Designation: D 3154 – 91 (Reapproved 1995)

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~~An American National Standard~~

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

This standard is issued under the fixed designation D 3154; 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:*

D 1071 Test Methods for Volumetric Measurement of Gaseous Fuel Samples[2]

D 1193 Specification for Reagent Water[3]

D 1356 Terminology Relating to Sampling and Analysis of Atmospheres[4]

D 3195 Practice for Rotameter Calibration[4]

D 3631 Test Methods for Measuring Surface Atmospheric Pressure[4]

D 3685/D 3685M Test Methods for Sampling and Determination of Particulate Matter in Stack Gases[4]

D 3796 Practice for Calibration of Type S Pitot Tubes[4]

E 1 Specification for ASTM Thermometers[5]

E 337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)[4]

2.2 *EPA Standards:*

EPA-600/9-76-005 Quality Assurance Handbook for Air Pollution Measurement Systems. Vol I. Principles[6]

EPA-600/4-77-027b Quality Assurance Handbook for Air Pollution Measurement Systems. Vol. III. Stationary Source Specific Methods[6]

2.3 *ASME Standards:*

ASME Performance Test Code: PTC 19.10-1968, Flue and Exhaust Gas Analysis[7]

ASME Performance Test Code: PTC 19.10-1981 Part 10, Flue and Exhaust Measurements: Instruments and Apparatus[7]

ASME Performance Test Code: PTC 38-1980, Determining the Concentration of Particulate Matter in a Gas Stream[7]

2.4 *Code of Federal Regulation:*

CFR Part 50 Standards of Performance for Stationary Sources, Appendix A; Test Methods 1 through 4[6]

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[1] This test method is under the jurisdiction of ASTM Committee D~~-~~22 on Sampling and Analysis of Atmospheres and is the direct responsibility of Subcommittee D22.03 on Ambient Atmospheres and Source Emissions.

Current edition approved ~~March 15, 1991.~~ Sept. 10, 2000. Published ~~May 1991.~~ November 2000. Originally published as D 3154 – 72. Last previous edition ~~D 3154 – 72$^{\epsilon 1}$.~~ D 3154 – 91 (1995).

[2] *Annual Book of ASTM Standards*, Vol 05.05.

[3] *Annual Book of ASTM Standards*, Vol 11.01.

[4] *Annual Book of ASTM Standards*, Vol 11.03.

[5] *Annual Book of ASTM Standards*, Vol 14.03.

[6] Available from Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

[7] Available from American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017.

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of terms used in this test method, refer to Terminology D 1356.

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:
= $128.9\ \text{m/s}\ \frac{(\text{g/g} - \text{mol})}{(K)}^{1/2}$, (SI),
= $85.29\ \text{ft/s}\ \frac{(\text{lb/lb} - \text{mol})}{(R)}^{1/2}$, (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, *ds*m^3/h (*ds*ft^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* m^3(*d*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*m^3(*d*ft^3).
$V_{wc(std)}$ = volume of water vapor condensed, corrected to standard conditions, *s*m^3 (*s*ft^3).
$V_{wsg\ (std)}$ = volume of water vapor collected in silica gel, corrected to standard conditions, *s*m^3 (*s*ft^3).
W_f = final mass of silica gel or silica gel plus impinger, g.
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 gage 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 D 3685/D 3685M, as well as the ASME Methods given in 2.3 and Footnote 8,[8] the CFR given in 2.4, and the publication given in Footnote 9.[9]

~~5.2 This test method is basically oriented toward a steady-state flow and constant fluid conditions. It is recognized that deviations from steady state do occur.~~

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 gage 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 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 D 3796. However, use of the standard pitot tube, where feasible, will give additional accuracy.

6.2 *Differential Pressure Gage*—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).

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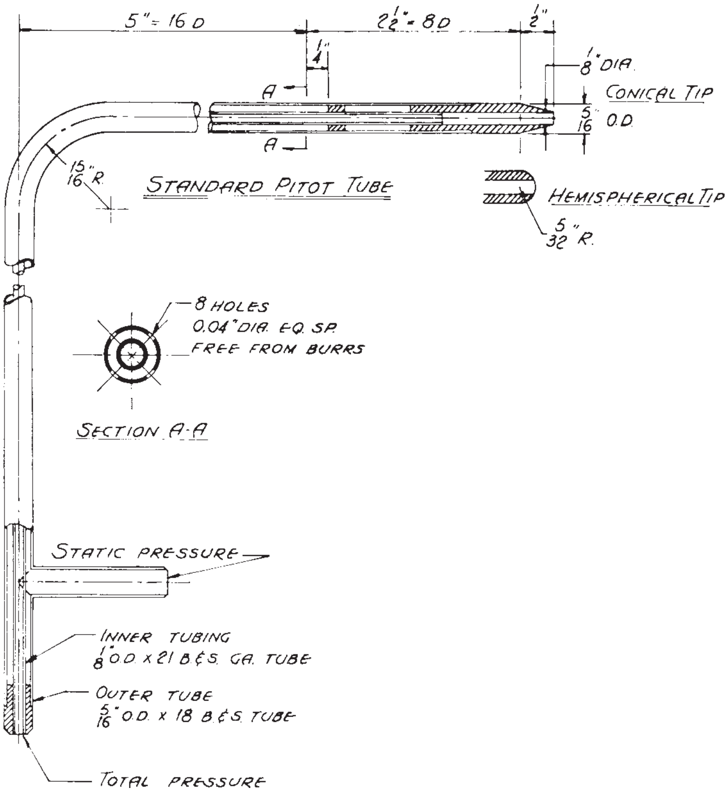
[8] Colen, P., Corey, R. C., and Meyers, J. W., "Methods and Instrumentation for Furnace Heat Absorption Studies; Temperature and Composition of Gases at Furnace Outlets" Transaction of the American Society of Mechanical Engineers, *71*, pp. 965–78, 1949.

