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Standard Test Method for Volumetric and Mass Flow Rate Measurement in a Duct Using Tracer Gas Dilution¹

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1. Scope

1.1 This test method describes the measurement of the volumetric and mass flow rate of a gas stream within a duct, stack, pipe, mine tunnel, or flue using a tracer gas dilution technique. For editorial convenience all references in the text will be to a duct, but it should be understood that this could refer equally well to a stack, pipe, mine tunnel, or flue. This test method is limited to those applications where the gas stream and the tracer gas can be treated as ideal gases at the conditions of the measurement. In this test method, the gas stream will be referred as air, though it could be any another gas that exhibits ideal gas law behavior.

1.2 This test method is not restricted to any particular tracer gas although experimental experience has shown that certain gases are used more readily than others as suitable tracer gases. It is preferable that the tracer gas not be a natural component of the gas stream.

1.3 Use of this test method requires a knowledge of the principles of gas analysis and instrumentation. Correct use of the formulas presented here requires consistent use of units.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.* For specific precautionary statements, see Section 7.

2. Referenced Documents

2.1 ASTM Standards:²

D3154 [Test Method for Average Velocity in a Duct \(Pitot Tube Method\)](#)

D3464 [Test Method for Average Velocity in a Duct Using a Thermal Anemometer](#)

E631 [Terminology of Building Constructions](#)

2.2 ~~ANSI/ASME Standard:~~ ANSI/ASME Standards:³

ANSI/ASMETC 19.1-1985(1994) [Measurement Uncertainty: Instrument Apparatus](#)

ANSI/ASME TC 19.1-1985 (1994) [Measurement Uncertainty: Instrument Apparatus](#)

3. Terminology

3.1

3.1 Definitions:

3.1.1 For definitions of general terms related to building construction used in this test method, refer to Terminology E631.

3.2 Definitions of Terms Specific to This Standard:

3.1.1

3.2.1 *ideal gas, n*—a gas or gas mixture for which the ratio of the pressure divided by product of the density and temperature is a constant.

3.1.2

3.2.2 *mass flow, n*—the total mass of air passing the sampling point per unit time (kg/s, lb/min).

3.1.3

3.2.3 *tracer gas, n*—a gas that can be mixed with air and measured in very low concentrations.

3.1.4

3.2.4 *tracer gas analyzer, n*—a device that measures the concentration of tracer gas in an air sample.

¹ This test method is under the jurisdiction of ASTM Committee E06 on Performance of Buildings and is the direct responsibility of Subcommittee E06.41 on Air Leakage and Ventilation Performance.

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

³ Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, <http://www.ansi.org>.

3.1.5

3.2.5 tracer gas mass concentration, n —the ratio of the mass of tracer gas in air to the total mass of the air-tracer mixture. For an ideal gas, the mass concentration is independent of temperature and pressure.

3.1.6

3.2.6 tracer gas molar concentration, n —the ratio of the number of moles of tracer gas in air to the total number of moles of the air-tracer mixture.

3.1.7

3.2.7 tracer gas volume concentration, n —the ratio of the volume of tracer gas in air to the total volume of the air-tracer mixture. For an ideal gas, the volume concentration is independent of temperature and pressure and is equal to the molar concentration.

3.1.8

3.2.8 volumetric flow, n —the total volume of air passing the sampling point per unit time (m^3/s , ft^3/min).

