Designation: D3154 – 00(Reapproved 2006)

Standard Test Method for Average Velocity in a Duct (Pitot Tube Method)[1]

This standard is issued under the fixed designation D3154; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method describes measurement of the average velocity of a gas stream for the purpose of determining gas flow in a stack, duct, or flue. Although technically complex, it is generally considered the most accurate and often the only practical test method for taking velocity measurements.

1.2 This test method is suitable for measuring gas velocities above 3 m/s (10 ft/s).

1.3 This test method provides procedures for determining stack gas composition and moisture content.

1.4 The values stated in SI units are to be regarded as standard. The inch-pound units given in parentheses are for information only.

1.5 This test method is applicable to conditions where steady-state flow occurs, and for constant fluid conditions. If these conditions are not meant, other methods must be used.

1.6 *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 determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1071 Test Methods for Volumetric Measurement of Gaseous Fuel Samples
D1193 Specification for Reagent Water
D1356 Terminology Relating to Sampling and Analysis of Atmospheres
D3195 Practice for Rotameter Calibration
D3631 Test Methods for Measuring Surface Atmospheric Pressure
D3685/D3685M Test Methods for Sampling and Determination of Particulate Matter in Stack Gases
D3796 Practice for Calibration of Type S Pitot Tubes
E1 Specification for ASTM Liquid-in-Glass Thermometers
E337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)

2.2 *EPA Standards:*

EPA-600/9-76-005 Quality Assurance Handbook for Air Pollution Measurement Systems. Vol I. Principles[3]
EPA-600/4-77-027b Quality Assurance Handbook for Air Pollution Measurement Systems. Vol. III. Stationary Source Specific Methods[3]

2.3 *ASME Standards:*

ASME Performance Test Code: PTC 19.10-1968, Flue and Exhaust Gas Analysis[4]
ASME Performance Test Code: PTC 19.10-1981 Part 10, Flue and Exhaust Measurements: Instruments and Apparatus[4]
ASME Performance Test Code: PTC 38-1980, Determining the Concentration of Particulate Matter in a Gas Stream[4]

2.4 *Code of Federal Regulation:*

CFR Part 50 Standards of Performance for Stationary Sources, Appendix A; Test Methods 1 through 4[3]

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of terms used in this test method, refer to Terminology D1356.

3.2 *Descriptions of Symbols Specific to This Standard:*

A = cross-sectional area of stack, m^2 (ft^2).
B_{ws} = water vapor in the gas stream, proportion by volume.
C_p = pitot tube coefficient, dimensionless.
D_s = internal diameter of stack, cm, (in.).
K_p = pitot tube constant:
$= 128.9\ \text{m/s} \left[\frac{(g/g-mol)}{(K)} \right]^{1/2}$, (SI),

[1] This test method is under the jurisdiction of ASTM Committee D22 on Air Quality and is the direct responsibility of Subcommittee D22.03 on Ambient Atmospheres and Source Emissions.

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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 U.S. Government Printing Office Superintendent of Documents, 732 N. Capitol St., NW, Mail Stop: SDE, Washington, DC 20401.

[4] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Three Park Ave., New York, NY 10016-5990.

= $85.29 \text{ ft/s} \left[\frac{(\text{lb/lb} - \text{mol})}{(R)} \right]^{1/2}$, (inch-pound).