[9] 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
1⁄8	3.2	1⁄2	12.7
5⁄32	4.0	15⁄16	23.8
1⁄4	6.4	2 1⁄2	63.5
5⁄16	7.9	5	127

FIG. 2 Standard Pitot Tube Details

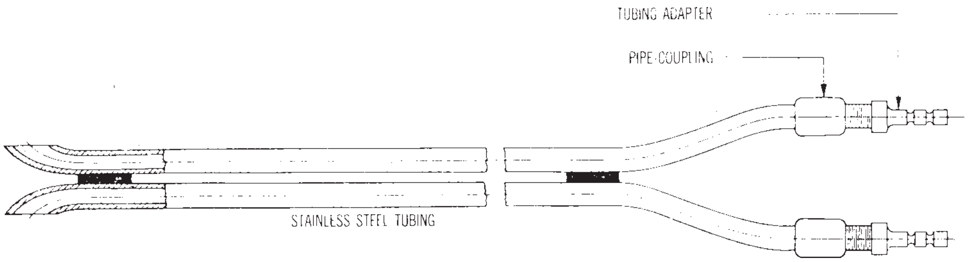


FIG. 3 Type 3 Pitot Tube (Special)

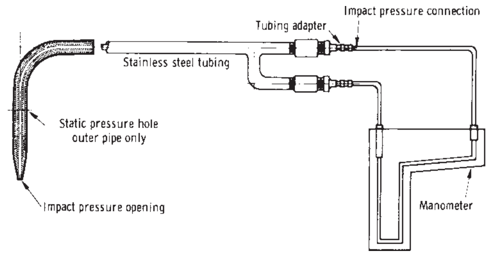


FIG. 1 Pitot Tube

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).

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 E 1, 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 D 3631.

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.

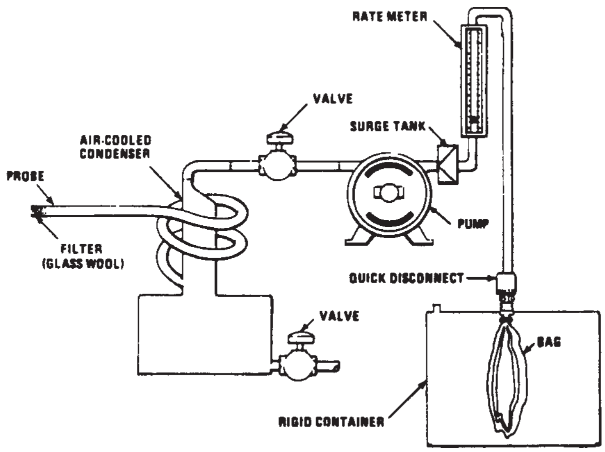


FIG. 4 Integrated Gas Sampling Train

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.

6.6.7 *Vacuum Gage*—A mercury manometer, or equivalent of 101.3 kPa (760 mm Hg) capacity, to be used for the sample train leak test. Test the gage 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.

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 gage. 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 Gage*—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 E 1.

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 gage, leak-free vacuum pump, thermometers, a dry gas meter, differential pressure gage and related equipment. See Test Method D 3685/D 3685M for details of this system.