3.2
3.3 Symbols:

C	= mass concentration ⁴ of tracer gas (ppb-mass, ppm-mass, ppt-mass)
C_U	= upstream mass concentration ⁴ of tracer gas (ppb-mass, ppm-mass, ppt-mass)
C_D	= downstream mass concentration ⁴ of tracer gas (ppb-mass, ppm-mass, ppt-mass)
C_I	= injection stream mass concentration ⁴ of tracer gas (ppb-mass, ppm-mass, ppt-mass)
c	= volume concentration ⁴ of tracer gas (ppb, ppm, ppt)
c_U	= upstream volume concentration ⁴ of tracer gas (ppb, ppm, ppt)
c_D	= downstream volume concentration ⁴ of tracer gas (ppb, ppm, ppt)
c_I	= injection volume concentration ⁴ of tracer gas (ppb, ppm, ppt)
F	= mass flow rate ⁵ (kg/s , g/min , lb/min)
F_I	= injection mass flow rate ⁵ (kg/s , g/min , lb/min)
F_U	= upstream mass flow rate ⁵ (kg/s , g/min , lb/min)
F_D	= downstream mass flow rate ⁵ (kg/s , g/min , lb/min)
f	= volumetric flow rate ⁵ (m^3/s , L/min , cfm)
f^{std}	= volumetric flow rate at standard conditions ⁵ (m^3/s , L/min , cfm)
f_I	= injection volumetric flow rate ⁵ (m^3/s , L/min , cfm)
f_U	= upstream volumetric flow rate ⁵ (m^3/s , L/min , cfm)
f_D	= downstream volumetric flow rate ⁵ (m^3/s , L/min , cfm)
f_I^{std}	= injection volumetric flow rate ⁵ at standard conditions (m^3/s , L/min , cfm)
f_U^{std}	= upstream volumetric flow rate ⁵ at standard conditions (m^3/s , L/min , cfm)
f_D^{std}	= downstream volumetric flow rate ⁵ at standard conditions (m^3/s , L/min , cfm)
ρ	= density ⁶ (kg/m^3 , g/L , lb/ft^3)
ρ_a	= density ⁶ of gas stream without any tracer (kg/m^3 , g/L , lb/ft^3)
ρ_t	= density ⁶ of the tracer gas (kg/m^3 , g/L , lb/ft^3)
ρ_I	= density ⁶ of the injection gas mixture (kg/m^3 , g/L , lb/ft^3)
ρ_U	= density ⁶ of the upstream gas mixture (kg/m^3 , g/L , lb/ft^3)
ρ_D	= density ⁶ of the downstream gas mixture (kg/m^3 , g/L , lb/ft^3)
ρ_U^t	= density ⁶ of the tracer gas at upstream conditions (kg/m^3 , g/L , lb/ft^3)
ρ_D^t	= density ⁶ of the tracer gas at downstream conditions (kg/m^3 , g/L , lb/ft^3)

4. Summary of Test Method

4.1 This test method describes the use of a tracer gas dilution technique to infer the volumetric flow rate through a duct. In practice, tracer gas is injected into a duct at a known mass or volumetric flow rate. Downstream of the injection point gas samples are taken and are analyzed for the resulting tracer concentration. The ratio of the injection flow rate and the downstream concentration represents the dilution volume per unit time or volumetric flow rate in the duct.

5. Significance and Use

5.1 The method presented here is a field method that may be used to determine mass and volume flow rates in ducts where flow conditions may be irregular and nonuniform. The gas flowing in the duct is considered to be an ideal gas. The method may be especially useful in those locations where conventional pitot tube or thermal anemometer velocity measurements are difficult or inappropriate due either to very low average flow velocity or the lack of a suitable run of duct upstream and downstream of the measurement location.

⁴ Equations in this test method assume that all mass or volume concentrations are in the same units.

⁵ Equations in this test method assume that all mass or volume flow rates are in the same units.

⁶ Equations in this test method assume that all densities are in the same units.

5.2 This test method can produce the volumetric flow rate at standard conditions without the need to determine gas stream composition, temperature, and water vapor content.

5.3 This test method is useful for determining mass or volumetric flow rates in HVAC ducts, fume hoods, vent stacks, and mine tunnels, as well as in performing model studies of pollution control devices.

5.4 This test method is based on first principles (conservation of mass) and does not require engineering assumptions.

5.5 This test method does not require the measurement of the area of the duct or stack.

5.6 The test method does not require flow straightening.

5.7 The test method is independent of flow conditions, such as angle, swirl, turbulence, reversals, and hence, does not require flow straightening.