m = mean velocity, m/s (ft/s).
M_d = molecular weight of stack gas, dry basis, g/g – mol (lb/lb – mol).
M_s = molecular weight of stack gas, wet basis, g/g – mol (lb/lb – mol).
M_w = molecular weight of water, 18.0 g/g – mol (18.0 lb/lb – mol).
N = number of sampling points across a diameter.
n = nth sampling point from center of stack.
Δp = velocity head of stack gas, kPa (in. water).
P_{static} = static pressure of stack gas, kPa (in. water).
P_{bar} = barometric pressure, kPa (in. Hg).
P_m = absolute pressure at the dry gas meter (for this test method it equals P_{bar}), kPa (in. Hg).
P_s = absolute stack gas pressure, kPa (mm Hg).
P_{std} = standard ambient atmospheric pressure, 101.3 kPa (760 mm Hg).
% CO_2 = percent CO_2 in the stack gas, by volume, dry basis.
$\%(N_2 + CO)$ = sum of the percents of N_2 and CO in the stack gas, by volume, dry basis.
$\%O_2$ = percent O_2 in the stack gas, by volume, dry basis.
Q_{std} = dry volumetric stack gas flow rate corrected to standard conditions, $d\text{sm}^3$/h ($d\text{sft}^3$/h).
R = ideal gas constant, 0.08312 (kPa) (m^2)/g – mol) (K) – (SI system) or 21.85 (in. Hg) (ft^2)/(lb – mole) (°R) – (inch-pound).
r_n = radial distance from center of stack to nth sampling point, cm (in.).
ρ_w = density of water, 0.9971 g/mL (0.002194 lb/mL) at 25°C (77°F).
S_T = between laboratory bias, m/s (ft/s).
S_s = among single laboratory bias, m/s (ft/s).
T_m = absolute average dry gas meter temperature, K (°R).
T_s = stack gas temperature, K (° R).
T_{std} = standard absolute temperature, 298 K (537° R).
V_i = initial volume of condenser water, mL.
V_f = final volume of condenser water, mL.
V_m = volume of gas sample measured by the dry gas meter, $d\text{m}^3$ ($d\text{ft}^3$).
v_s = stack gas velocity, m/s (ft/s).
$V_{m(std)}$ = volume of gas sample measured by the dry gas meter, corrected to standard conditions, $d\text{m}^3$ ($d\text{ft}^3$).
$V_{wc(std)}$ = volume of water vapor condensed, corrected to standard conditions, $s\text{m}^3$ ($s\text{ft}^3$).
$V_{wsg(std)}$ = volume of water vapor collected in silica gel, corrected to standard conditions, $s\text{m}^3$ ($s\text{ft}^3$).
W_f = final mass of silica gel or silica gel plus impinger, g.

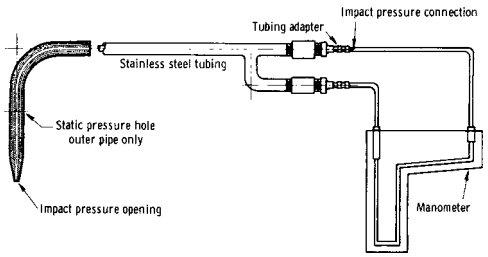


FIG. 1 Pitot Tube

W_i = initial mass of silica gel or silica gel plus impinger, g.
Y = dry gas meter calibration factor.
0.28 = molecular weight of nitrogen or carbon monoxide, divided by 100.
0.32 = molecular weight of oxygen, divided by 100.
0.44 = molecular weight of carbon dioxide, divided by 100.
3600 = conversion factor, s/h.

4. Summary of Test Method

4.1 This test method describes the use of instrumentation, equipment, and operational procedures necessary for the measurement and calculation of the average velocity of air or gas flows in flues, ducts, or stacks utilizing the pitot tube principle, with a manometer or draft gauge for pressure measurement. The stack gas composition and moisture content are determined, using an Orsat analyzer for composition, and condensation techniques for moisture.

5. Significance and Use

5.1 The procedures presented in this test method are available, in part, in Test Method D3685/D3685M, as well as the ASME Methods given in 2.3 and Footnote 8,[5] the CFR given in 2.4, and the publication given in Footnote 9.[6]