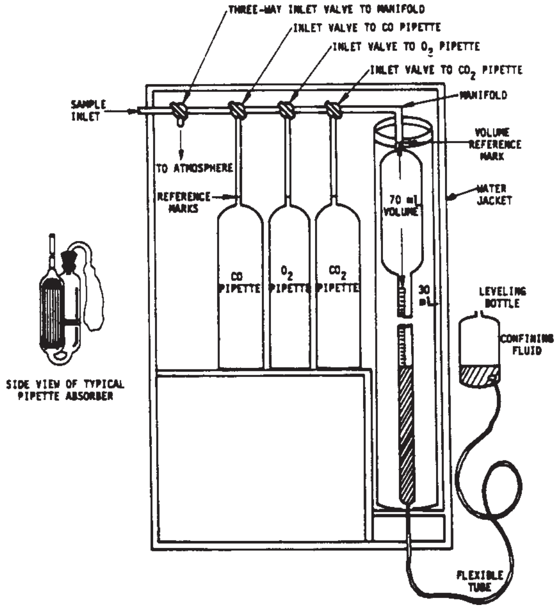


FIG. 5 Orsat Apparatus

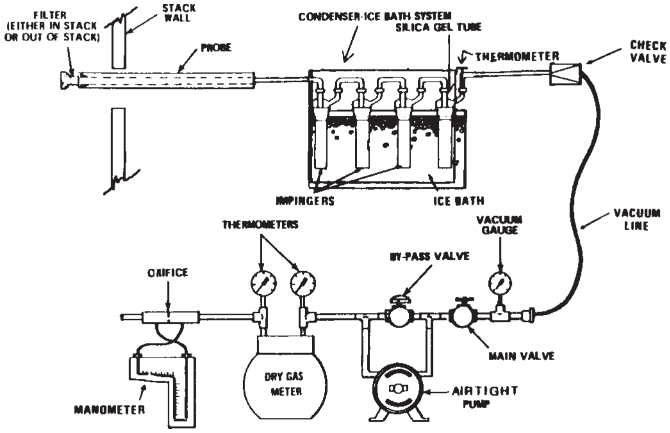


FIG. 6 Moisture Sampling Train

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 $\leq$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.[10]

7.2 *Purity of Water*—Water shall be Type 2 reagent water, conforming to Specification D 1193.

7.3 *Alkaline Pyrogallic Acid Reagent,*[11] 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*[11]—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,*[11] (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,*[11] (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.

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[10] *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. Pharmacope~~utie~~al Convention, Inc. (USPC), Rockville, MD.

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

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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:

$$2\,(length \times width)/(length + width) \tag{1}$$

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:

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

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.

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.)

9.1.5 Take velocity readings, holding the pitot tube parallel to the duct wall, facing into the direction of gas flow, only at the traverse points and not at the centerline or at the walls. This method allows for wall thickness, breach fittings, etc., so that only the internal dimensions are considered.

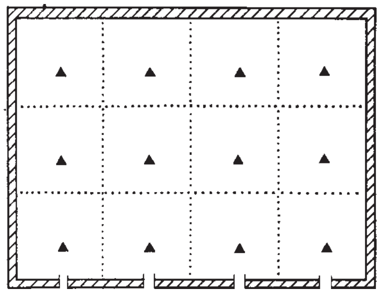

FIG. 7 Traverse Positions and Rectangular Flue

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

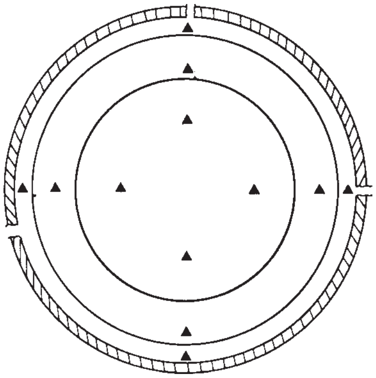

FIG. 8 Traverse Positions and Round Flue

TABLE 2 Location of Traverse Points in Circular Stacks

(Percent of Stack Diameter From Inside Wall to Traverse Point)

Traverse Point Number on a Diameter	Number of Traverse Points on a Diameter											
	2	4	6	8	10	12	14	16	18	20	22	24
1	14.6	6.7	4.4	3.2	2.6	2.1	1.8	1.6	1.4	1.3	1.1	1.1
2	85.4	25.0	14.6	10.5	8.2	6.7	5.7	4.9	4.4	3.9	3.5	3.2
3	...	75.0	29.6	19.4	14.6	11.8	9.9	8.5	7.5	6.7	6.0	5.5
4	...	73.3	70.4	32.3	22.6	17.7	14.6	12.5	10.9	9.7	8.7	7.9
5	...	...	85.4	67.7	34.2	25.0	20.1	16.9	14.6	12.9	11.6	10.5
6	...	...	95.6	80.6	65.8	35.6	26.9	22.0	18.8	16.5	14.6	13.2
7	...	...	...	89.5	77.4	64.4	36.6	28.3	23.6	20.4	18.0	16.1
8	...	...	...	96.8	85.4	75.0	63.4	37.5	29.6	25.0	21.6	19.4
9	...	...	...	...	91.8	82.3	73.1	62.5	38.6	30.6	26.2	23.0
10	...	...	...	...	97.4	88.2	79.9	71.7	61.8	38.9	31.5	27.2
11	...	...	...	...	...	93.3	85.3	78.0	70.4	61.2	39.3	32.3
12	...	...	...	...	...	97.9	90.1	83.1	76.4	69.4	60.7	39.8
13	...	...	...	...	...	...	94.3	87.5	81.2	75.0	68.5	60.2
14	...	...	...	...	...	...	98.2	91.5	85.4	79.6	73.8	67.7
15	...	...	...	...	...	...	...	95.1	89.1	83.5	78.2	72.8
16	...	...	...	...	...	...	...	98.4	92.5	87.1	82.0	77.0
17	...	...	...	...	...	...	...	...	95.6	90.3	85.4	80.6
18	...	...	...	...	...	...	...	...	98.6	93.3	88.4	83.9
19	...	...	...	...	...	...	...	...	...	96.1	91.3	86.8
20	...	...	...	...	...	...	...	...	...	98.7	94.0	89.5
21	...	...	...	...	...	...	...	...	...	...	96.5	92.1
22	...	...	...	...	...	...	...	...	...	...	98.9	94.5
23	...	...	...	...	...	...	...	...	...	...	...	96.8
24	...	...	...	...	...	...	...	...	...	...	...	98.9

