THRESHOLD

Interlaboratory Cooperative Study of the Precision of the Determination of

THE AVERAGE VELOCITY IN A DUCT (Pitot Tube Method) using ASTM Method D 3154-72

DS 55-S7

Interlaboratory Cooperative Study | AVERAGE VELOCITY IN A DUCT | 05-055070-17 | DS 55-S7

AMERICAN SOCIETY FOR TESTING AND MATERIALS

THRESHOLD ASTM

FINAL REPORT

on

INTERLABORATORY COOPERATIVE STUDY OF THE PRECISION OF THE DETERMINATION OF THE AVERAGE VELOCITY IN A DUCT (Pitot Tube Method) USING ASTM METHOD D 3154-72

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INTERLABORATORY COOPERATIVE STUDY OF THE PRECISION OF THE DETERMINATION OF THE AVERAGE VELOCITY IN A DUCT USING ASTM METHOD D 3154-72 (PITOT TUBE METHOD)

by

J. E. Howes, Jr., R. N. Pesut, and J. F. Foster

INTRODUCTION

In 1971 in recognition of the important relationship between the measurement and the effective control of air pollution, American Society for Testing and Materials (ASTM) initiated a pioneering program, designated Project Threshold, to validate methods for measuring contaminants in the ambient atmosphere and in source emissions. The first phase of the program was devoted to evaluation of methods for measuring the content of nitrogen dioxide (D 1607-69), sulfur dioxide (D 2914-70T), dustfall (D 1739-70), total sulfation (D 2010-65), particulate matter (D 1704-61), and lead (D 3112) in the atmosphere[(1-5)*].

Methods for the measurement of the relative density of black smoke (D 3211-75T)[(6)], oxides of nitrogen (D 1608-60), sulfur oxides (D 3226-73T), particulates (D 2928), and particulates and collected residue (proposed method) in source emissions have been evaluated in Phase 2 of Project Threshold.

The interlaboratory "round-robin" approach has been applied to Project Threshold by bringing together groups of competent laboratories for concurrent performance of the test procedures under actual field conditions. Each participating laboratory is responsible for providing personnel and equipment, assembling apparatus, sampling, and analyzing collected samples either on-site or at their own facility. The coordination of the testing program, statistical analysis of the data, and evaluation of the measurement methods based on the experimental results has been performed by Battelle's Columbus Laboratories.

This report presents the results obtained from an experimental study

*References are given on Page 40.

of the precision of measurements of the average velocity of stack gases using ASTM Method D 3154-72 (Pitot Tube Method)[7]. The study was performed in conjunction with evaluation of methods for measurement of particulates and collected residue in source emissions.

SUMMARY OF RESULTS

A statistical analysis of 163 average velocity determinations using ASTM Method D 3154-72 by nine different laboratories at four different field locations produced the following results:

- The standard error of variations among single determinations by different laboratories, S_T(between-laboratory), over the velocity range of about 30 to 130 feet per second may be estimated by the equation:

  $$S_T(\text{between-laboratory}) = 0.21 \sqrt{m},$$

  where S_T and m, the mean velocity are expressed in feet per second.
- The precision of average velocity measurements is highly correlated with the variability in velocity pressure readings.
- Variability of gas moisture content and gas temperature measurements are reported. However, rather large coefficients of variation, up to about 7 percent in gas temperature and 90 percent in gas moisture in extreme cases, did not significantly affect the precision of the average velocity measurements.

EXPERIMENTAL PROGRAM

ASTM Method D 3154-72

ASTM Method D 3154-72 describes the procedures and the equipment requirements for determining the average velocity of a gas stream in a duct, stack, or flue. Average velocity is determined from velocity pressure measurements at selected points in the flue with either a standard or a Staubscheibe (Type "S") pitot tube. The number of points in a flue at which velocity measurements are performed is determined by flue size and the uniformity of the flow pattern at the measurement location. Associated measurements of gas temperature, static pressure, moisture content of the gas, and gas composition are required to complete the calculation of average velocity.

In general, the Test Method is applicable to average velocity measurements in a variety of situations in which relatively steady-state flow and gases of constant fluid properties are encountered. A specific application of the method is the measurement of velocity in conjunction with the determination of the particulate concentration in source emissions, as in ASTM Method D 2928-71[8] and a proposed particulate and collected residue method[9]. The Type "S" pitot tube is usually preferred in this application since it is less susceptible to plugging at higher particulate concentrations and it easily fits through the 3- or 4-inch-diameter sampling ports which are normally available.

The official text of ASTM Method D 3154-72 is reproduced in Appendix A of this report. Appendices to the description of the Test Method present a discussion of the operational principle of the pitot tube and sources of error which are frequently encountered in the practical application the technique.

Equipment

Type "S" pitot tubes were used for all velocity measurements in this study. Correction factors for the pitot tubes used by the cooperating laboratories were determined by comparison with a Type "S" pitot tube calibrated by National Bureau of Standards. Prior to tests at each site, each cooperator's pitot tube and the NBS calibrated tube were placed side-by-side in the duct or stack and a series of concurrent velocity pressure readings were obtained. The correction factors for each tube were calculated from the readings by the following equations:

$$CP = \frac{\sum_{i=1}^{n} 0.84\sqrt{\frac{hs_i}{hc_i}}}{n},$$

where

CP = pitot tube correction factor

0.84 = correction factor for NBS calibrated pitot tube

hs_i = velocity pressure for i^{th} reading with NBS calibrated pitot tube

hc_i = velocity pressure for i^{th} reading with cooperator's pitot tube

n = number of pairs of velocity pressure readings obtained.

The calibration procedure yielded correction factors in the range 0.81 to 0.87 for all pitot tubes used in the tests. The individual pitot tube correction factors calculated from pairs of calibration readings were usually in good agreement (± 0.01). In the few instances in which a laboratory participated at several sites and used the same equipment the average correction factors agreed very closely, e.g., for one laboratory the CP values determined at three different sites were 0.86, 0.86, 0.87.

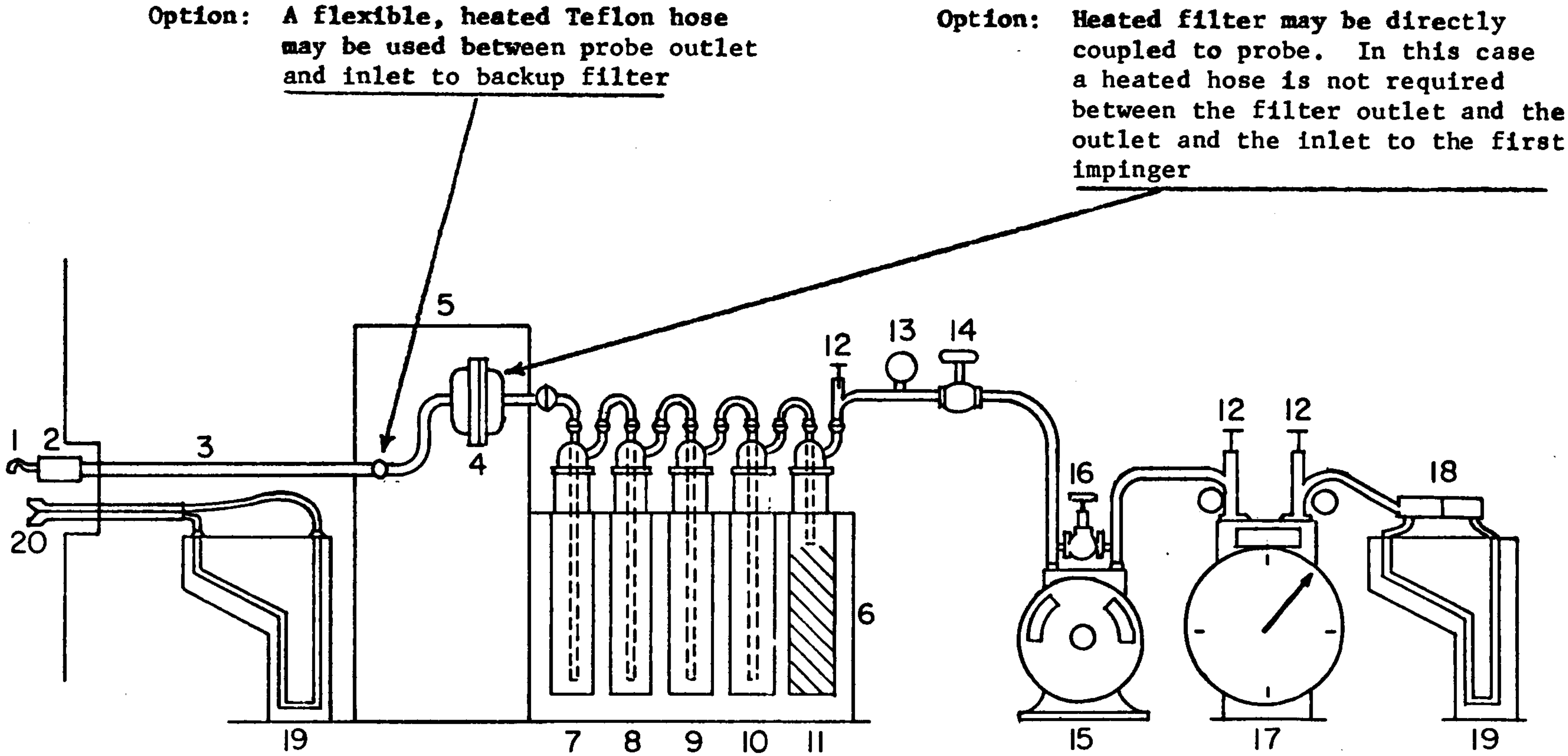
The NBS data on the pitot tube used for the calibrations are presented in Appendix B.