6. Apparatus

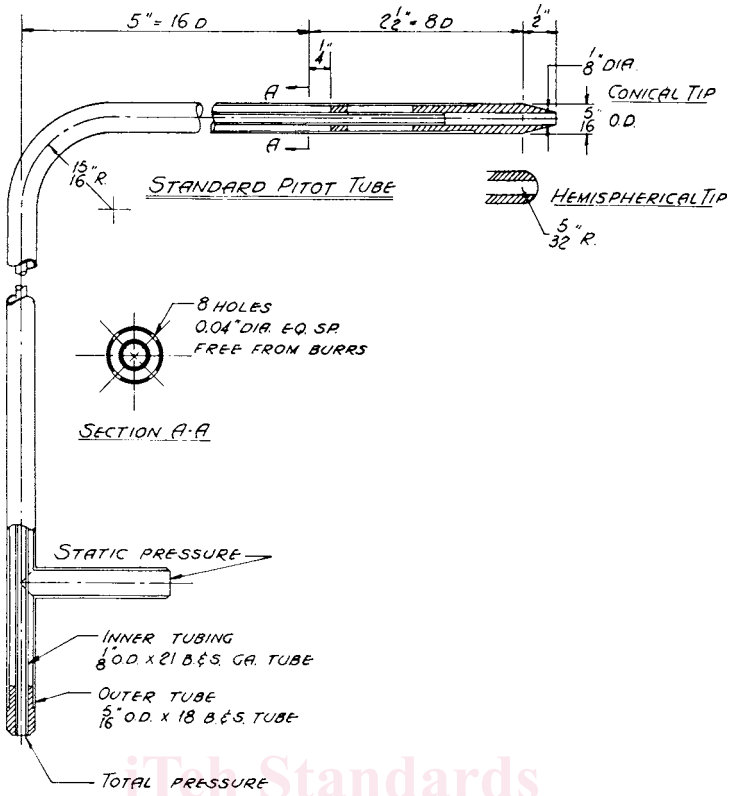
6.1 *Pitot Tube,* used in conjunction with a suitable manometer, provides the method for determining the velocity in a duct. The construction of a standard pitot tube and the method of connecting it to a draft gauge are shown in Fig. 1. Details are shown in Fig. 2.

6.1.1 To minimize the stem effect when the physical dimensions of the pitot tube are too large with respect to the flow scale, the diameter of the pitot tube barrel shall not exceed 1/30 the size of the duct diameter.

6.1.2 At locations where the standard pitot tube cannot be used in accordance with the sampling plan (see 8.1), or where dust or moisture or both are present that may clog the small

[5] Colen, P., Corey, R. C., and Meyers, J. W., "Methods and Instrumentation for Furnace Heat Absorption Studies; Temperature and Composition of Gases at Furnace Outlets" Transaction of the American Society of Mechanical Engineers, *71*, pp. 965–78, 1949.

[6] Bulletin WP-50, Western Precipitation Division, Joy Manufacturing Co., "Methods for Determination of Velocity, Dust, and Mist Content of Gases."



Metric Equivalents

in.	mm	in.	mm
⅛	3.2	½	12.7
5/32	4.0	15/16	23.8
¼	6.4	2½	63.5
5/16	7.9	5	127

FIG. 2 Standard Pitot Tube Details

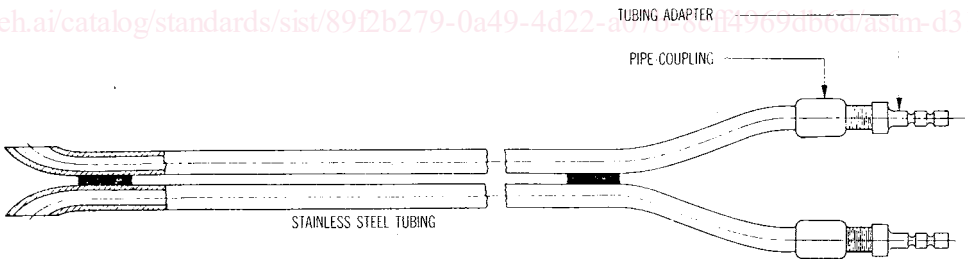


FIG. 3 Type 3 Pitot Tube (Special)

holes in this instrument, a calibrated Staubscheibe pitot tube, commonly called a Type "S" pitot tube, shown in Fig. 3, shall be used.

6.1.3 The Type "S" pitot tube may be used in all applications, provided that it has been calibrated. See Practice D3796. However, use of the standard pitot tube, where feasible, will give additional accuracy.

6.2 *Differential Pressure Gauge*—A liquid-filled inclined manometer or an equivalent device used to measure the velocity head. See Fig. 1. It is equipped with a 250 mm (10 in.) water column inclined manometer that has 0.25 mm (0.01 in.) divisions on the 0-to-25 mm (1 in.) inclined scale, and 2.5 mm (0.1 in.) divisions on the 25 to 250-mm (1 to 10-in.) vertical scale. This type manometer (or other gauge of equivalent sensitivity) is satisfactory for measurements of Δp values as low as 12.5 Pa (0.05 in. H_2O).

6.3 *U-Tube Manometer*—A water or mercury filled instrument capable of measuring stack pressures to within 0.33 kPa (2.5 mm Hg).