9.2 Before use, leak-test the differential pressure gage as follows:

9.2.1 Level and zero the manometer.

9.2.2 Vent both sides to the atmosphere and place tubing on one side, and blow into the tubing to displace the liquid level at least 30 % of scale.

9.2.3 Close off the open end, and observe the manometer for 15 s. If there is no change in the liquid level, that side of the manometer is leak free.

9.2.4 Repeat the test on the other side of the manometer.

9.3 Leak-test the pitot tube as follows:

9.3.1 Blow through each leg of the pitot tube alternately blocking and opening the other ports to ensure that the tube is not plugged. Connect the legs of the pitot tube to the manometer. Apply a small pressure differential and then pinch off the tubes at the pitot tube. This differential should hold steady for 15 s if the connecting tubes are leak free. The manometer should return to zero when the tubes are released. Repeat this leak check with a large pressure differential.

9.4 *Gas Density Determination Equipment* :

9.4.1 Fill the Orsat analyzer burets and the leveling bulb with the appropriate solutions. Place a few pieces of chemically clean copper coil or wire in the CO buret. Check for leaks as follows:

9.4.1.1 Allow the apparatus to reach ambient temperature with the manifold valve open and the three pipet valves closed.

9.4.1.2 Bring the liquid in each absorption pipet up to the reference mark by opening the pipet valves one at a time and by slowly lowering the leveling bottle. Pinch off the rubber tube to the leveling bottle with the heel of the hand to quickly stop the liquid flow. Close the pipet valves.

9.4.1.3 Displace the indicating fluid until a value is obtained in the narrow part of the buret, and quickly close the manifold inlet valve.

9.4.1.4 Place the leveling bottle on the top of the Orsat case, record the meniscus value in the buret.

9.4.1.5 Wait at least 4 min, and record the meniscus value in the buret again. A change of ≥0.2 mL in the value indicates a leak in the system. A drop in reagent level to below the capillary tube over a 4-min period indicates a leak in that pipet.

9.4.2 Check the pump, surge tank, and rotameter in the following manner:

9.4.2.1 Assemble the pump, surge tank, and rotameter as shown in Fig. 4.

9.4.2.2 Place a needle valve and vacuum gage at the pump inlet using a T-connector.

9.4.2.3 Turn on the pump and close the needle valve until a vacuum of 17 kPa (125 mm Hg) is obtained. The pumping rate at this vacuum shall be at least 1 L/min (0.035 ft^3/min) and rotameters should indicate a steady value when the flow is adjusted between 0.5 and 1 L/min (0.018 and 0.035 ft^3/min).

9.4.3 Leak-test the collection bag as follows:

9.4.3.1 Connect the flexible bag to a water manometer and pressurize it to 7 to 15 kPa (5 to 10 cm Hg).

9.4.3.2 Allow it to stand for about 10 min.

9.4.3.3 Any displacement in the manometer indicates a leak.

9.4.4 Leak-test the water manometer as follows:

9.4.4.1 Place a flexible tube on the gage opening.

9.4.4.2 Apply a positive pressure of from 7 to 15 kPa (5 to 10 cm Hg) on the manometer by blowing on and then pinching off the tube. The pressure value shall remain steady for about 10 min.

9.4.4.3 Check each side of the manometer separately.

9.4.5 Leak-test the vacuum gage as follows:

9.4.5.1 Pull a 50 kPa (380 mm Hg) vacuum on the gage, and pinch off the tube. No deflection shall be noted in the pressure value over a 10-min period.

9.5 *Gas Moisture Measuring Equipment* :

9.5.1 *Condenser Preparation*—Place known volumes of water in the first and second impingers (usually 100 mL each). Immerse the impinger tubes tips at least 13 mm (0.5 in.) into the water. Leave the third impinger empty to trap entrained water. Place a known amount (about 200 g) of silica gel (see 7.10) in the fourth impinger. Alternatively, weigh each impinger and its contents on the trip balance to the nearest 0.5 g.

9.5.2 Adjust the probe heater to operating temperature, and place crushed ice and water around the impingers.

9.5.3 Place a loosely packed filter of glass wool in the end of the probe, and connect the probe to the sampling train.

9.5.4 Leak-test the sampling train as follows:

9.5.4.1 Disconnect the orifice meter line from the downstream orifice pressure tap (the one closest to the exhaust of the orifice), and plug this tap.

