle duct test setup](image)

**9.3.5 Single- and Multiple-Nozzle Chamber Design.** Figure 20 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 Size.** 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 downstream of the upstream settling means shall be measured and shall not exceed the average velocity by more than 20%.
9.3.6 Nozzle Duct Airflow Calculations. ASME PTC 19.5\(^7\) and ASME MFC-3M\(^8\) 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 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\textsuperscript{6}.

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\textsuperscript{7} 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 temperature $t_1$, °C (°F)
- f. Nozzle inlet humidity measurement in the form of relative humidity, dew point, or wet bulb temperature in compliance with ASHRAE Standard 41.6\textsuperscript{4}.

**Informative Note:** 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 Thermodynamic Properties of Air.** Nozzle inlet density for dry and moist air shall be obtained from ASHRAE RP-1485\textsuperscript{4} using nozzle inlet absolute pressure, temperature, and humidity.

**Informative Note:** Software based upon ASHRAE RP-1485 is available.

**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

- $\mu =$ 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

- $\mu =$ dynamic viscosity, lbm/(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 9-16.

\[
D_h = \frac{2ab}{a+b} \quad (9-16)
\]

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 Reynolds number \( Re_D \) shall be obtained from Equation 9-17.

\[
Re_D = \frac{\rho_1 V D_h}{\mu_1}, \text{ dimensionless} \quad (9-17)
\]

where
- \( \rho_1 \) = nozzle inlet air density, kg/m\(^3\) (lbm/ft\(^3\))
- \( V \) = nozzle throat average air velocity, m/s (ft/s)
- \( D_h \) = hydraulic diameter, m (ft)
- \( \mu_1 \) = nozzle inlet air dynamic viscosity, Ns/m\(^2\) (lbm/s-ft)

9.3.6.3.3 Single-Nozzle Duct Beta Ratio. The single-nozzle beta ratio for the nozzle in a single-nozzle duct shall be obtained from Equation 9-18. If airflow operating temperatures are not within ±6ºC (±10ºF) of the of the ambient temperature during the dimensional measurements, parameters \( d \), \( D_h \), and \( \beta \) shall be corrected to account for thermal expansion in compliance with ASME PTC 19.57 Section 3-10.

\[
\beta = \left( \frac{d}{D_h} \right), \text{ dimensionless} \quad (9-18)
\]

9.3.6.3.4 Volumetric Airflow Rates in a Single-Nozzle Duct. Volumetric Airflow Rates. Single-nozzle duct volumetric airflow rates shall be obtained from Equation 9-19 in SI units or Equation 9-20 in I-P units.

In SI units:

\[
Q = CAe \sqrt{\frac{2(\Delta p)}{\rho_1(1-E\beta^4)}} \quad (9-19)
\]

where
- \( Q \) = nozzle volumetric airflow rate, m\(^3\)/s
- \( C \) = nozzle discharge coefficient, dimensionless
- \( A \) = nozzle throat area, m\(^2\)
- \( e \) = nozzle expansibility factor, dimensionless
- \( \Delta p \) = nozzle differential pressure, Pa
- \( \rho_1 \) = nozzle inlet air density, kg/m\(^3\)
- \( E \) = flow kinetic energy coefficient = 1.043\(^6\)
- \( \beta = d/D_h \), dimensionless
In I-P units:

\[
Q = 1097.8CA\epsilon \sqrt{\frac{\Delta p}{\rho_1(1-E\beta^4)}}
\]  

(9-20)

where

- \( Q \) = nozzle volumetric airflow rate, cfm
- \( C \) = nozzle discharge coefficient, dimensionless
- \( A \) = nozzle throat area, ft\(^2\)
- \( \epsilon \) = nozzle expansibility factor, dimensionless
- \( \Delta p \) = nozzle differential pressure, in. of water
- \( \rho_1 \) = nozzle inlet air density, lbm/ft\(^3\)
- \( E \) = flow kinetic energy coefficient = 1.043\(^6\), dimensionless
- \( \beta \) = \( d/D_h \), dimensionless
- 1097.8 = units conversion coefficient, dimensionless

### Informative Note:

The superscript “6” in “1.043\(^6\)” above is reference number, not an exponent.