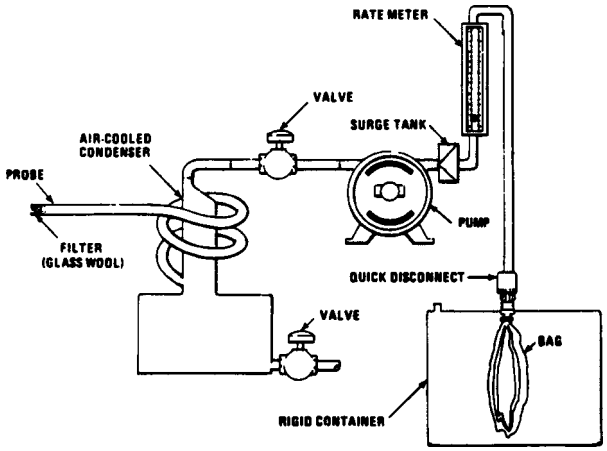


FIG. 4 Integrated Gas Sampling Train

6.4 *Thermocouple*—A device for measuring temperature utilizing the fact that a small voltage is generated whenever two junctions of two dissimilar metals in an electric circuit are at different temperature levels.

6.4.1 *Potentiometer*—An instrument for measuring small voltages, or for comparing small voltages with a known voltage, used in conjuncture with the thermocouple.

6.4.2 *Thermometer*—An ASTM thermometer meeting the requirements of Specification E1, for measuring the gas temperatures of small ducts.

6.5 *Mercury Barometer*—An instrument capable of measuring ambient atmospheric pressure to 0.5 kPa. See Test Methods D3631.

6.6 *Gas Density Determination Equipment*—See Fig. 4.

6.6.1 *Probe*—A stainless steel or borosilicate glass tube, equipped with an in-stack or out-of-stack filter to remove particulate matter.

6.6.2 *Condenser*—A water-cooled condenser that will not remove O_2, CO_2, CO, and N_2, to remove excess moisture if the gas stream contains over 2 % moisture by volume. The main consideration is that the condenser volume be kept to the minimum size because it will be more difficult to purge the sample train before collecting a sample if the condenser is too large. A 63-mm (0.25-in.) stainless steel coil, or equivalent, connected to a water collection chamber with a capacity of about 40 mL is sufficient.

6.6.3 *Valve*—A needle valve to adjust the sample gas flow rate.

6.6.4 *Pump*—A leak-free diaphragm pump, to transport the sample gas to the flexible bag. A small surge tank shall be installed between the pump and the rate meter to eliminate the pulsation effect of the pump on the rate meter. Leak-test the pump, surge tank and rate meter (see 6.6.5), as described in 9.4.2.

6.6.5 *Rate Meter*—A rotameter or equivalent rate meter, capable of measuring flow rates to within ±2 % of the selected flow rate.

6.6.6 *Flexible Bag*—A leak-free inert plastic bag, having the capacity adequate for the selected flow rate and length of time of the test. A capacity of 90 L (3.2 ft^3) is usually sufficient. The bag shall be leak-tested before each test, as described in 9.4.3.

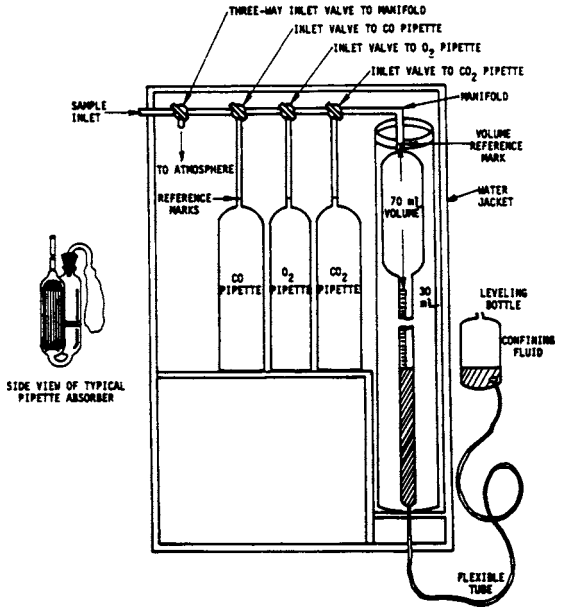


FIG. 5 Orsat Apparatus

6.6.7 *Vacuum Gauge*—A mercury manometer, or equivalent of 101.3 kPa (760 mm Hg) capacity, to be used for the sample train leak test. Test the gauge as described in 9.4.5.