9.5.4.2 Vent the negative side of the inclined manometer to the atmosphere. If it is equipped with a three-way valve, this step can be performed by turning the three-way valve that is on the negative side of the orifice-inclined manometer to the vent position.

9.5.4.3 Place a one-hole rubber stopper with a tube through the hole in the exit of the orifice, and connect a piece of tubing to the tube.

9.5.4.4 Open the positive side of the orifice-inclined manometer to the "reading" position. If the inclined manometer is equipped with a three-way valve, this will be to the line position.

9.5.4.5 Plug the inlet to the vacuum pump. If a quick disconnect with a leak-free check valve is used on the control module, the inlet will not have to be plugged.

9.5.4.6 Open the main valve and the bypass valve.

9.5.4.7 Blow into the tubing connected to the end of the orifice until a pressure of about 15 to 25 kPa (130 to 175 mm Hg) has been built up in the system.

9.5.4.8 Plug or crimp the tubing to maintain this pressure.

9.5.4.9 Observe the pressure reading for a 1 min period. No noticeable movement in the manometer fluid should occur. If the meter box has a leak, a bubbling-type leak-check solution may aid in locating leaks.

9.5.4.10 After the metering system has been determined to be leak-free by the positive leak-check procedure, check the vacuum system to and from the pump by plugging the air inlet to the meter box. If a quick disconnect with a leak-free stopper system is presently on the meter box, then the inlet will not have to be plugged. Turn on the pump, pull a vacuum within 10 kPa (75 mm

Hg) of absolute zero, and observe the dry gas meter. If the leakage exceeds 150 mL/min (0.005 ft^3/min), find the leaks and minimize them until the above specification is met.

NOTE 1—For metering systems having diaphragm pumps, the above procedure will not detect leaks within the pump. For these cases, perform a 10 min calibration run at 570 mL/min (0.02 ft^3/min); at the end of the run, record the values of the differences of the measured wet test meter and the dry gas volumes; divide the difference by ten to obtain the leak rate. The leak rate shall not exceed 570 mL/min.

10. Calibration

10.1 Calibrate the S-type pitot tube in accordance with Practice D 3796.

10.2 Calibration of the thermocouples and thermometers shall be traceable to National Institute of Standards and Technology (NIST).

10.3 Calibrate the rotameters in accordance with Practice D 3195.

10.4 Calibrate the dry gas meters in accordance with Test Methods D 1071.

10.5 Calibrate the graduated cylinder (see 6.7.7) by weighing with water.

10.6 Calibrate the trip balance, (see 6.7.7) using Class-S weights.

10.7 Calibrate the Orsat analyzer using ambient air, and using cylinders containing known concentrations of CO_2. Calibration tests shall be performed before every third field test, or every three months, whichever is shorter.

11. Procedure

11.1 *Velocity Tests*:

11.1.1 Record the velocity head at each selected sample point.

11.1.1.1 When the readings at the sample points are fluctuating, average the manometer readings on a time-weighed basis. Two traverse readings in short succession will also help to average out the velocity variations.

11.1.1.2 Perform a post-sampling leak-test similar to the pre-sampling test. See 9.3.

11.1.2 Record the gas temperature with the standard metal thermocouple and potentiometer. In larger ducts, record the temperature at the same locations the velocity head is recorded. If possible, perform temperature and velocity traverses simultaneously. Unshielded thermocouples may be used to a temperature of about 370°C (700°F). For higher temperatures, use a high-velocity gas-aspirated shielded thermocouple.

11.1.2.1 In small ducts, a standard mercury bulb thermometer (see 6.4.2) inserted into the duct may be used. Carefully seal the access hole to prevent in-leakage of outside air. Allow sufficient time for the thermometer to reach equilibrium before recording the value.

11.1.2.2 If there are frequent variations in the gas temperature during the time of testing due to process changes, a continuous recording of the temperature will be required.

11.1.3 Record the ambient barometric pressure at the test site, using the mercury barometer (see 6.5). See Method D 3631.

11.1.4 Record the static pressure of the gas using the U-tube manometer (see 6.3). The absolute pressure in the duct is equal to the atmospheric pressure plus or minus the static pressure in the duct depending on whether it is under vacuum or pressure:

$$P_s = P_{bar} \pm P_{static} \qquad \text{(SI system)} \tag{3}$$

$$= P_{bar} \pm P_{static}/13.6 \qquad \text{(inch}-\text{pound system)} \tag{4}$$

11.1.4.1 The static pressure need only be determined at a single point in the duct in most cases. Check this pressure occasionally through the test period.

11.2 *Determination of Gas Molecular Weight*:

11.2.1 Sample each point chosen for the velocity traverse, keeping the flow rate constant. Collect from 30 to 90 L (1 to 3 ft^3), simultaneously with the pitot traverse.