5.8 The dry volumetric airflow can be determined by drying the air samples without measuring the water vapor concentration.

6. Apparatus

6.1 The apparatus includes a source of tracer gas, means for distributing the tracer gas in the duct, means for obtaining air samples from the duct, and a gas analyzer to measure tracer gas concentrations in the air samples.

6.2 *Tracer Gas*—See Appendix X1 for information on tracer gases and equipment used to measure their concentrations. Appendix X1 also contains tracer gas target concentrations and safety information.

6.3 *Tracer Gas Injection Source*—This normally is a cylinder of compressed tracer gas either pure or diluted in a carrier such as air or nitrogen. Tracer release from the cylinder is controlled by a critical orifice or nozzle, a metering valve, an electronic mass flow meter or mass flow controller, or other gas flow rate measurement and control device. A rotameter is not recommended for this measurement unless of special design, calibration, and a corresponding decrease in measurement accuracy is acceptable.

6.4 *Tracer Gas Distribution*—A single tube or a tubing network is inserted into the duct to dispense tracer gas. The tube or tubes may have either a single or multiple release points for tracer gas. For large cross-section ducts a network that distributes tracer gas over a wide area will facilitate measurement.

6.5 *Tracer Sampling*—This is performed using tubing inserted into the duct downstream of the injection point. A single tube is inserted into the duct. Air samples are removed from the duct by means of a sampling pump to distribute tracer laden air to the analyzer either directly or by means of syringe samples.

6.6 *Gas Analyzer*—This device must be suited for the tracer gas used and the concentrations expected in the duct being measured. It should be calibrated properly and exhibit an accuracy of better than $\pm 3\%$ at concentrations employed in the measurement.

7. Hazards

7.1 Safety is the responsibility of the user of this test method. Tracer gases have safe maximum concentration limits due to health and, in some cases, explosive potential. Table 1 presents, as a guide, the maximum allowable concentration in air for some tracer gasses that can be used for airflow measurements. The tracer gas supplier must provide a Material Safety Data Sheet (MSDS) that will provide information about health, fire, and explosion hazards.

7.2 *Health Limitations*—Use current OSHA information on the permissible exposure limit (PEL), or the ACGIH threshold limit value (TLV) if the particular tracer is not listed with a PEL, to determine the safe concentration for the gas chosen for the test. Never exceed the maximum safe concentration. It is good practice to use a concentration that is at most one tenth of the maximum safe concentration. Avoid using tracer gases for which no PEL or TLV exists.

7.3 *Compressed Gas Equipment*—Observe the supplier's safety information and CGA information on the transportation, use, and storage of compressed gas cylinders, regulators, and related equipment.

8. Procedure for Measuring Mass and Volumetric Flowrate

8.1 Inject tracer of known concentration, $C_I(c_I)$, and at a known rate, $F_I(f_I)$, into a flowing duct using procedures provided in Section 9.

8.1.1 If the tracer gas analyzer is field calibrated using a single point method, the injection rate, or injection concentration, or a combination thereof, should be adjusted to produce a concentration at the sample location that is the same as the calibration concentration to within $\pm 20\%$.

8.1.2 If the tracer gas analyzer is field calibrated using two calibration points, the injection rate, or injection concentration, or a combination thereof, should be adjusted to produce a concentration at the sample location that lies between the two calibration points.

8.1.3 If the tracer gas analyzer is field calibrated using more than two calibration points, the injection rate, or injection concentration, or a combination thereof, should be adjusted to produce a concentration at the sample location that lies at the approximate midpoint of the calibration range.

8.2 Obtain at least N measurements of the resulting concentrations, C_D^i , at least ten diameters, or equivalent hydraulic diameters for nonround cross section ducts, downstream of the injection at the center of $N-1$ equal areas of the duct cross section and one at the center of the duct. The number N is determined by Table 2 depending on the duct size.