6.6.8 *Orsat Gas Analyzer*—See Fig. 5. The Orsat gas analyzer is used to analyze the gas sample for CO_2, O_2, and CO stack gas concentrations, by successively passing the gas through adsorbents that remove the specific gaseous components. The difference in gas volumes before and after the absorptions represents the amount of constituent gas in the sample.

6.6.8.1 The analyzer shown in Fig. 5 includes a glass buret to measure the gas volume of the sample, a water jacket to maintain constant temperature, a manifold to control the gas flow, three absorption pipets (to remove CO_2, O_2, and CO), rubber expansion bags, and a liquid-filled leveling bottle to move the gas sample within the analyzer.

6.6.8.2 For CO_2 values >4 %, a standard Orsat gas analyzer with a buret with 0.2 mL divisions and spacings divisions of about 1 mm (0.14 in.) is satisfactory. For lower CO_2 values or for O_2 values >15 %, a buret with 0.1 mL divisions with spacings of >1 mm shall be used.

6.6.8.3 The analyzer shall be leak-tested before and after each test, as described in 9.4.1.1.

6.7 *Gas Moisture Measuring Equipment*— See Fig. 6.

6.7.1 *Probe*—See 6.6.1.

6.7.1.1 *Probe Heater*—A heating system to maintain the exit gas stack temperature at 120 ± 14°C (250 ± 25°F) during sampling.

6.7.1.2 The probe shall be checked for breaks and leaks before each test, and the heater shall be checked to verify that it can maintain an exit air temperature of 100°C (212°F) when air is passed through the system at about 20 L/min (0.75 ft^3/min).

6.7.2 *Condensers*—Four glass impingers connected in series with leak-free ground-glass fittings or equivalent leak-free noncontaminating fittings.

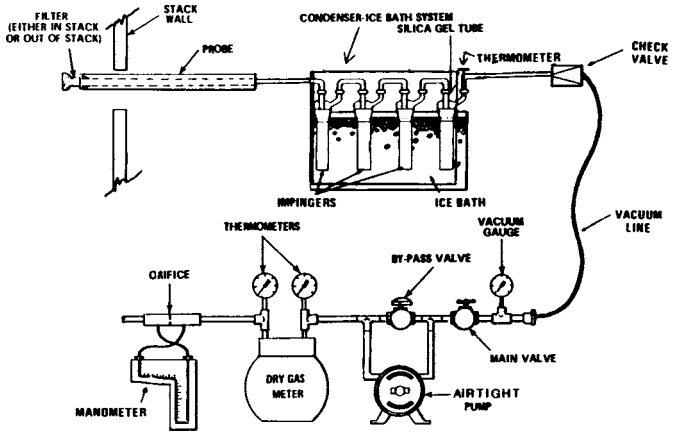


FIG. 6 Moisture Sampling Train

6.7.2.1 The first, third and fourth impingers shall be a Greenburg-Smith type, modified by replacing the inserts with unconstricted 13 mm (0.5 in.) inside diameter glass tube extending to within 13 mm of the flask bottom. The second impinger shall be of the standard Greenburg-Smith type.

6.7.2.2 The fourth impinger outlet connecting shall be such that it will allow insertion of a temperature gauge. See 6.7.3.

6.7.2.3 The standard Greenburg-Smith impinger shall be tested before use by allowing water to drain from the inner tube. If water does not drain from the filled inner tube within 8 s, replace the impinger.

6.7.3 *Temperature Gauge*—A thermometer capable of measuring within 1°C (2°F), and located at the outlet of the fourth impinger. See 6.7.2.2 and Specification E1.

6.7.4 *Cooling System*—An ice bath condenser with crushed ice to contain the impingers and to condense the moisture in the sample gas stream.

6.7.5 *Metering System*—A metering system, consisting of a vacuum gauge, leak-free vacuum pump, thermometers, a dry gas meter, differential pressure gauge and related equipment. See Test Method D3685/D3685M for details of this system.

6.7.5.1 The system shall be leak-tested before and after each test, at both positive and negative pressures, following the directions in 9.5.4.

6.7.6 *Barometer*—See 6.5.