11.2.2 Disconnect, seal, and remove the flexible bag. Allow it to sit for about 30 min to ensure mixing and temperature equilibrium. Perform the analysis as follows:

11.2.3 First flush the manifold with dry nitrogen (at pressure slightly above atmospheric) as follows:

11.2.3.1 Open the inlet stopcock at far left of the manifold, after closing all other stopcocks.

11.2.3.2 Raise the leveling bottle to bring the level of the liquid in the buret to the uppermost graduation mark.

11.2.3.3 Close the inlet stopcock to the manifold.

11.2.3.4 Return the leveling bottle to the rest position.

11.2.3.5 Attach the nitrogen source to the manifold inlet.

11.2.3.6 Open the manifold inlet stopcock slowly, causing the liquid level in the buret to fall to the bottom graduation mark, then close the inlet stopcock.

11.2.3.7 With one hand, slowly open the manifold inlet stopcock, and with the other hand raise the leveling bottle to bring the buret liquid level back to the uppermost graduation mark.

11.2.3.8 Close the inlet stopcock as soon as the buret liquid level reaches the top graduation mark, and remove the nitrogen source.

11.2.4 Transfer sample gas to analyzer as follows:

11.2.4.1 Connect the sample container (flexible bag) to the manifold inlet stopcock.

11.2.4.2 Open the stopcock on the flexible bag, then open the manifold inlet stopcock to the vent position. (A three-way stopcock is convenient.)

11.2.4.3 Allow a 10 to 15 mL portion of the sample to slowly purge the connection and vent to atmosphere, then close the manifold inlet stopcock.

11.2.5 Draw the sample to be analyzed into the buret as follows:

11.2.5.1 Open the manifold inlet stopcock and allow sample to flow slowly through the manifold and into the first (CO_2) buret.

11.2.5.2 Allow slightly more than 100 mL of sample to be drawn into the buret, then close the inlet stopcock.

11.2.5.3 Adjust the leveling bottle so that bottom of the meniscus in the bottle is on the exact same horizontal plane as the buret bottom graduation mark.

11.2.5.4 Open the inlet stopcock and slowly vent the excess sample, then close the stopcock as soon as the bottom of meniscus in the buret is also on the exact same plane as the buret bottom graduation mark.

11.2.6 Absorb CO_2 as follows:

11.2.6.1 Raise the leveling bottle on the buret to place sample gas in the buret under slight pressure to avoid possibility of accidentally draining absorption solution into the manifold.

11.2.6.2 Open the CO_2 buret stopcock, and raise the leveling bottle until confining solution in the buret reaches the capillary stem at the top of the buret, thus forcing sample into the pipet, being careful not to force confining solution into the manifold.

11.2.6.3 Lower the leveling bottle to draw the sample back into the buret, being careful not to allow absorption solution to wet the stopcock, or escape from the manifold. If this occurs, the sample would be lost, or the stopcock contaminated. In either event, clean the stopcock, discard the stopcock and start over again.

11.2.6.4 Repeat the lowering and raising of the leveling bottle until there appears to be no further contraction in the gas volume.

11.2.6.5 Finally, draw the absorption fluid back into the pipet (by lowering the leveling bottle) until the solution reaches the point just below the pipet stopcock, then close the pipet stopcock. Remove any foam on the solution surface by first moving the surface up and down at the point where the pipet capillary joins the expanded section of the pipet body, then bringing the level up to the stopcock body and closing the stopcock.

11.2.6.6 Adjust the leveling bottle until the liquid levels in the buret and in the bottle are on the same exact horizontal plane, as observed with the operator's eye on the same plane as the water levels. This will compensate for any changes in ambient atmospheric pressure.

11.2.6.7 Allow the buret to drain for about 1 min.

11.2.6.8 With eye on the same horizontal plane as the mark to be read, record the buret level to 0.05 mL from the bottom of the buret. (If a Schellback buret is used, record the value from the point where the ribbons above and below the meniscus appear to come to a point.)

11.2.6.9 Calculate the percentage of CO_2 as follows:

$$\% \ CO_2 = (\textit{decrease in volume}/\textit{volume of sample})\ (100) \tag{5}$$

11.2.6.10 Determine the percentage of O_2 and CO by repeating the steps described in 11.2.6, using first the O_2 buret, then the CO buret.

11.2.7 Calculate the dry molecular weight of the gas as described in Eq 6.

11.2.8 Repeat the analysis with other aliquots from the same sample until the calculated molecular weights of any three analyses agree within ≤0.3 g/mol.

11.2.9 Perform another leak-test of the equipment, as described in 9.4.

11.3 *Gas Moisture Determination* :

11.3.1 Sample at each traverse point at approximately 20 L/min (0.75 ft^3/min), taking appropriate readings of gas temperature, pressure, meter readings, etc.

11.3.2 At the completion of sampling, perform a leak-test of the equipment. See 9.5.4.

11.3.3 Measure the volume of the water in the first three impingers to the nearest mL (or measure the mass of the water and impingers to the nearest gram), and the increase in mass of the silica gel impinger to the nearest gram.