In all tests, velocity measurements were performed with the pitot tubes used in conjunction with a particulate sampling equipment as illustrated in Figure 1. The pitot tubes were attached alongside the probe with the tip adjacent to the nozzle of the particulate sampling train. The typical probe-pitot tube arrangement is shown in the photograph in Figure 2. The probe was also equipped with a thermocouple to measure stack gas temperature at each traverse point.

The lines between the pitot tubes and manometers were 25 to 50 feet and they were usually contained in the umbilical of the particulate sampling systems.

Velocity pressures were read out on the dual scale manometers incorporated in the control modules of the particulate sampling systems. All manometer had an inclined scale over the range of 0-1 inch of water and a vertical scale over the remainder of the range.

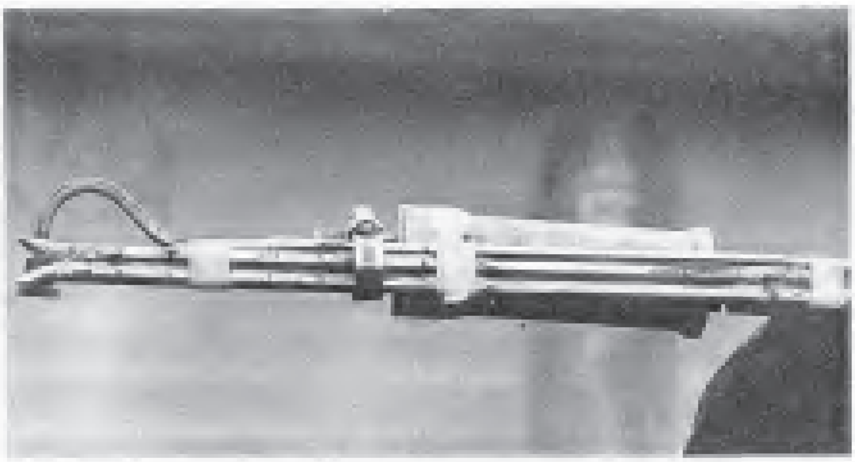
The moisture content of the flue gas was determined by its



1. Nozzle
2. Thimble or flat filter
3. Stainless steel probe
4. Backup filter holder
5. Heated box for filter
6. Ice bath for impingers
7. Modified impinger, dry
8. Modified impinger with 100 ml water
9. Modified impinger with 100 ml water
10. Modified impinger, dry
11. Silica gel trap
12. Thermometer
13. Vacuum gauge
14. Flow control valve
15. Pump
16. Flow control valve
17. Dry test meter
18. Calibrated orifice
19. Manometer
20. "S" type pitot tube

FIGURE 1. EQUIPMENT TRAIN USED FOR PARTICULATE AND COLLECTED RESIDUE MEASUREMENTS (D 2928-71 AND PROPOSED METHOD) AND VELOCITY DETERMINATIONS (D 3154-72)

a. Probe Equipped With Flat Filter



b. Probe Equipped With Thimble

FIGURE 2. TYPICAL PROBE-PITOT TUBE ARRANGEMENTS FOR PARTICULATE SAMPLING (D 2928-72 AND PROPOSED METHOD) AND VELOCITY MEASUREMENTS (D 3154-71)

condensation in the impinger train of the particulate system. Most of the water vapor was condensed in four serially connected, modified Greenburg-Smith impingers held at about 70 F by immersion in an ice bath. A final step of moisture removal was provided by a desiccant trap, usually 200 grams or more of silica gel, also cooled to about 70 F with ice.

Static pressure was measured with a manometer connected to a 1/4-inch tap in the stack or duct.

The quantity of CO_2 and O_2 in the flue gas was determined by Orsat analysis. Nitrogen was assumed to comprise the balance of the gas composition.

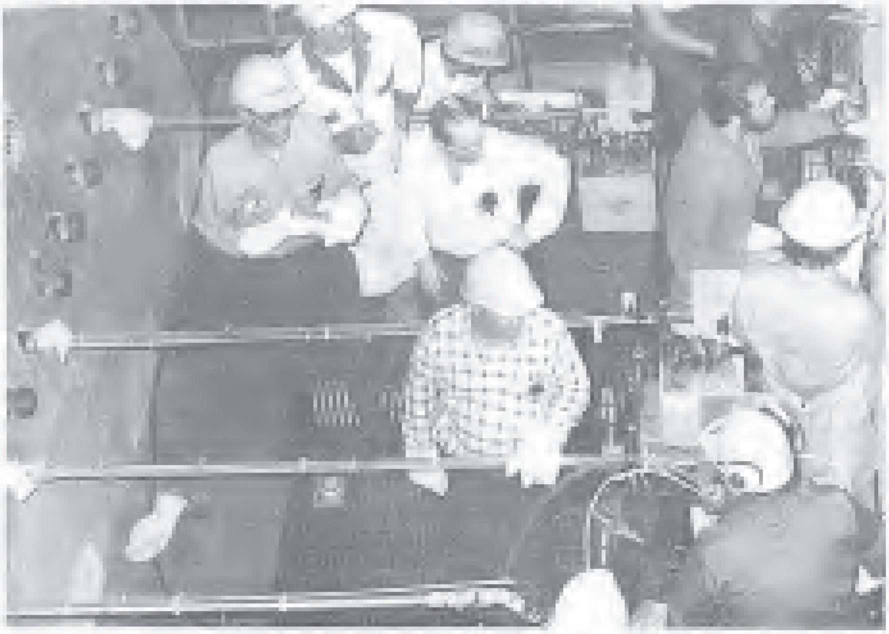
Test Procedure

A test series was conducted at each site in which four cooperating laboratories concurrently determined average velocity in accordance with the procedures described in ASTM Method D 3154-72. Due to spatial limitations, all laboratories could not make concurrent velocity pressure and gas temperature measurements at the same traverse point at the same time. Consequently, a test procedure was adopted in which the laboratories performed concurrent measurements at different traverse points. The laboratories moved from point-to-point and port-to-port in a pattern until measurements were obtained at all traverse points. Photographs of the cooperating laboratories performing concurrent velocity measurements at Sites I and IV are presented in Figure 3.

The traverse points at which the laboratories performed measurements at each site are shown in Figures 4 through 7. These figures also present typical values of velocity pressure in inches of water and gas temperature in degrees Fahrenheit at each traverse point used in the tests.

Tables 1 through 4 show the sequence in which laboratories moved from port-to-port in making velocity traverse measurements. In all tests, measurements at each port were taken starting at the point farthest from the duct or stack wall and proceding to the traverse points nearer the wall.