#### 9.3.6.3.5 Single-Nozzle Limits of Use in a Single-Nozzle Duct

The nozzle geometry in Figure 18 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 Single-Nozzle Expansibility Factor in a Single-Nozzle Duct

The dimensionless expansibility factor \( \epsilon \) for a long radius nozzle shall be obtained from Equation 9-21.

\[
\epsilon = \left[ \frac{2}{\gamma} \left( \frac{\gamma}{\gamma-1} \right) \left( \frac{1-\beta \gamma}{\gamma-1-\beta \gamma} \right)^{1/2} \right]^{1/2}, \text{ dimensionless}
\]

(9-21)

where

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

#### 9.3.6.3.7 Nozzle Discharge Coefficient in a Single-Nozzle Duct Discharge Coefficient

The dimensionless discharge coefficient \( C \) for a long radius nozzle is a function of \( \beta \) 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 9-22.

\[
C = 0.99855 - \left[ \frac{7.006}{\sqrt{Re_d}} \right] + \left[ \frac{134.6}{Re_d} \right], \text{ dimensionless}
\]

(9-22)

#### 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 \( \pm 0.005 \).

**9.3.6.3.9 Standard Airflow Rate in a Single-Nozzle Duct Standard Airflow Rate.** The standard airflow rate for single nozzles shall be calculated using Equation 9-23 in SI units or Equation 9-24 in I-P units, where \( \rho_1 \) is the nozzle inlet air density, kg/m\(^3\) (lbm/ft\(^3\)) and \( Q \) is the volumetric airflow rate using Equation 9-19 in SI units or Equation 9-20 in I-P units.

\[
\text{Standard Cubic Meters/Second} = \frac{\rho_1 Q}{1.202} \quad (9-23)
\]

\[
\text{Standard Cubic Feet/Minute (scfm)} = \frac{\rho_1 Q}{0.075} \quad (9-24)
\]

**9.3.6.3.10 Mass Airflow Rate in a Single-Nozzle Duct Mass Airflow Rate.** The mass airflow rate for single nozzles shall be obtained from Equation 9-25, where \( \rho_1 \) is the nozzle inlet air density, kg/m\(^3\) (lbm/ft\(^3\)) and \( Q \) is the volumetric airflow rate, m\(^3\)/s (cfm), using Equation 9-19 in SI units or Equation 9-20 in I-P units.

\[
\dot{m} = \rho_1 Q, \text{ kg/s (lbm/min)} \quad (9-25)
\]

**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 RP-2334.

**9.3.6.4.1 Throat Diameter in Single- and Multiple-Nozzle Chambers, Throat Diameter.** If airflow operating temperatures are not within \( \pm 6^\circ C \) (\( \pm 10^\circ F \)) 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\(^7\) Section 3-10.

**9.3.6.4.2 Reynolds Number in Single- and Multiple-Nozzle Chambers, Reynolds Number.** The multiple nozzle Reynolds \( Re_D \) number for each nozzle in use shall be obtained from Equation 9-26.

\[
Re_D = \frac{\rho_1 V d}{\mu_1}, \text{ dimensionless} \quad (9-26)
\]

where
- \( \rho_1 \) = nozzle inlet air density, kg/m\(^3\) (lbm/ft\(^3\))
- \( V \) = nozzle throat average air velocity, m/s (ft/s)
- \( d \) = nozzle throat diameter, m (ft)
- \( \mu_1 \) = nozzle inlet dynamic viscosity, Ns/m\(^2\) (lbm/s-ft)

**9.3.6.4.3 Beta Ratio for Single- and Multiple-Nozzle Chambers, Beta Ratio.** \( \beta = 0 \) for single- and multiple-nozzle chambers.