11.4 *Gas Moisture Determination in Saturated or Droplet-Laden Stacks*:

11.4.1 Attach a temperature sensor capable of measuring to ± 1°C (2°F) to the probe, and measure the stack gas temperature at each traverse point.

11.4.2 Measure the stack absolute pressure.

11.5 Determine the cross-sectional area of the stack or duct at the sampling location. Use actual measurements rather than relying on drawings, if at all possible. If the duct floor is covered with an appreciable amount of dust or particulate matter, measure only to the top of the dust layer.

12. Calculation

12.1 Calculate the dry molecular weight of the flue gas, using the data recorded during 11.2 as follows:

~~$M_d = [0.44] + [0.32]] + [0.28]]$~~ (6)

$$M_d = [0.44]\ CO_2] + [0.32]O_2] + [0.28] \tag{6}$$

12.2 Determine the moisture content of the flue gas, using the data recorded during 11.3.

12.2.1 *Condensed Water Vapor Volume* :

$$V_{wc(std)} = \frac{(V_f - V_i)\rho_w RT_{std}}{(P_{std}M_w)} = K_1(V_f - V_i) \tag{7}$$

where:

K_1 = 0.001354 m^3/g for SI units, or,
= 0.047829 ft^3/g for inch-pound units.

12.2.2 *Water Vapor volume Collected in Silica Gel*:

$$V_{wsg(srd)} = \frac{(W_f - W_i)RT_{std}}{(P_{std}M_w)} = K_2(W_f - W_i) \tag{8}$$

where:

K_2 = 0.001358 m^3/g for SI units, or,
= 0.0472 ft^3/g for inch-pound units.

12.3 *Dry Gas Volume Corrected to Standard Conditions*:

$$V_{m(std)} = (V_mY)\frac{T_{std}}{T_m}\frac{P_m}{P_{std}} = \frac{K_3V_mYP_m}{T_m} \tag{9}$$

where:

K_3 = 2.942 K/kPa for SI units, or,
= 17.95 °R/in. Hg for inch-pound units.

12.4 Calculate the moisture content of the stack gas:

$$B_{ws} = \frac{(V_{wc(std)} + V_{wsg(std)})}{(V_{wc(std)} + V_{wsg(std)} + V_{m(std)})} \tag{10}$$

12.4.1 In moisture saturated or droplet-laden gas streams, use two calculation methods for the moisture content of the stack gas; one using a value based on the saturated conditions (see Eq 11 or Eq 12), the other using the results of the impinger analysis (see Eq 10). Use the lower of these two B_{ws} values.

12.4.1.1 Using saturated conditions:

$$B_{ws} = \frac{S.V.P.}{P_{bar} + P_{static}} \qquad \text{(SI system)} \tag{11}$$

$$B_{ws} = \frac{S.V.P.}{P_{bar} + \frac{P_{static}}{13.6}} \qquad \text{(inch−pound system)} \tag{12}$$

where:

S.V.P. = saturation vapor pressure from Table labeled X2.1 in Test Method E 337, in kPa.

NOTE 2—Pressure values in Table labeled X2.1 in Test Method E 337 are in Pa, and must be converted to kPa for Eq 11 or in. Hg for Eq 12.

12.4.2 Determine the molecular weight of the stack gas on the wet basis as follows:

$$M_s = M_d \times (1 - B_{ws}) + (18.0B_{ws}) \tag{13}$$

12.5 *Average Stack Gas Velocity*—Determine the average of the square roots of the velocity heads and the average stack gas temperatures at all the points recorded during the velocity and temperature traverses, and calculate the average velocity as follows:

$$v_s = K_pC_p(\sqrt{\Delta p})_{avg}\sqrt{\frac{(T_s)_{avg}}{P_sM_s}} \tag{14}$$

NOTE 3—**Caution:** It is important to note that the average of the square roots of the velocity heads is used. The velocity heads cannot first be averaged and then the square root of the average determined.

12.6 *Average Stack Gas Volumetric Flow Rate*—Determine the average stack gas volumetric flow rate as follows:

$$Q_{std} = 3600(1 - B_{ws})v_sA\frac{T_{std}}{T_{s(avg)}}\frac{P_s}{P_{std}} \tag{15}$$

13. Quality Assurance Procedures

13.1 The EPA QA manuals referenced in 2.2contain useful quality assurance criteria for performing this test method.

14. Records

14.1 The EPA QA manual (EPA-600/4-77-027b) referenced in 2.2 contains data recording forms that may be used to document calibration and testing of equipment, and for recording field test data.

15. Precision and Bias [12]

15.1 *Precision*:

15.1.1 The precision of velocity measurements is correlated with the variability in velocity head values. See Fig. 9.

15.1.2 Coefficients of variation, up to about seven percent in gas temperature and 90 % in gas moisture, did not significantly affect the precision of the average velocity measurements.