8.3 If recirculation is possible or likely, N samples C_U^i in the center of duct upstream of the injection point should be taken within 10 s of the time a downstream sample is taken. If recirculation does not exist, take at least one upstream sample before and after taking the downstream samples.

TABLE 1 Tracer Gases and Safety Issues

Tracer Gas	TLV ^A	Toxicity	Chemical Reactivity	Comments
Hydrogen	Asphyxiant	Nontoxic	Highly reactive in presence of heat, flame, or O ₂	Fire and explosion hazard when exposed to heat, flame, or O ₂
Helium	Asphyxiant	Nontoxic	Inert	
Carbon Monoxide	25 ppm	Combines with hemoglobin to cause anoxia	Highly reactive with O ₂	Fire and explosion hazard when exposed to heat or flame
Carbon Dioxide	5000 ppm	Can be an eye irritant	Reacts vigorously with some metals; soluble in water	
Sulfur Hexafluoride	1000 ppm	Nontoxic	Inert	Thermal decomposition yields highly toxic compounds
Nitrous Oxide	25 ppm	Moderately toxic	Violent reaction with aluminum; water soluble	Can form explosive mixture with air; ignites at high temperature
Ethane	Asphyxiant	Nontoxic	Flammable	Incompatible with chlorine and oxidizing materials
Methane	Asphyxiant	Nontoxic	Flammable	Incompatible with chlorine and oxidizing materials
Octafluorocyclobutane (Halocarbon C-318)	1000 ppm	Low toxicity	Nonflammable	Thermal decomposition yields highly toxic compounds
Bromotrifluoromethane (Halocarbon 13B1)	500 ppm	Moderately toxic by inhalation	Incompatible with aluminum	Dangerous in a fire
Dichlorodifluoromethane (Halocarbon 12)	1000 ppm	Central nervous system and eye irritant; can be narcotic at high levels	Nonflammable; can react violently with aluminum	Thermal decomposition yields highly toxic compounds
Dichlorotetrafluoromethane (Halocarbon 116)	1000 ppm	Can be asphyxiant, mildly irritating, narcotic at high levels	Can react violently with aluminum	Thermal decomposition yields highly toxic compounds

^A *Threshold Limit Values for Chemical Substances in the Work Environment*, American Conference of Governmental Industrial Hygienists (ACGIH), 1997.

TABLE 2 Minimum Number of Down Stream Sample Locations

Duct Cross Sectional Area m ² (ft ²)	Number of Areas	Number of Samples
Less than 0.2 (2)	4	5
0.2 to 2.3 (2 to 25)	12	13
Greater than 2.3 (25)	20	21

8.4 At each time a downstream sample is taken, the injection flow rate F_I^i shall be recorded.

8.5 Calculate the following quantities in either mass, volume, or dry concentration depending on results desired:

8.5.1 The average downstream concentration C_D :

$$C_D = \frac{1}{N_D} \sum_{i=1}^{N_D} C_D^i \quad (1)$$

where N_D is the number of downstream sample locations.

8.5.2 The average upstream concentration C_U :

$$C_U = \frac{1}{N_U} \sum_{i=1}^{N_U} C_U^i \quad (2)$$

where N_U is the number of upstream sample locations.

8.5.3 The average injection flow F_I (or the corresponding volumetric flow rate):

$$F_I = \frac{1}{N_I} \sum_{i=1}^{N_I} F_I^i \quad (3)$$

where N_I is the number of flow rate measurements.