**9.3.6.4.4 Nozzle Limits of Use in Single- and Multiple-Nozzle Chambers, Limits of Use.** The nozzle geometry in Figure 18 fits into ASME’s long radius nozzle type, and the throat
velocity requirement in Section 9.3.2.2 confirms that the single-nozzle 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 \( \varepsilon \) for a long radius nozzle is shown in Equation 9-27.

\[
\varepsilon = \left[ \frac{\gamma}{\gamma - 1} \left( 1 - \frac{r^\gamma}{r^{\gamma - 1}} \right) \right]^{1/2}, \text{ dimensionless} \hspace{1cm} (9-27)
\]

where

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

\[ \gamma = \text{ratio of constant pressure to constant volume specific heat, dimensionless} \]

For each nozzle in single- and multiple-nozzle chambers, substitution of \( \gamma = 1.4 \) and \( \beta = 0 \) into Equation 9-27 results in Equation 9-28. The multiple-nozzle expansibility factor for each nozzle shall be obtained from Equation 9-28.

\[ \varepsilon = 1 - 0.548(1 - r), \text{ dimensionless} \hspace{1cm} (9-28) \]

**9.3.6.4.6 Discharge Coefficient for Nozzle Single- and Multiple-Nozzle Chamber Nozzles.** Discharge coefficients shall be calculated for each nozzle in use from Equation 9-29 using the Reynolds number from Equation 9-26.

\[
C = 0.99855 - \frac{7.006}{\sqrt{Re_d}} + \frac{134.6}{Re_d}, \text{ dimensionless} \hspace{1cm} (9-29)
\]

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 9-30 in SI units or from Equation 9-31 in I-P units where the area is measured at the plane of the throat taps or nozzle exit for nozzles without throat taps.\(^6\) The denominator in these equations includes the term \( 1 - E \beta^4 \). However, \( \beta = 0 \) for multiple-nozzles, so \( 1 - E \beta^4 = 1 \), and Equations 9-30 and 9-31 become Equations 9-32 and 9-33.

In SI units:

\[
Q = \left[ \sum_{i=1}^{N} (C_i) A_i \right] \varepsilon \frac{2 \Delta p}{\rho_1 (1 - E \beta^4)}, \text{ m}^3/\text{s} \hspace{1cm} (9-30)
\]

where

- \( Q \) = volumetric flow rate, m\(^3\)/s
- \( N \) = number of nozzles in use, dimensionless
- \( C \) = discharge coefficient, dimensionless
- \( A \) = nozzle throat area, m\(^2\)
\[ \varepsilon = \text{nozzle expansibility factor, dimensionless} \]
\[ \Delta p = \text{nozzle differential pressure, Pa} \]
\[ \rho_1 = \text{nozzle inlet air density, kg/m}^3 \]
\[ E = \text{flow kinetic energy coefficient} = 1.043^6, \text{dimensionless} \]
\[ \beta = 0 \]

**Informative Note:** The superscript “6” in “1.043^6” above is reference number, not an exponent.

**In I-P units:**
\[
Q = 1097.8 \left[ \sum_{i=1}^{N} (C_i A_i) \right] \varepsilon \left( \frac{\Delta p}{\sqrt{\rho_1 (1 - E \beta^2)}} \right) 
\]
(9-31)

**In SI units:**
\[
Q = \left[ \sum_{i=1}^{N} (C_i A_i) \right] \varepsilon \left( \frac{\Delta p}{\rho_1} \right) 
\]
(9-32)

where
- \( Q \) = nozzle volumetric flow rate, cfm
- \( N \) = number of nozzles in use, dimensionless
- \( C \) = discharge coefficient, dimensionless
- \( A \) = nozzle throat area, ft\(^2\)
- \( \varepsilon \) = expansibility factor, dimensionless
- \( \Delta p \) = nozzle differential pressure, (in. of water)
- \( \rho_1 \) = nozzle inlet air density, lbm/ft\(^3\)
- \( E \) = flow kinetic energy coefficient = 1.043\(^6\), dimensionless
- \( \beta \) = 0
- 1097.8 = units conversion coefficient, dimensionless