15.1.3 The most significant source of variability in the velocity measurement is that associated with the velocity head pressure. The following factors that affect velocity pressure readings will have a significant bearing on the precision of average velocity measurements:

15.1.3.1 Manometer zero and level,

15.1.3.2 Technique used in reading manometer liquid level,

15.1.3.3 Use of a capillary to damp fluctuations in manometer readings,

15.1.3.4 Pitot tube calibration,

15.1.3.5 Length of the tubing between the pitot tube and the manometer,

15.1.3.6 Plugging of the pitot tube by particulate matter in gas streams,

15.1.3.7 Leaks in tubing or connectors, and

15.1.3.8 Departures in the process from steady state conditions.

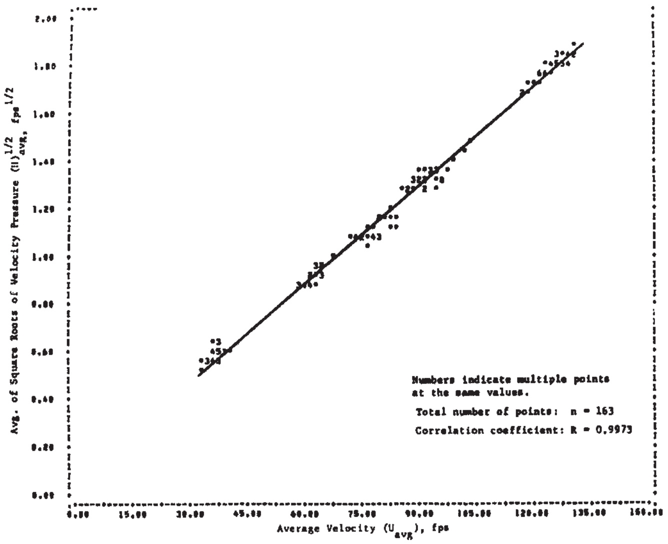

FIG. 9 Scattergram Showing Correlation Between Velocity Head and Average Velocity

15.2 *Bias*:

15.2.1 A statistical analysis of 163 average velocity determinations by nine different laboratories at four different locations produced the following results:

15.2.2 The standard bias of variations among single determinations by different laboratories, S_T (between-laboratories), over the velocity range of about 10 to 100 m/s (30 to 130 ft/s) is given by the following equation:

$$S_T = 0.21\sqrt{m} \qquad (16)$$

15.2.3 See Fig. 10 for a representation of these results.

15.3 A practical application of the standard bias estimate is the construction of confidence limits obtained using this test method. If it is assumed that a laboratory's measurements of the average velocity by this test method is unbiased, and further that the distribution of this measurement by various laboratories follows a normal distribution, then a 95 % confidence limit for a single laboratory's measurement can be determined as the following observed measurement:

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[12] Howes, J. E., Pesut, R. N., and Foster, J. F., "Interlaboratory Cooperative Study of the Precision and Accuracy of ASTM D 3154 – 72, Method for the Determination of the Average Velocity in a Duct (Pitot Tube Method)~~"~~," ASTM Data Series Publication DS:55-S7, ASTM~~, 1916 Race Street, Philadelphia,~~ 100 Barr Harbor Drive, West Conshohocken, PA ~~19103.~~ 19428–2959.

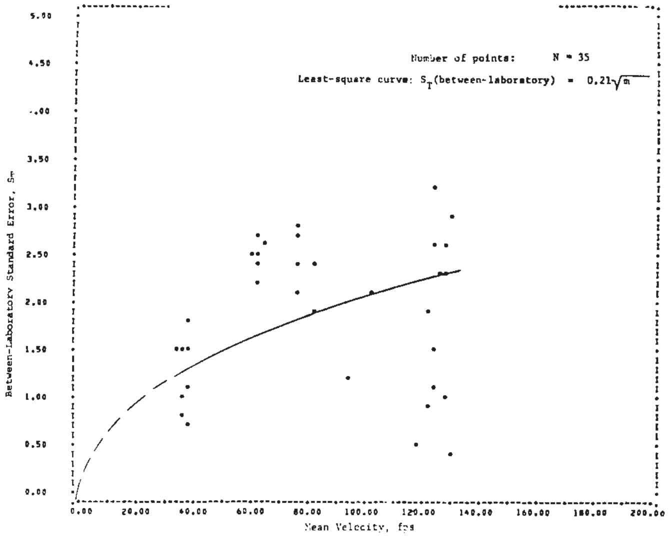

FIG. 10 Scattergram and Least Square Curve Relating Between-Laboratory Bias and Mean Velocity

$$S_s = 1.96\ S_T \tag{17}$$

15.4 If a large number of laboratories were to make simultaneous measurements of this average velocity, it would be expected that approximately 95 % of these simultaneous measurements lie within this confidence interval. Alternatively, realizing that between-laboratory variability exists, this 95 % confidence interval represents a reasonable estimate of the range in which any single measurement of the average velocity will fall.

16. Keywords

16.1 stack gas velocity; pitot traverse; pitot tube; Staubscheibe pitot tube; Type S pitot tube; Orsat; Orsat analyzer; Method 1; Method 2; Method 3; Method 4; stack gas moisture; stack gas molecular weight; stack gas density

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