8.5.3.1 The mass flow rate in the duct is given by:

$$F_U = \frac{(C_I - C_D)}{(C_D - C_U)} F_I \quad (\text{mass concentrations}) \quad (4)$$

8.5.3.2 The volumetric flow rate in the duct is given by:

$$f_U = \frac{(C_I - C_D)}{(C_D - C_U)} \cdot \frac{\rho_I}{\rho_U} \cdot f_I \text{ (mass concentrations)} \quad (5)$$

$$f_U = \frac{c_I - r_{na}c_D - (1 - r_{na})c_Ic_D}{c_D - c_U} \cdot \frac{\rho_I^I}{\rho_U^I} \cdot f_I \text{ (volume concentrations)} \quad (6)$$

where $r_{na} \equiv \frac{\rho_n}{\rho_a}$ is the ratio of the density of the main constituent of the injection gas mixture to the density of the gas stream without any tracer. If $c_I = 1$, then $r_{na} = 1$.

8.6 The volumetric flow rate in the duct at standard conditions is given by:

$$f_U^{std} = \frac{c_I - r_{na}c_D - (1 - r_{na})c_Ic_D}{(c_D - c_U)} \cdot f_I^{std} \text{ (volume concentrations)} \quad (7)$$

8.7 The dry gas flow rate in the duct at standard conditions is given by:

$$f_U^{(d)std} = \frac{c_I}{(c_D^{(d)} - c_U^{(d)})} \cdot f_I^{std} \text{ if } \frac{c_I}{c_D} < 0.001 \text{ (dry volume concentrations)} \quad (8)$$

where the superscript (*d*) refers to quantities at dry conditions.

8.7.1 Dry volume concentrations are obtained by drying the gas sample before analysis. It is important that the drying technique used should not remove any of the tracer gas. This can be checked by drying a sample of the calibration standard using the drying techniques and comparing the measured dry concentrations with the calibration standard. The two concentrations should be the same within the precision of the analyzer as determined in Appendix X2.

9. Procedures for Injecting Tracer Gas

9.1 Inject tracer gas at a known, constant rate using metered injection. To accomplish this a critical orifice, critical orifice metering valve, an electronic mass flow meter or an electronic mass flow controller may be used in conjunction with a source of pure or diluted tracer gas. The flow measuring device shall be calibrated and its accuracy certified by a method that is traceable to NIST. The calibration shall be performed with an injection gas of the same approximate concentration as will be used in an actual measurement.

9.1.1 Reliance on scale factors to convert a flow meter calibration using one gas to predict the calibration on a second gas is not acceptable unless the accuracy of the conversion factor has been demonstrated experimentally for the type of meter used.

9.1.2 The total uncertainty (uncertainty in flowrate and uncertainty in injection concentration) in the tracer gas injection rate shall be less than 3 %. The bias of the assumed injection rate shall be no more than 3 % of the true rate.

9.2 Injection of tracer gas may be via a single tube or via a manifold consisting of several tubes connected to the flow injection metering device. In the case of a manifold, flow through each branch of the manifold should be approximately equal. The tube or tubes may have either a single or multiple release points for tracer gas.

10. Procedures for Sampling Tracer Gas

10.1 Sampling is performed using a single tube connected to a pump that draws air samples to the exterior of the duct for analysis. Use a separate sampling tube for the downstream and for the upstream air sample.

10.2 Samples of air may be routed directly to the analyzer or grab samples using syringes, sample bags, or other appropriate containers may be taken for subsequent analysis.

10.3 If good mixing⁷ is not obtained, enhance the mixing by one of the following procedures:

10.3.1 Move⁸ the sample point further downstream from the tracer injection point. When flowing air encounters a rapid change in direction, mixing within the duct is assisted; hence, moving the sample point to a location past one or more bends in the flow will enhance mixing.

10.3.2 Move⁸ the tracer injection point further upstream from the sample point. When flowing air encounters a rapid change in direction, mixing within the duct is assisted; hence, moving the injection point to a location past one or more bends in the flow will materially enhance mixing. Often moving the injection point upstream of an air handling fan can enhance mixing. Note that centrifugal fans are not as efficient at mixing as are vaneaxial fans.

10.3.3 Enhance the uniformity of the tracer injection by increasing the number of injection tubes or the number of injection holes in each tube.