6.7.7 *Graduated Cylinder or Triple Beam Balance or Both,* to measure the water condensed in the impingers. Accuracy shall be ± 1 mL or ± 1 g. Cylinder shall be Class A, 250 mL, with ≤2 mL subdivisions.

6.7.8 *Stack Gas Temperature Sensor*—A thermocouple or equivalent, to measure stack gas temperature to within ±1°C (2°F) when the stack gas is suspected of being saturated or containing water droplets.

7. Reagents and Materials

7.1 *Purity of Reagents*—Reagent grade chemicals shall be used in all tests. All reagents shall conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society where such specifications are available.[7]

7.2 *Purity of Water*—Water shall be Type 2 reagent water, conforming to Specification D1193.

7.3 *Alkaline Pyrogallic Acid Reagent,*[8]used as O_2 absorption solution. Mix 40 mL of pyrogallic acid solution (see 7.9) with 69 mL of KOH solution (see 7.8). Mix just before use. In cold weather, some KOH may precipitate. If so, add enough water to redissolve the KOH.

7.4 *Confining Solution*[8]—Add 200 g of sodium sulfate (Na_2SO_4) (see 7.11) to 50 mL of concentrated sulfuric acid (H_2SO_4) (see 7.12), and add a few drops of methyl orange indicator solution (see 7.7). Dilute to 1 L.

7.5 *Cuprous Chloride Solution,*[8](135 g/L)—Dissolve 180 g of cuprous chloride (Cu_2Cl_2) in 1 L of concentrated HCl (see 7.6). Add 330 mL of water, and boil gently in a loosely covered flask containing coils of sheet copper until the color disappears. Cool and transfer to a stock bottle, containing a few pieces of copper coil or wire. This solution is used for absorbing CO.

7.6 *Hydrochloric Acid (Concentrated),* HCl, sp. gr. 1.19.

7.7 *Methyl Orange Indicator Solution*— Dissolve 0.1 g of the sodium salt of para-dimethylaminoazobenzene-sulfonic acid (methyl orange) in water, and dilute to 100 mL.

7.8 *Potassium Hydroxide Solution,*[8](355 g/L)—Dissolve 355 g potassium hydroxide (KOH) (cp electrolytic, not purified with alcohol) in water and dilute to 1 L. If a precipitate forms, pour off the clear liquid after settling. Keep the solution in a rubber-stoppered stock bottle. It is used as the CO_2 absorbing reagent.

7.9 *Pyrogallic Acid Solution*, (740 g/L)—Dissolve 200 g of white resublimated pyrogallic acid (pyrogallol or 1,2,3-trihydroxybenzene) in 270 mL of water warm enough to dissolve the pyrogallic acid. Cool to room temperature, and transfer to a rubber-stoppered stock bottle.

7.10 *Silica Gel*—Water-absorbing crystals, indicating.

7.11 *Sodium Sulfate,* (Na_2SO_4).

7.12 *Sulfuric Acid* (Concentrated), H_2SO_4, sp. gr. 1.84.

8. Sampling

8.1 *Selection of Sampling Site*—Select a sampling site that is at least eight stack or duct diameters downstream and two diameters upstream from any bend, expansion, contraction, or visible flame.

[7] *Reagent Chemicals, American Chemical Society Specifications*, American Chemical Society, Washington, DC. For suggestions on the testing of reagents not listed by the American Chemical Society, see *Analar Standards for Laboratory Chemicals*, BDH Ltd., Poole, Dorset, U.K., and the *United States Pharmacopeia and National Formulary*, U.S. Pharmacopeial Convention, Inc. (USPC), Rockville, MD.

[8] See ASME Performance Test Code: PTC 19.10-1968. This edition is referenced because the 1981 edition does not describe preparation of the Orsat reagents. The PTC also describes other solutions that may be used.

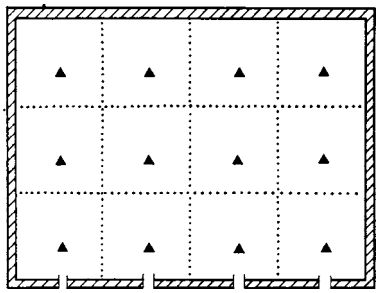


FIG. 7 Traverse Positions and Rectangular Flue

8.1.1 If the above is impractical, select a site that comes as close as possible to meeting the above conditions.

8.1.2 If there is a possibility of cyclonic or non-linear flow, perform a cyclonic flow test as described in EPA-600/4-77-027b, Section 3.0.1.