The velocity pressure and gas temperature readings at the traverse points were taken during particulate sampling periods which were 4 to 6 minutes in duration. The velocity traverses were completed over the 48 to 144-minute time periods required for the particulate tests. Each laboratory determined the gas moisture content from sampling performed during the



a. At Site I

b. At Site IV

FIGURE 3. COOPERATING LABORATORIES PERFORMING CONCURRENT PARTICULATE, COLLECTED RESIDUE, AND VELOCITY MEASUREMENT

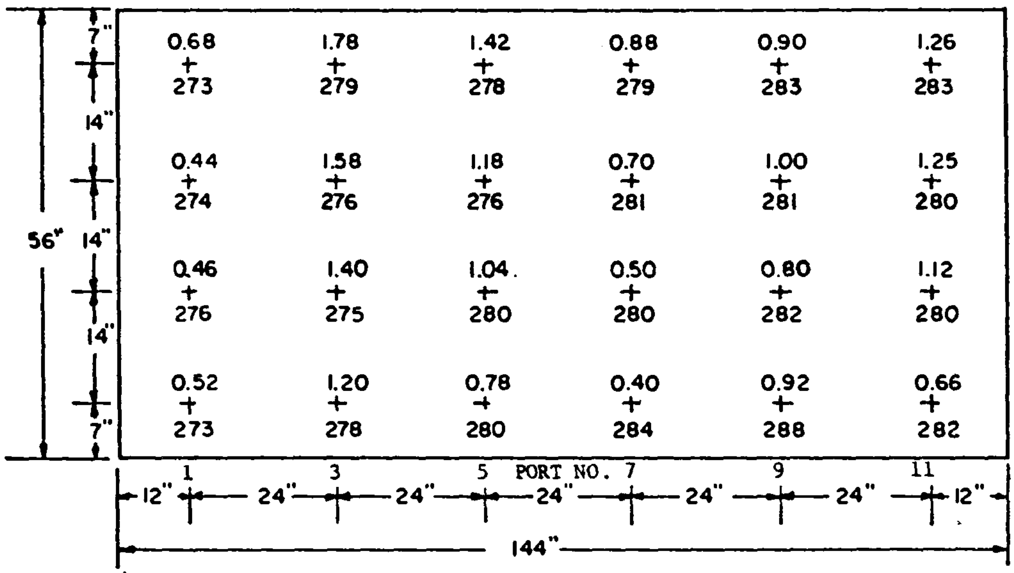


FIGURE 4. TYPICAL VELOCITY PRESSURE AND TEMPERATURE MEASUREMENTS AT SAMPLING POINTS IN THE DUCT AT TEST SITE I

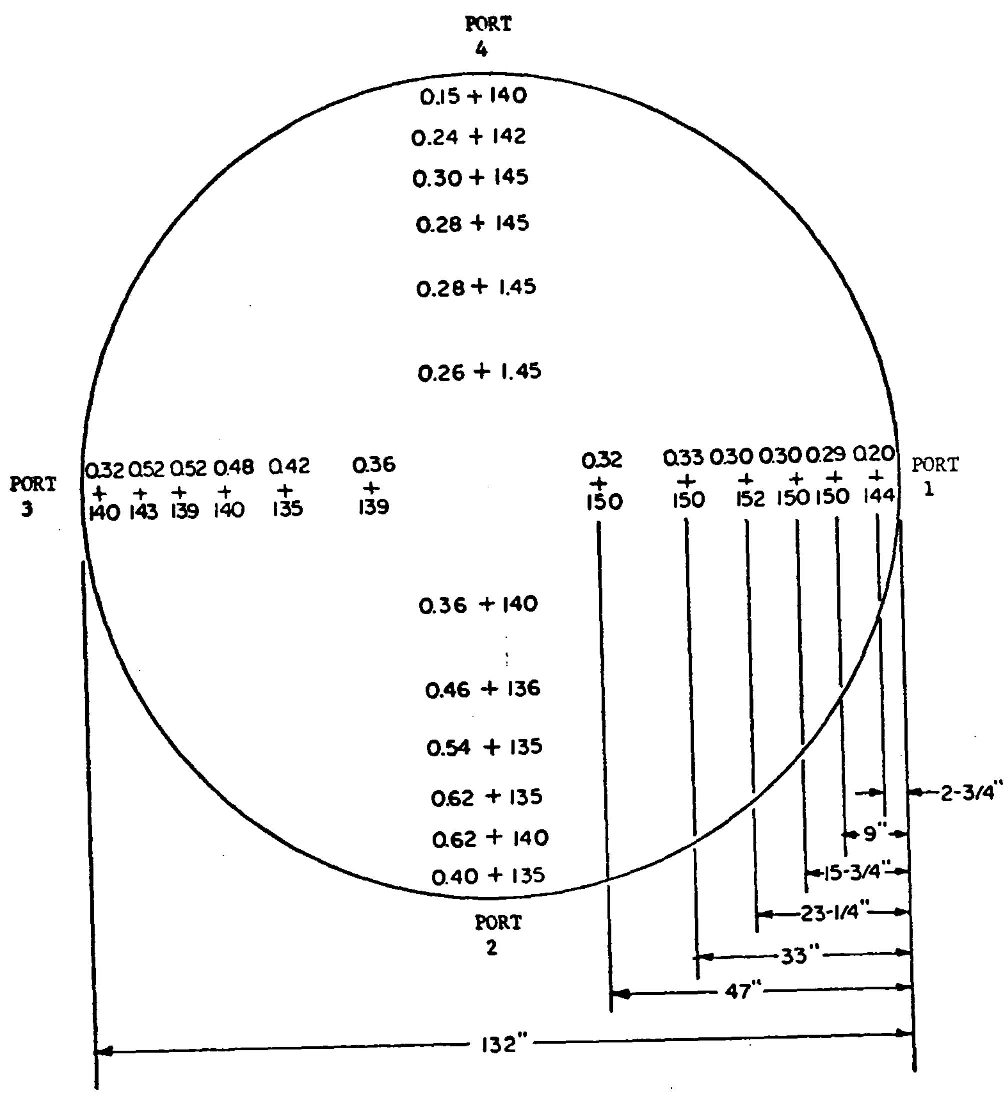


FIGURE 5. TYPICAL VELOCITY PRESSURE AND TEMPERATURE MEASUREMENTS AT SAMPLING POINTS IN THE STACK AT TEST SITE II

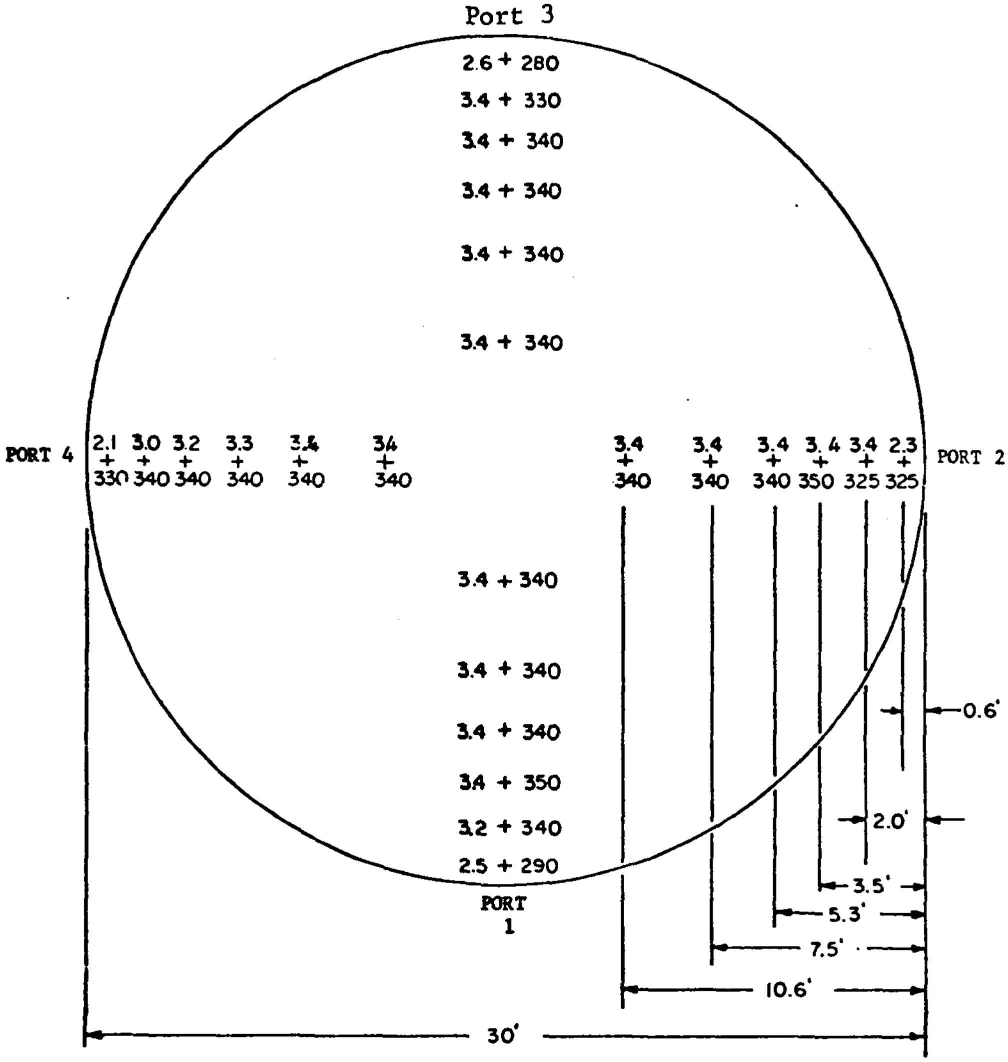


FIGURE 6. TYPICAL VELOCITY PRESSURE TEMPERATURE MEASUREMENTS AT SAMPLING POINTS IN STACK AT TEST SITE III

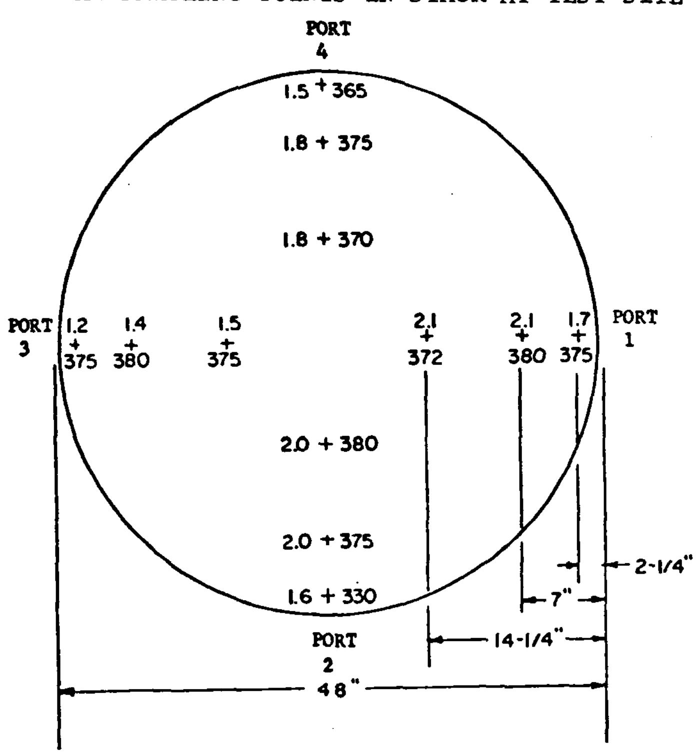


FIGURE 7. TYPICAL VELOCITY PRESSURE AND TEMPERATURE MEASUREMENTS AT SAMPLING POINTS IN STACK AT TEST SITE IV

TABLE 1. TEST PATTERN FOR VELOCITY MEASUREMENTS AT SITE I

Time Period[b]	Port Number[a]					
	1	3	5	7	9	11
I	B	A	D		C	
II		B	A	D		C
III	C		B	A	D	
IV		C		B	A	D
V	D		C		B	A
VI	A	D		C		B

(a) Entries below are laboratory code Designations.
(b) Test duration was 144 minutes.

TABLE 2. TEST PATTERN FOR VELOCITY MEASUREMENTS AT SITE II

Time Period[b]	Port Number[a]			
	1	2	3	4
Odd Numbered Tests				
I	D	B	C	A
II	A	D	B	C
III	C	A	D	B
IV	B	C	A	D
Even Numbered Tests				
I	B	C	A	D
II	C	A	D	B
III	A	D	B	C
IV	D	B	C	A

(a) Entries below are laboratory code designations.
(b) Test duration was 120 minutes.

TABLE 3. TEST PATTERN FOR VELOCITY MEASUREMENTS AT SITE III

Time Period[b]	Port Number[a] 1	2	3	4
Odd Numbered Tests				
I	B	A	D	C
II	C	B	A	D
III	D	C	B	A
IV	A	D	C	B
Even Numbered Tests				
I	A	D	C	B
II	D	C	B	A
III	C	B	A	D
IV	B	A	D	C

(a) Entries below are laboratory code designations.
(b) Test duration was 120 minutes.

TABLE 4. TEST PATTERN FOR VELOCITY MEASUREMENTS AT SITE IV

Time Period[b]	Port Number[a] 1	2	3	4
Tests 1,3,5,7				
I	C	B	D	A
II	A	C	B	D
III	D	A	C	B
IV	B	D	A	C
Tests 2,4,6,8				
I	B	D	A	C
II	D	A	C	B
III	A	C	B	D
IV	C	B	D	A
Tests 9,11,13				
I	C	F	E	A
II	A	C	F	E
III	E	A	C	F
IV	F	E	A	C
Tests 10,12,14				
I	F	E	A	C
II	E	A	C	F
III	A	C	F	E
IV	C	F	E	A

(a) Entries below are laboratory code designations.
(b) Test duration was 48 minutes.

particulate measurements.

Measurements of the barometric pressure, static pressure of the stack and gas composition by Orsat analysis were performed by the Coordinating Laboratory at least once during each test period.

Test Site Descriptions

The characteristics of the four test sites at which Method D 3154-72 was evaluated are summarized in Table 5.

Site I

The tests at Site I were performed on a 120-MW oil-fired unit of an electrical generating station. During the testing period the unit was operated under steady-state conditions at full load capacity.