11. Tracer Gas Analysis Requirements

11.1 The tracer gas analyzer shall be calibrated using calibration standards that bracket the anticipated measured concentration using the procedures given in Appendix X2.

⁷ The lack of good mixing results in an increase in the uncertainty in the determination of the duct airflow rate (see Eq 11). Good practice usually results in a variation in tracer concentration across the duct of less than 10 %.

⁸ In moving the sample or injection locations, care should be taken so that there is no leakage into or out of the duct between the point of injection and the downstream sample locations.

11.2 Determine the accuracy of the gas analyzer in order to estimate the accuracy of a given concentration reading. Calibrate the analyzer with several tracer gas concentration standards to estimate bias. Biases of samples exhibiting low tracer gas concentrations (relative to the ultimate sensitivity of the analyzer) and deviations in the detector response from the empirical relationship between concentration and analyzer output all affect the accuracy of the gas analyzer. A gas analyzer whose bias is less than 1 % for all concentrations encountered in the measurement may be assumed to be unbiased for the purpose of this test method.

11.3 The precision of the gas analyzer is a measure of reproducibility. Make an estimate of the precision of the gas analyzer by using replicate measurements. See Appendix X2 for details on assessing analyzer precision.

11.4 The zero concentration response of the gas analyzer shall be demonstrated by injecting a zero tracer concentration air mixture into the analyzer and noting the analyzer response, if any.

11.5 It must be demonstrated using the procedure of Appendix X3 that the gas analyzer response is not affected by potential interference due to other gases that may be present in the duct. To demonstrate this one can sample the duct in the absence of tracer and note the analyzer response, if any.

12. Calculation of Test Errors

12.1 The uncertainty of the test results depends on the instrumentation used and on the mixing obtained in the test. The bias, ΔF , of the results is given by the following equation:

$$\frac{\Delta F}{F} = \sqrt{\left(\frac{\Delta C_I}{C_I}\right)^2 + \left(\frac{\Delta F_I}{F_I}\right)^2 + \frac{(\Delta C_D)^2 + (\Delta C_U)^2}{(C_D - C_U)^2}} \quad (9)$$

where:

ΔC_I = the uncertainty in the injection gas concentration,

ΔF_I = the uncertainty in the injection flow rate,

ΔC_D = the calibration uncertainty in the downstream concentration (Appendix X2), and

ΔC_U = the calibration uncertainty in the upstream concentration (Appendix X2).

12.2 The precision ∂F in the flow is given by the following equation:

$$\frac{\partial F}{F} = t(N-1, 0.95) \sqrt{\frac{\partial F_I^2}{(F_I)^2} + \frac{\partial (C_D - C_U)^2}{(C_D - C_U)^2}} \quad (10)$$

where:

$\partial F_I^2 = \frac{1}{N-1} \sum_{i=1}^N (F_I^i - F_I)^2$ is the square of the standard deviation of the injection flow rate, and

$\partial (C_D - C_U)^2 = \frac{1}{N-1} \sum_{i=1}^N (C_D^i - C_U^i - C_D + C_U)^2$ is the square of the standard deviation of the difference in the downstream and upstream tracer concentration and $t(N-1, 0.95)$ is the two-sided confidence limits of the Student Distribution for $N-1$ and probability 0.95.

The total uncertainty, $\frac{\partial_T F}{F}$, is the square root of the sum of the squares of the bias and the precision.

$$(11) \quad \partial TFF = (\Delta FF)^2 + (\partial FF)^2$$

12.3 Note that Eq 11 is equivalent to the measurement uncertainty derived in ANSI/ASME TC 19.1–1985 (1994).

13. Precision and Bias

13.1 The precision and error of the test results depend on the precision and error of the instrument and tracer gases used. The precision and bias in this test method can be assessed using the error analysis of Section 12 if the precision and error of each instrument and tracer gas is known.

14. Keywords

14.1 ducts; flow rate; mass flow; stacks; tracer gas; volumetric flow