**Informative Note:** The superscript “6” in “1.043^6” above is reference number, not an exponent.

**In SI units:**
\[
Q = \left[ \sum_{i=1}^{N} (C_i A_i) \right] \varepsilon \left( \frac{\Delta p}{\rho_1} \right) 
\]
(9-32)

where
- \( Q \) = volumetric flow rate, m\(^3\)/s
- \( N \) = number of nozzles in use, dimensionless
- \( C \) = discharge coefficient, dimensionless
- \( A \) = nozzle throat area, m\(^2\)
- \( \varepsilon \) = nozzle expansibility factor, dimensionless
- \( \Delta p \) = nozzle differential pressure, Pa
\[ \rho_1 = \text{nozzle inlet air density, kg/m}^3 \]

\[ \beta = 0 \]

In I-P units:

\[ Q = 1097.8 \left[ \sum_{i=1}^{N} (C_i A_i) \right] \frac{\Delta p}{\rho_1} \]  

(9-33)

where

- \( Q = \text{nozzle volumetric flow rate, cfm} \)
- \( N = \text{number of nozzles in use, dimensionless} \)
- \( C = \text{discharge coefficient, dimensionless} \)
- \( A = \text{nozzle throat area, ft}^2 \)
- \( \varepsilon = \text{expansibility factor, dimensionless} \)
- \( \Delta p = \text{nozzle differential pressure, (in. of water)} \)
- \( \rho_1 = \text{nozzle inlet air density, lbm/ft}^3 \)
- \( \beta = 0 \)

\[ 1097.8 = \text{units conversion coefficient, dimensionless} \]

### 9.3.6.4.8 Standard Airflow Rate Single- and Multiple-Nozzle Chamber, Standard Airflow Rate

The standard airflow rate shall be calculated in compliance with Section 4.5 using Equation 9-34 in SI units or Equation 9-35 in I-P units, where \( \rho_1 \) is the nozzle inlet air density, kg/m\(^3\) (lbm/ft\(^3\)) and \( Q \) is the volumetric airflow rate using Equation 9-32 in SI units or Equation 9-33 in I-P units.

\[ \text{Standard Cubic Meters/Second} = \frac{\rho_1 Q}{1.202} \]  

(9-34)

\[ \text{Standard Cubic Feet/Minute (scfm)} = \frac{\rho_1 Q}{0.075} \]  

(9-35)

### 9.3.6.4.12 Mass Airflow Rate for Single- and Multiple-Nozzle Chambers, Mass Airflow Rate

The mass airflow rate for single- and multiple-nozzle chambers shall be obtained from Equation 9-36, where \( \rho_1 \) is the nozzle inlet air density, kg/m\(^3\) (lbm/ft\(^3\)) and \( Q \) is the volumetric airflow rate using Equation 9-32 in SI units or Equation 9-33 in I-P units.

\[ \dot{m} = \rho_1 Q, \text{ kg/s (lbm/min)} \]  

(9-36)
10. MEASUREMENT UNCERTAINTY

10.1 Uncertainty Requirements

An estimate of the measurement uncertainty, performed in compliance with ASME PTC 19.1, shall accompany each air velocity and 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.

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

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

F1.1 Cross Sections of Test Single- and Multiple-Nozzle Chambers. The cross section of test single- and 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 test single- and multiple-nozzle chambers, or to connect round UUTs to rectangular test single- and multiple-nozzle chambers. For a rectangular test single- and multiple-nozzle chamber 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 test single- and multiple-nozzle chamber or test duct, the geometrically equivalent diameter \( m \) is equal to the interior diameter.

\[
m = \sqrt{\frac{4ab}{\pi}}
\]  
(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 0.5\(m\) or 1.5\(d_L\) 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 nozzle chambers where 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- and Multiple-Nozzle Chamber Size. The chamber geometrically equivalent diameter 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 0.1D downstream of the upstream settling means shall be measured and shall not exceed the average velocity by more than 20\%.
FIGURE F-2: Inlet single- and multiple-nozzle chamber setup

**F3 Nozzle Airflow Calculations.** ASME PTC 19.5\(^7\) and ASME MFC-3M\(^8,9\) describe measurement of fluid flow in pipes using orifices, flow nozzles, and venturi tubes, including construction proportions and port locations. Multiple-nozzle 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 RP-2334\(^6\).