The velocity measurements were made in six ports located in a vertical run of the rectangular duct which is one of a pair that conducts the flue gas from the induction fan to the stack. The flow is approximately uniform between the two ducts. Curvature in the duct causes some irregularities in the flow pattern at this test location.

Site II

Site II tests were performed at a foundry on a stack carrying emissions from a total of five arc melting, arc holding, and induction furnaces. The operation of the arc melting furnaces is cyclic and results in relatively rapid (within minutes) gas temperature variations over the range of 90 to 200 F.

Velocity measurements were made at four ports at the 75-ft level of the stack. The test ports, which are spaced at 90 degrees, are located about 40 ft (about four stack diameters) above the stack inlet.

Site III

The Site III tests were conducted at a large coal-fired electrical generating station. The station has two units which have a total production

TABLE 5. SUMMARY OF TEST SITE CHARACTERISTICS

Site Characteristic	Site I	Site II	Site III	Site IV
Type of Operation	Electrical generation (120-Mw unit)	Foundry	Electrical generation (two - 800-Mw units)	Portland Cement Mfg. (dry process)
Emission Source	Oil-fired boiler	Arc furnaces	Coal-fired boilers	Coal-fired kiln
Emission Control Equipment	Electrostatic precipitator	Baghouse	Electrostatic precipitator	Electrostatic precipitator
Fuel Data				
Feed Rate	63,000 lb/hr	NA[a]	500 ton/hr	5500 lb/hr
Excess Air	30% [b]	NA	50% [b]	
Composition - C (wt. percent)	86.5	NA	(fixed, dry) 50.6	(fixed, dry) 52.9
- H	12.6	NA	--	--
- N	0.25	NA	--	--
- S	0.43	NA	3 - 4	2.8
			Volatiles 33.5	Volatiles 36.0
Flue Gas Data				
Average Velocity, fps	60	38	120	72-97
Average Gas Temperature, F	280	95-180	330	340-370
Composition - CO_2 Volume Percent	11.6	Negligible	12.0	10.0
- O_2 Volume Percent	5.4	21 (air)	6.8	13.4
- H_2O Volume Percent	8-10	1-2	5-7	4-6
- SO_2 ppm	225	Negligible	2200	800-1500
- NO_2 ppm	185	Negligible	400	120-250
Stack Data				
Size	4.67 ft x 12 ft	11-ft diameter	30-ft diameter	4-ft diameter
Height	(duct prior to stack)	100 ft	1200 ft	50 ft

(a) NA - not applicable.
(b) Based on Orsat analysis at test port location.

capacity of about 1600 MW. During most of the tests, the units operated at an output of about 1400 MW. During Tests 12 and 13, one of the units was operated at reduced load capacity.

Velocity was determined in the stack which handles the combustion products for both units. The four test ports, which are spaced at 90 degrees around the stack, are located at the 300-ft stack level. The port location is at least eight stack diameters above the inlets at the base of the stack.

Site IV

Test Site IV is a dry process portland cement manufacturing plant. Measurements were made on two different stacks carrying emissions from 10-ft-diameter by 154-ft-long cement kilns.