8.2 In rectangular ducts, divide the cross-sectional area into equal rectangular subareas as shown in Fig. 7. The number of areas to be used depends on the flow pattern and duct size. Use Table 1 to find the minimum number of areas when sampling at least eight equivalent diameters downstream and two equivalent diameters upstream from the nearest flow disturbance. The equivalent diameter is as follows:

$$2\,(length \times width)/(length + width) \quad (1)$$

If a site less than eight diameters downstream and two diameters upstream from a flow disturbance is used increase the number of sampling points in accordance with 8.5.

8.3 In circular stacks or ducts divide the area concentrically as shown in Fig. 8. The minimum number of areas to use and the distance to the test point is shown in Table 2 or may be calculated as follows:

$$r_n = D_s\sqrt{\frac{(2n-1)}{4N}} \quad (2)$$

Conduct traverses across two diameter axes at right angles to each other. Again, if a site less than eight diameters downstream and two diameters upstream from a flow disturbance is used, increase the number of sampling points as noted in 8.8.

8.4 When sampling must be done in an irregular-shaped duct, divide the duct into equal areas of any shape, and measure the parameters at the centroid of each area.

8.5 Increase the number of sampling points when sampling less than eight diameters downstream and two diameters upstream from any flow disturbance. When only four to six diameters of straight duct are available, double the number of points used. Sampling sites less than four diameters downstream from any flow disturbance are special cases and each case shall be determined on its own merits in the field. Where sampling sites are less than two diameters downstream from any flow disturbances, reasonable accuracy with pitot tube measurements cannot be expected and another method for stack gas quantitation should be sought.

8.6 The velocity distribution shall be uniform throughout the traverse plane, such that 80 to 90 % of the measurements (11.1) are greater than 10 % of the maximum velocity. If less than 75 % of the measurements are greater than 10 % of the maximum velocity, choose an alternate sampling location.

TABLE 1 Minimum Number of Measurements for Rectangular Ducts

Cross Sectional Area of Sampling Sites, m^2 (ft^2)	Number of Measurements
Less than 0.2 (2)	4
0.2 to 2.3 (2 to 25)	12
Greater than 2.3 (25)	20

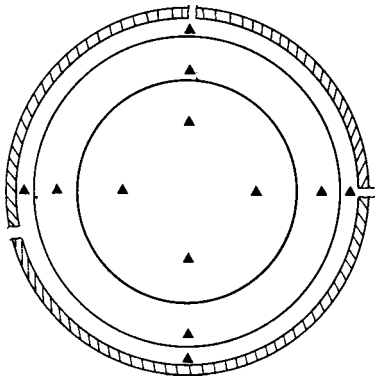


FIG. 8 Traverse Positions and Round Flue

8.7 The flow stream shall be at a right angle, ±10°, to the traverse plane.

8.7.1 Determine the angle of the flowstream by measuring the orientation of the pitot tube that produces the maximum velocity pressure value.

8.8 If the traverse plane is in the vicinity of a fan, locate it to minimize the effects of leakage in the portion of the system located between the fan and the traverse point.

8.9 Locate the traverse plane at the tip of the pitot tube, particularly when the plane must be in a converging or diverging duct.

9. Preparation of Apparatus

9.1 *Preparation of Pitot Tube*—A simple method for marking off the pitot tube for use in taking a velocity traverse is as follows:

9.1.1 Slide the pitot tube all the way through the sampling port, until the tip touches the far wall of the stack and the tip is aligned with the gas stream. Using a china marker or other suitable means, mark the pitot tube at a point immediately adjacent to the sampling port fitting.

9.1.2 Slide the pitot tube out of the port until the tip is even with the inner wall of the stack. Again mark the pitot tube at a point immediately adjacent to the sampling port fitting.

9.1.3 The distance between the two lines is the internal diameter of the stack (D_s). Mark the centerline halfway between these two points.

9.1.4 Mark the traverse points on the pitot tube after referring to Table 2 or use Eq 2. (It is advisable to mark the traverse points in one manner and the centerline and end points in a different manner.)