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\(^7\) 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 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\(^11\).

**F3.2 Thermodynamic Properties of Air.** Nozzle inlet density for dry and moist air shall be obtained from ASHRAE RP-1485\(^1\) using nozzle inlet absolute pressure, temperature, and humidity.

**Informative Note:** Software based upon ASHRAE RP-1485 is available.

**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\(^6\).

**F4.1 Multiple-Nozzle Throat Diameter.** If airflow operating temperatures are not within ±6°C (±10°F) 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 19.57 Section 3-10.

**F4.2 Multiple-Nozzle Reynolds Number.** The multiple-nozzle Reynolds number for each nozzle in use shall be obtained from Equation F-2.

$$Re_d = \frac{\rho_1 V d}{\mu_1}$$  \hspace{2cm} (F-2)

where

- $\rho_1 =$ nozzle inlet air density, kg/m³ (lbm/ft³)
- $V =$ nozzle throat average air velocity, m/s (ft/s)
- $d =$ nozzle throat diameter, m (ft)
- $\mu_1 =$ nozzle inlet dynamic viscosity, Ns/m² (lbm/s-ft)

**F4.3 Single- and Multiple-Nozzle Beta Ratio.** Based upon Reference 6, $\beta = 0$ for single- and multiple-nozzle chambers.

**F4.4 Multiple-Nozzle Limits of Use.** The nozzle geometry in Figure 18 fits into ASME’s long radius nozzle type, and the throat velocity requirement in Section 9.3.3.2 confirms that each nozzle will be operating within the long-radius nozzle limits prescribed by ASME.

**F4.5 Multiple-Nozzle Expansibility Factor.** The dimensionless expansibility factor $\varepsilon$ for a long radius nozzle is shown in Equation F-3.

$$\varepsilon = \left[ \frac{2}{r \gamma} \left( \frac{\gamma}{\gamma - 1} \left( \frac{1 - r^\gamma}{1 - r} \right) \left( \frac{1 - \beta^4}{1 - \beta r^\gamma} \right) \right) \right]^{1/2}$$  \hspace{2cm} (F-3)

where

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

For single- and multiple-nozzle chambers, substitution of $\gamma = 1.4$ and $\beta = 0$ into Equation F-3 results in Equation F-4. The single- and multiple-nozzle expansibility factor for each nozzle shall be obtained from Equation F-4.

$$\varepsilon = 1 - 0.548(1 - r)$$  \hspace{2cm} (F-4)

**F4.6 Multiple-Nozzle Discharge Coefficient.** Nozzle discharge coefficients shall be calculated for each nozzle in use from Equation F-5 using the Reynolds number from Equation F-2.

$$C = 0.99855 - \left[ \frac{7.006}{\sqrt{Re_d}} \right] + \left[ \frac{134.6}{Re_d} \right]$$  \hspace{2cm} (F-5)
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**

Volumetric Airflow Rate. The volumetric airflow rate for single- and multiple-nozzle shall be obtained from Equation F-6 in SI units or from Equation F-7 in I-P units where the area is measured at the plane of the throat taps or nozzle exit for nozzles without throat taps. The denominator in these equations includes the term $(1 - E \beta^4)$. However, $\beta = 0$ for single- and multiple-nozzles, so $(1 - E \beta^4) = 1$, and Equations F-6 and F-7 become Equations F-8 and F-9.

\[
Q = \left[ \sum_{i=1}^{N} (C_i A_i) \right] \frac{2 \Delta p}{\rho_1 (1 - E \beta^4)} \text{ m}^3/\text{s} \quad (F-6)
\]

\[
Q = \left[ \sum_{i=1}^{N} (C_i A_i) \right] \frac{2 \Delta p}{\rho_1 (1 - E \beta^4)} \text{ m}^3/\text{s} \quad (F-6)
\]

where
- $Q =$ volumetric flow rate, m$^3$/s
- $N =$ number of nozzles in use, dimensionless
- $C =$ discharge coefficient, dimensionless
- $A =$ nozzle throat area, m$^2$
- $\varepsilon =$ nozzle expansibility factor, dimensionless
- $\Delta p =$ nozzle differential pressure, Pa
- $\rho_1 =$ nozzle inlet air density, kg/m$^3$
- $E =$ flow kinetic energy coefficient = 1.043$^6$, dimensionless
- $\beta = 0$