Tests 1 through 8 and 9 through 14 were performed on different stacks. Test ports in both stacks are located at 90-degree angles at a stack height of about 28 feet (about seven stack diameters) above the induction fan.

Particulate emissions which ranged from about 2 to 13 grains/SCFD, caused problems with restriction and plugging of pitot tubes at this site.

Participating Laboratories

A total of nine laboratories participated in the tests in which the stack gas velocity measurements were performed. The participants were teams from the following organizations:

George D. Clayton and Associates
The Detroit Edision Company
General Motors Corporation
Huron Cement Division of National Gypsum Company
Public Service Electric and Gas Company (New Jersey)
Research Triangle Institute
TRW
Western Electric Company
York Research Corporation.

Throughout this report the data generated by the various laboratories are concealed by using a set of code letters. The code letters designate different laboratories at each site. Four laboratories participated in the tests at Site I, II, and III and six laboratories took part in the Site IV tests.

STATISTICAL ANALYSIS OF VELOCITY MEASUREMENTS

Measure of Precision

ASTM Method D 2906-70T[11] defines precision as "the degree of agreement within a set of observations or test results obtained when using a method". The document further defines specific sources of variability in measuring precision, namely

> Single-operator precision - the precision of a set of statistically independent observations, all obtained as directed in the method and obtained over the shortest practical time interval in one laboratory by a single operator using one apparatus and randomized specimens from one sample of the material being tested.
>
> Within-laboratory precision - the precision of a set of statistically independent test results all obtained by one laboratory using a single sample of material and with each test result obtained by a different operator with each operator using one apparatus to obtain the same number of observations by testing randomized specimens over the shortest practical time interval.
>
> Between-laboratory precision - the precision of a set of statistically independent test results all of which are obtained by testing the same sample of material and each of which is obtained in a different laboratory by one operator using one apparatus to obtain the same number of observations by testing randomized specimens over the shortest practical time interval.

The estimates of these measures of precision are typically derived from an analysis of variance. In section 5.4 of ASTM Method D 2906-70T, components of variance obtained from an analysis of variance table are given the following notations:

S_S^2 = the single operator component of variance, or the residual error component of variance

S_W^2 = the within-laboratory component of variance (which has been called "repeatability" in previous Project Threshold Reports)

S_B^2 = the between-laboratory component of variance (which has been called "reproducibility" in previous Project Threshold Reports).

With the above components of variance, the standard errors (S_T) of specific types of averages are calculated as follows:

Single-operator standard error

$$S_T \text{ (single-operator)} = (S_S^2/n)^{1/2}$$

Within-laboratory standard error

$$S_T \text{ (within-laboratory)} = [S_W^2+(S_S^2/n)]^{1/2}$$

Between-laboratory standard error

$$S_T\text{(between-laboratory)}=[S_B^2+S_W^2+(S_S^2/n)]^{1/2},$$

where n is the number of observations by a single operator averaged into a determination.

The experimental study to evaluate ASTM Method D 3154-72 provides an estimate of between-laboratory standard error [S_T(between-laboratory)] for the measurement ot average velocity with a Type "S" pitot tube. Field testing limitations did not permit conduct of the testing pattern in such a manner that the components of variance between-laboratory, S_B^2, within-laboratory, S_W^2, and for a single operator, S_S^2, could be computed. At each site groups of four laboratories made velocity measurements with each laboratory making one measurement per test. This procedure yields the between-laboratory standard error S_T^2, but does not yield the components of variance, S_B^2, S_W^2, or S_S^2. For this situation the standard error measure of the between-laboratory precision S_T is the same as the standard deviation of the four concurrent velocity measurements. It should be noted from the above definition that S_T includes the components of variance associated with the single operator S_S^2, within-laboratory S_W^2, and between-laboratory S_B^2. Thus, S_T should not to be confused with either S_W^2 (repeatability) or S_B^2 (reproducibility), as defined and used in previous Project Threshold reports.

Additional discussions of the measurements of precision are given by Mandel[10] and in ASTM publications[11, 12].

Experimental Results

A total of 44 tests by 9 different cooperating laboratories were performed at 4 different field sites to generate data for the statistical evaluation of ASTM Method D 3154-72. The test data are summarized by site in Tables 6 through 9. The tables list the following data for each site, test, and laboratory.

CP	Type "S" pitot tube correction factor determined from calibration procedure, dimensionless
H_{avg}	Average velocity pressure in duct or stack, inches of water
$(H)^{1/2}_{avg}$	Average of the square roots of the velocity pressures, (inches of water)$^{1/2}$
TS	Average of gas temperature measurements at each traverse point in the duct or stack, F
PS	Absolute pressure in duct or stack, inches of mercury
O2, %	Oxygen concentration in flue gas based on Orsat analysis, volume percent
CO2 %	Carbon dioxide concentration in flue gas basedon Orsat analysis, volume percent
W, %	Moisture in flue gas based on condensate volume, volume percent
MD	Average molecular weight of flue gas, pound per pound mole, dry basis
U_{avg}	Average flue gas velocity, feet per second.

In calculating the moisture content of the flue gas in accordance with Equation (4) in Paragraph 7.5.1.1 of the Test Method, the term V_w, water vapor volume remaining in the meter volume, was omitted. In the equipment used for the tests, essentially all water vapor was removed by passing the gas sample stream through a desiccant trap prior to the dry test meter. Therefore, the gas was metered under dry conditions.

The average flue gas velocity, U_{avg}, was calculated using Equation (8) in Paragraph 8.2 of the Test Method.

TABLE 6. SUMMARY OF SITE I VELOCITY MEASUREMENTS

SITE	TEST	LAB	CP	H AVG	$(H)^{1/2}$ AVG	TS AVG	PS	O2,%	CO2,%	W,%	MD	U AVG ,FPS
I	1[a]	A	0.83									
		B	0.87									
		C	0.85									
		D	0.84									
I	2	A	0.83	1.09	1.02	278.	29.70	5.0	11.2	7.91	30.0	66.91
		B	0.87	0.87	0.91	278.	29.70	5.0	11.2	8.45	30.0	62.84
		C	0.85	0.86	0.91	274.	29.70	5.0	11.2	9.90	30.0	61.21
		D	0.84	0.91	0.93	280.	29.70	5.0	11.2	4.80	30.0	61.64
I	3	A	0.83	1.03	0.99	278.	29.75	5.0	11.2	9.42	30.0	65.16
		B	0.87	0.84	0.89	280.	29.75	5.0	11.2	9.06	30.0	61.13
		C	0.85	0.82	0.89	278.	29.75	5.0	11.2	9.71	30.0	59.94
		D	0.84	0.87	0.92	276.	27.75	5.0	11.2	7.56	30.0	62.87
I	4	A	0.83	0.96	0.96	275.	30.10	4.8	11.6	8.18	30.0	62.42
		B	0.87	0.91	0.94	278.	30.10	4.8	11.6	8.47	30.0	63.91
		C	0.85	0.89	0.92	267.	30.10	4.8	11.6	9.45	30.0	61.07
		D	0.84	0.84	0.89	258.	30.10	4.8	11.6	8.39	30.0	57.96
I	5	A	0.83	0.99	0.98	277.	30.00	4.8	11.6	10.58	30.0	64.00
		B	0.87	0.85	0.90	281.	30.00	4.8	11.6	8.87	30.0	61.98
		C	0.85	0.80	0.88	271.	30.00	4.8	11.6	9.29	30.0	58.46
		D	0.84	0.86	0.91	258.	30.00	4.8	11.6	9.43	30.0	59.43
I	6	A	0.83	0.99	0.97	279.	30.20	5.4	11.6	9.37	30.1	63.36
		B	0.87	0.94	0.95	281.	30.20	5.4	11.6	9.75	30.1	64.98
		C	0.85	0.86	0.91	256.	30.20	5.4	11.6	9.45	30.1	59.62
		D	0.84	0.87	0.91	260.	30.20	5.4	11.6	7.89	30.1	59.27
I	7	A	0.83	0.98	0.97	280.	30.20	5.4	11.6	8.59	30.1	63.36
		B	0.87	0.92	0.94	277.	30.20	5.4	11.6	9.24	30.1	64.33
		C	0.85	0.87	0.91	279.	30.20	5.4	11.6	10.06	30.1	61.04
		D	0.84	0.87	0.91	257.	30.20	5.4	11.6	5.99	30.1	59.01

(a) Equipment malfunctions by two laboratories, test aborted.