**Informative Note:** The superscript “6” in “1.043$^6$” above is reference number, not an exponent.

\[
Q = 1097.8 \left[ \sum_{i=1}^{N} (C_i A_i) \right] \frac{\Delta p}{\rho_1 (1 - E \beta^4)} \text{ cfm} \quad (F-7)
\]

\[
Q = 1097.8 \left[ \sum_{i=1}^{N} (C_i A_i) \right] \frac{\Delta p}{\rho_1 (1 - E \beta^4)} \text{ cfm} \quad (F-7)
\]

where
- $Q =$ nozzle volumetric flow rate, cfm
- $N =$ number of nozzles in use, dimensionless
- $C =$ discharge coefficient, dimensionless
- $A =$ nozzle throat area, ft$^2$
- $\varepsilon =$ expansibility factor, dimensionless
- $\Delta p =$ nozzle differential pressure, (in. of water)
- $\rho_1 =$ nozzle inlet air density, lbm/ft$^3$
- $E =$ flow kinetic energy coefficient = 1.043$^6$, dimensionless
- $\beta = 0$
1097.8 = units conversion coefficient, dimensionless

**Informative Note:** The superscript “6” in “1.0436” above is reference number, not an exponent.

\[
Q = \left[\sum_{i=1}^{N}(C_i A_i)\right] \varepsilon \sqrt{\frac{2\Delta p}{\rho_1}} \text{ m}^3/\text{s} \quad (F-8)
\]

where
- \( Q \) = volumetric flow rate, m\(^3\)/s
- \( N \) = number of nozzles in use, dimensionless
- \( C \) = discharge coefficient, dimensionless
- \( A \) = nozzle throat area, m\(^2\)
- \( \varepsilon \) = nozzle expansibility factor, dimensionless
- \( \Delta p \) = nozzle differential pressure, Pa
- \( \rho_1 \) = nozzle inlet air density, kg/m\(^3\)
- \( \beta = 0 \)

\[
Q = 1097.8 \left[\sum_{i=1}^{N}(C_i A_i)\right] \varepsilon \sqrt{\frac{2\Delta p}{\rho_1}} \text{ cfm} \quad (F-9)
\]

where
- \( Q \) = nozzle volumetric flow rate, cfm
- \( N \) = number of nozzles in use, dimensionless
- \( C \) = discharge coefficient, dimensionless
- \( A \) = nozzle throat area, ft\(^2\)
- \( \varepsilon \) = expansibility factor, dimensionless
- \( \Delta p \) = nozzle differential pressure, (in. of water)
- \( \rho_1 \) = nozzle inlet air density, lbm/ft\(^3\)
- \( \beta = 0 \)

1097.8 = units conversion coefficient, dimensionless

**F4.8 Standard Airflow Rate for Single- and Multiple-Nozzle Chambers Standard Airflow Rate.** The standard airflow rate shall be calculated in compliance with Section 4.5 using Equation F-10 in SI units or Equation F-11 in SI units.

\[
\text{Standard Cubic Meters/Second} = \frac{\rho_1 Q}{1.202} \quad (F-10)
\]

\[
\text{Standard Cubic Feet/Minute (scfm)} = \frac{\rho_1 Q}{0.075} \quad (F-11)
\]

**F4.9 Mass Airflow Rate for Single- and Multiple-Nozzle Chambers Mass Airflow Rate.** The mass airflow rate for multiple-nozzle chambers shall be obtained from Equation F-12.
\[ \dot{m} = \rho_1 Q \quad \text{kg/s (lb}_m/\text{min)} \]  

(F-12)