TABLE 7. SUMMARY OF SITE II VELOCITY MEASUREMENTS.

SITE	TEST	LAB	CP	H AVG	(H)^1/2 AVG	TS AVG	PS	O2,%	CO2,%	W,%	MD	U AVG ,FPS
II	1	A	0.82	0.39	0.61	135.	28.83	21.0	0.0	0.80	28.8	36.40
		B	0.87	0.41	0.63	139.	28.83	21.0	0.0	0.56	28.8	40.01
		C	0.81	0.43	0.65	133.	28.83	21.0	0.0	0.54	28.8	37.92
		D[a]	0.86									
II	2	A	0.82	0.40	0.63	155.	28.89	21.0	0.0	1.15	28.8	37.75
		B	0.87	0.36	0.59	161.	28.89	21.0	0.0	1.49	28.8	37.93
		C	0.81	0.41	0.63	152.	28.89	21.0	0.0	1.16	28.8	37.71
		D	0.86	0.39	0.62	165.	28.89	21.0	0.0	1.85	28.8	39.29
II	3	A	0.82	0.37	0.60	142.	28.82	21.0	0.0	1.79	28.8	35.87
		B	0.87	0.39	0.62	137.	28.82	21.0	0.0	0.71	28.8	38.92
		C	0.81	0.42	0.64	139.	28.82	21.0	0.0	1.27	28.8	37.53
		D[b]	0.86									
II	4	A	0.82	0.39	0.62	106.	28.73	21.0	0.0	1.31	28.8	35.88
		B[a]	0.87									
		C	0.81	0.42	0.64	107.	28.73	21.0	0.0	1.15	28.8	36.66
		D	0.86	0.38	0.61	111.	28.73	21.0	0.0	1.41	28.8	37.51
II	5	A	0.82	0.41	0.63	112.	28.73	21.0	0.0	1.32	28.8	36.97
		B	0.87	0.41	0.63	115.	28.73	21.0	0.0	1.48	28.8	39.45
		C	0.81	0.44	0.65	110.	28.73	21.0	0.0	0.80	28.8	37.57
		D	0.86	0.38	0.61	110.	28.73	21.0	0.0	1.45	28.8	37.36
II	6	A	0.82	0.33	0.57	166.	28.95	21.0	0.0	1.29	28.8	34.58
		B	0.87	0.36	0.59	159.	28.95	21.0	0.0	0.85	28.8	37.84
		C	0.81	0.38	0.61	162.	28.95	21.0	0.0	1.01	28.8	36.21
		D	0.86	0.36	0.59	171.	28.95	21.0	0.0	1.18	28.8	37.94
II	7	A	0.82	0.31	0.55	137.	28.68	21.0	0.0	1.54	28.8	33.07
		B	0.87	0.33	0.57	127.	28.68	21.0	0.0	1.48	28.8	35.97
		C	0.81	0.32	0.56	133.	28.68	21.0	0.0	1.15	28.8	33.13
		D	0.86	0.33	0.57	142.	28.68	21.0	0.0	1.47	28.8	35.53
	8	A	0.82	0.34	0.57	129.	28.73	21.0	0.0	1.56	28.8	34.08
		B	0.87	0.34	0.58	136.	28.73	21.0	0.0	1.21	28.8	36.45
		C	0.81	0.35	0.59	129.	28.73	21.0	0.0	1.99	28.8	34.42
		D	0.86	0.33	0.57	136.	28.73	21.0	0.0	1.62	28.8	35.62

(a) Equipment malfunction, laboratory unable to complete tests.
(b) EPA Method 5 glass probe broken during test.

TABLE 8. SUMMARY OF SITE III VELOCITY MEASUREMENTS

SITE	TEST	LAB	CP	H AVG	$(H)^{1/2}$ AVG	TS AVG	PS	O2,%	CO2,%	W,%	MD	U AVG ,FPS
III	1	A	0.83	3.20	1.78	331.	28.53	7.2	12.0	6.56	30.2	122.76
		B	0.84	3.25	1.80	318.	28.53	7.2	12.0	5.59	30.2	124.31
		C	0.84	3.30	1.81	323.	28.53	7.2	12.0	6.34	30.2	125.61
		D	0.84	3.30	1.81	329.	28.53	7.2	12.0	6.23	30.2	126.26
III	2	A	0.83	3.12	1.76	329.	28.80	7.2	12.0	7.01	30.2	120.87
		B	0.84	3.23	1.80	331.	28.80	7.2	12.0	5.60	30.2	124.39
		C	0.84	3.05	1.74	323.	28.80	7.2	12.0	6.05	30.2	120.14
		D	0.84	3.07	1.75	328.	28.80	7.2	12.0	6.24	30.2	121.03
III	3	A	0.83	2.97	1.72	330.	28.82	7.6	11.6	6.65	30.2	117.93
		B	0.84	2.90	1.70	327.	28.82	7.6	11.6	6.53	30.2	117.76
		C	0.84	2.87	1.69	324.	28.82	7.6	11.6	6.33	30.2	116.71
		D	0.84	2.86	1.69	329.	28.82	7.6	11.6	6.22	30.2	117.00
III	4	A	0.83	3.15	1.77	330.	29.00	6.8	12.6	6.69	30.3	120.80
		B	0.84	3.16	1.77	334.	29.00	6.8	12.6	6.85	30.3	122.93
		C	0.84	3.17	1.78	326.	29.00	6.8	12.6	6.73	30.3	122.33
		D	0.84	3.11	1.76	333.	29.00	6.8	12.6	6.68	30.3	121.88
III	5	A	0.83	3.20	1.79	330.	28.92	6.8	12.4	6.91	30.3	122.10
		B	0.84	3.13	1.77	333.	28.92	6.8	12.4	6.77	30.3	122.48
		C	0.84	3.21	1.79	333.	28.92	6.8	12.4	5.80	30.3	123.62
		D	0.84	3.19	1.78	337.	28.92	6.8	12.4	8.85	30.3	124.56
III	6	A	0.83	3.54	1.88	330.	28.11	6.2	12.8	7.87	30.3	130.57
		B[a]	0.84									[a]
		C	0.84	3.30	1.81	315.	28.11	6.2	12.8	7.42	30.3	125.75
		D	0.84	3.46	1.86	336.	28.11	6.2	12.8	7.73	30.3	131.15
III	7	A	0.83	3.47	1.86	330.	28.07	6.8	12.4	8.18	30.3	129.46
		B[a]	0.84									[a]
		C	0.84	3.37	1.83	329.	28.07	6.8	12.4	7.31	30.3	128.64
		D	0.84	3.34	1.82	335.	28.07	6.8	12.4	7.38	30.3	128.74
III	8	A	0.83	3.50	1.87	300.	28.51	6.4	12.6	7.52	30.3	126.27
		B	0.84	3.40	1.84	341.	28.51	6.4	12.6	6.58	30.3	129.29
		C	0.84	3.33	1.82	302.	28.51	6.4	12.6	6.73	30.3	124.40
		D	0.84	3.47	1.86	335.	28.51	6.4	12.6	7.18	30.3	130.13

TABLE 8. SUMMARY OF SITE III VELOCITY MEASUREMENTS (Continued)

SITE	TEST	LAB	CP	H AVG	(H)1/2 AVG	TS AVG	PS	O2,%	CO2,%	W,%	MD	U AVG ,FPS
III	9	A	0.83	3.36	1.83	300.	28.55	6.4	12.6	7.48	30.3	123.58
		B	0.84	3.30	1.82	342.	28.55	6.4	12.6	6.67	30.3	127.39
		C	0.84	3.19	1.78	305.	28.55	6.4	12.6	6.54	30.3	121.79
		D	0.84	3.30	1.82	336.	28.55	6.4	12.6	6.86	30.3	126.82
III	10	A(b)	0.83									
		B	0.84	3.35	1.83	336.	28.71	6.2	12.6	7.37	30.3	127.45
		C	0.84	3.14	1.77	311.	28.71	6.2	12.6	6.68	30.3	121.18
		D	0.84	3.27	1.81	333.	28.71	6.2	12.6	7.28	30.3	125.85
III	11	A	0.83	3.40	1.84	330.	28.60	6.2	12.6	7.42	30.3	126.66
		B	0.84	3.34	1.83	345.	28.60	6.2	12.6	7.58	30.3	128.43
		C	0.84	3.21	1.78	311.	28.60	6.2	12.6	8.04	30.3	122.99
		D	0.84	3.33	1.82	338.	28.60	6.2	12.6	7.24	30.3	127.51
III	12	A	0.83	1.92	1.38	309.	28.72	9.6	9.4	5.92	29.9	93.83
		B	0.84	1.89	1.37	317.	28.72	9.6	9.4	5.10	29.9	94.64
		C	0.84	1.81	1.34	306.	28.72	9.6	9.4	5.76	29.9	91.99
		D	0.84	1.89	1.37	313.	28.72	9.6	9.4	5.92	29.9	94.68
III	13	A	0.83	2.28	1.51	330.	28.64	6.6	12.4	7.19	30.2	103.55
		B(c)	0.84									
		C	0.84	2.07	1.43	325.	28.64	6.6	12.4	7.14	30.2	99.22
		D	0.84	2.15	1.46	332.	28.64	6.6	12.4	6.99	30.2	101.87
III	14	A	0.83	3.40	1.84	330.	28.67	6.4	12.4	8.15	30.2	126.72
		B	0.84	3.36	1.83	341.	28.67	6.4	12.4	8.03	30.2	128.42
		C	0.84	3.26	1.80	316.	28.67	6.4	12.4	7.19	30.2	124.12
		D	0.84	3.46	1.86	334.	28.67	6.4	12.4	7.51	30.2	129.63
III	15	A	0.83	3.41	1.84	330.	28.66	6.4	12.6	8.12	30.3	126.95
		B	0.84	3.40	1.84	343.	28.66	6.4	12.6	5.99	30.3	128.72
		C	0.84	3.38	1.83	321.	28.66	6.4	12.6	5.80	30.3	126.35
		D	0.84	3.35	1.83	336.	28.66	6.4	12.6	7.86	30.3	127.78

(a) Laboratory unable to participate in test due to leak in particulate sampling probe.
(b) Particulate sampling thimble ruptured during test.
(c) Equipment malfunction, laboratory did not complete test.

TABLE 9. SUMMARY OF SITE IV VELOCITY MEASUREMENTS

SITE	TEST	LAB	CP	H AVG	(H)1/2 AVG	TS AVG	PS	O2,%	CO2,%	W,%	MD	U AVG ,FPS
IV	1	A	0.81	1.86	1.36	378.	29.36	13.4	10.0	5.17	30.1	92.31
		B	0.81	1.66	1.28	344.	29.36	13.4	10.0	4.72	30.1	85.40
		C[(a)]	0.86	1.85	1.35	358.	29.36	13.4	10.0	5.51	30.1	96.64
		D[(a)]	0.86									
IV	2	A	0.81	1.75	1.31	361.	29.32	13.4	10.0	5.69	30.1	88.26
		B	0.81	1.90	1.37	353.	29.32	13.4	10.0	5.05	30.1	92.19
		C[(a)]	0.86	1.78	1.33	367.	29.32	13.4	10.0	4.58	30.1	95.40
		D[(a)]	0.86									
IV	3	A	0.81	1.80	1.33	350.	29.28	13.4	10.0	5.23	30.1	89.50
		B	0.81	1.83	1.35	353.	29.28	13.4	10.0	4.50	30.1	90.26
		C	0.86	1.81	1.34	364.	29.28	13.4	10.0	4.82	30.1	96.03
		D	0.86	1.25	1.10	364.	29.28	13.4	10.0	5.02	30.1	78.64
IV	4	A	0.81	1.70	1.29	347.	29.29	13.4	10.0	6.17	30.1	86.85
		B	0.81	1.86	1.36	352.	29.29	13.4	10.0	3.69	30.1	90.71
		C	0.86	1.79	1.33	363.	29.29	13.4	10.0	4.45	30.1	95.48
		D	0.86	1.78	1.33	363.	29.29	13.4	10.0	6.82	30.1	95.74
IV	5	A	0.81	1.71	1.30	358.	29.32	13.4	10.0	5.57	30.1	87.50
		B	0.81	1.84	1.35	370.	29.32	13.4	10.0	4.49	30.1	91.32
		C	0.86	1.66	1.28	371.	29.32	13.4	10.0	4.25	30.1	92.23
		D	0.86	1.72	1.31	371.	29.32	13.4	10.0	5.43	30.1	94.36
IV	6	A	0.81	1.42	1.18	350.	29.35	13.4	10.0	5.69	30.1	79.21
		B	0.81	1.95	1.39	368.	29.35	13.0	10.0	4.13	30.1	93.68
		C	0.86	1.87	1.36	361.	29.35	13.4	10.0	4.79	30.1	97.36
		D	0.86	1.80	1.34	361.	29.35	13.4	10.0	4.99	30.1	95.57
IV	7	A	0.81	1.77	1.32	355.	29.45	13.4	10.0	5.41	30.1	88.52
		B	0.81	1.95	1.39	358.	29.45	13.4	10.0	4.52	30.1	93.04
		C	0.86	1.78	1.33	363.	29.45	13.4	10.0	5.74	30.1	95.00
		D	0.86	1.81	1.34	363.	29.45	13.4	10.0	5.30	30.1	95.88
IV	8	A	0.81	1.78	1.33	356.	29.46	13.4	10.0	6.51	30.1	89.17
		B	0.81	1.83	1.34	338.	29.46	13.4	10.0	4.44	30.1	89.04
		C	0.86	1.67	1.28	368.	29.46	13.4	10.0	5.77	30.1	92.24
		D	0.86	1.81	1.34	367.	29.46	13.4	10.0	6.00	30.1	96.35

TABLE 9. SUMMARY OF SITE IV VELOCITY MEASUREMENTS (Continued)

SITE	TEST	LAB	CP	H AVG	(H)^1/2 AVG	TS AVG	PS	O2,%	CO2,%	W,%	MD	U AVG ,FPS
IV	9	A	0.81	1.27	1.12	375.	29.26	12.0	12.0	7.15	30.4	76.45
		E	0.86	1.19	1.09	354.	29.26	12.0	12.0	4.44	30.4	77.40
		C	0.86	1.21	1.10	380.	29.26	12.0	12.0	6.33	30.4	79.46
		F	0.81	1.17	1.08	360.	29.26	12.0	12.0	6.49	30.4	72.74
IV	10	A	0.81	1.18	1.08	384.	29.25	12.0	12.0	7.76	30.4	74.34
		E	0.86	1.19	1.09	370.	29.25	12.0	12.0	4.79	30.4	78.03
		C	0.86	1.19	1.09	390.	29.25	12.0	12.0	5.24	30.4	78.99
		F	0.81	1.18	1.09	367.	29.25	12.0	12.0	5.74	30.4	73.37
IV	11	A	0.81	1.21	1.09	390.	29.21	12.0	12.0	8.23	30.4	75.45
		E	0.86	1.15	1.07	370.	29.21	12.0	12.0	4.46	30.4	76.85
		C	0.86	1.19	1.09	394.	29.21	12.0	12.0	6.37	30.4	79.45
		F	0.81	1.17	1.08	365.	29.21	12.0	12.0	7.30	30.4	73.42
IV	12	A	0.81	1.17	1.08	361.	29.19	12.0	12.0	6.29	30.4	72.96
		E	0.86	1.20	1.09	347.	29.19	12.0	12.0	1.59	30.4	76.87
		C	0.86	1.18	1.08	365.	29.19	12.0	12.0	4.48	30.4	77.55
		F	0.81	1.21	1.10	337.	29.19	12.0	12.0	5.27	30.4	72.95
IV	13	A	0.81	1.44	1.20	388.	29.16	12.0	12.0	7.63	30.4	82.43
		E	0.86	1.35	1.16	371.	29.16	12.0	12.0	3.95	30.4	83.13
		C	0.86	1.31	1.14	388.	29.16	12.0	12.0	5.25	30.4	83.05
		F	0.81	1.36	1.16	379.	29.16	12.0	12.0	5.91	30.4	79.40
IV	14	A	0.81	1.39	1.18	387.	29.18	12.0	12.0	6.69	30.4	80.68
		E	0.86	1.36	1.16	373.	29.18	12.0	12.0	3.99	30.4	83.60
		C	0.86	1.33	1.15	392.	29.18	12.0	12.0	5.19	30.4	83.67
		F	0.81	1.33	1.15	375.	29.18	12.0	12.0	5.91	30.4	78.42

(a) Equipment malfunction, laboratory unable to complete tests.

Analysis of Precision

Statistical analyses of the average velocity measurements are presented in Table 10. The table gives the number of measurements per test, n; the mean value of the average velocity test measurements, m; and the standard-error for between-laboratory measurements expressed as the standard deviation (S_T) and the coefficient of variation (CV) for the tests at each field site. The standard deviation of the velocity measurements was calculated by the equation:

$$S_T(\text{between-laboratory}) = \sqrt{\frac{\sum_{i=1}^{n} (X_i - m)^2}{n-1}} \qquad (1)$$

where m is the test mean, X_i is velocity value determined by the i^{th} laboratory and n is the number of velocity measurements per test.

The coefficient of variation expressed in percent, is calculated from the test mean (m) and the standard deviation (S_T) using the equation:

$$CV,\% = \frac{S_T\,(100)}{m} \quad . \qquad (2)$$

An expression of the standard error of the Test Method over the velocity ranged studied is derived from the individual test values of mean velocity (m) and standard deviation (S_T) given in Table 10. Figure 8 is a scattergram in which 35 pairs of m and S_T values are plotted. Data generated in Site IV, Tests 1 through 8, have been excluded.(*) The curve shown in Figure 8 is derived from a regression equation of the form $\hat{s} = b\sqrt{m}$ which was fitted to the data points by the method of weighted least squares. Weighting was used to compensate for unequal sample size and unequal variance along the regression curve. The fitting procedure yields the equation $\hat{S}_T = 0.21\sqrt{m}$ as the estimate of the true regression curve. The standard deviation of residuals about the regression curve is 0.73. The curve $\hat{S}_T = 0.21\sqrt{m}$ provides an estimate of the reproducibility of the Test Method over the average velocity range of about 35 to 130 fps. The Method yields good reproducibility in velocity measurements with about a 3 percent coefficient of variation at 50 fps, improving to about 2 percent at 100 fps.

(*) High dust loadings encountered during these tests caused abnormal data variations due to plugging of the pitot tubes.

TABLE 10. STATISTICAL ANALYSIS OF VELOCITY DETERMINATIONS

Site	Test Number	Number of Measurements, n	Velocity Data, fps		
			Mean, m	Std. Dev., S_T	CV, %
I	2	4	63.15	2.60	4.1
	3	4	62.28	2.27	3.6
	4	4	61.34	2.53	4.1
	5	4	60.97	2.51	4.1
	6	4	61.86	2.76	4.5
	7	4	61.97	2.40	3.9
II	1	3	38.11	1.81	4.8
	2	4	38.17	0.75	2.0
	3	3	37.44	1.52	4.1
	4	3	36.69	0.81	2.2
	5	4	37.84	1.10	2.9
	6	4	36.65	1.58	4.3
	7	4	34.43	1.53	4.4
	8	4	35.15	1.09	3.1
III	1	4	124.74	1.55	1.2
	2	4	121.61	1.90	1.6
	3	4	117.35	0.59	0.5
	4	4	121.99	0.90	0.7
	5	4	123.19	1.12	0.9
	6	3	129.16	2.96	2.3
	7	3	129.00	0.40	0.3
	8	4	127.52	2.66	2.1
	9	4	124.90	2.66	2.1
	10	3	124.83	3.26	2.6
	11	4	126.40	2.38	1.9
	12	4	93.79	1.26	1.3
	13	3	101.55	2.18	2.2
	14	4	127.22	2.39	1.9
	15	4	127.45	1.03	0.8
IV	1	3	91.45	5.67	6.2
	2	3	91.95	3.58	3.9
	3	4	88.53	7.40	8.4
	4	4	92.20	4.25	4.6
	5	4	91.35	2.87	3.1
	6	4	91.46	8.30	9.1
	7	4	93.11	3.28	3.5
	8	4	91.70	3.43	3.7
	9	4	76.51	2.81	3.7
	10	4	76.18	2.74	3.6
	11	4	76.29	2.53	3.3
	12	4	75.08	2.47	3.3
	13	4	82.00	1.76	2.2
	14	4	81.59	2.53	3.1

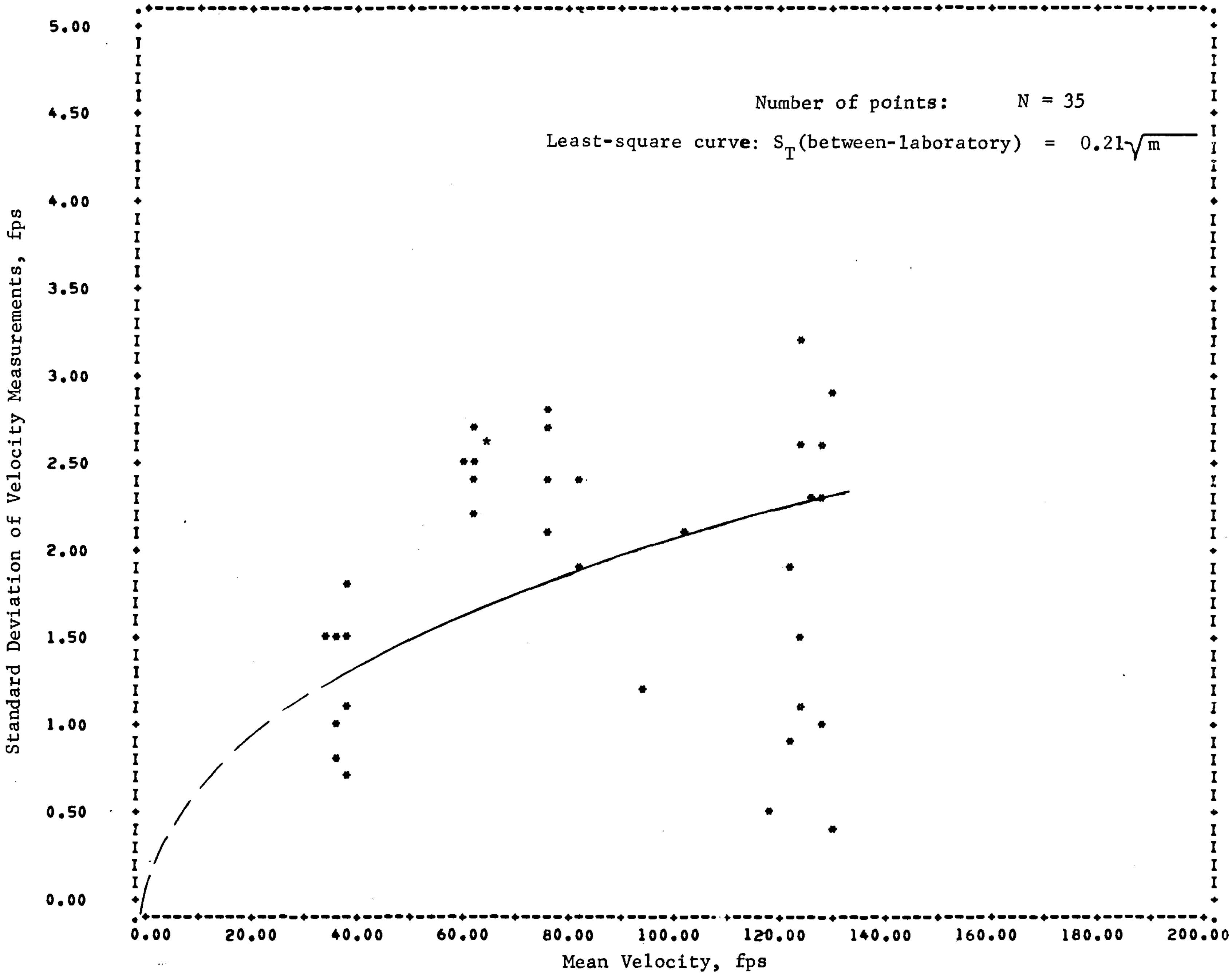


FIGURE 8. SCATTERGRAM AND LEAST-SQUARE CURVE RELATING BETWEEN-LABORATORY STANDARD ERROR TO MEAN VELOCITY FOR MEASUREMENTS USING ASTM D 3154-72.

Sources of Variability

The variability in the between-laboratory velocity measurements includes variations in the determinations of the velocity pressure, gas temperature, and moisture content of the gas. A statistical analysis of these measurements is given in Table 11. The table presents, for each test, the mean, standard deviation, and coefficient of variation of the velocity pressure (H_{avg}), percent moisture, and gas temperature measurements. The standard deviation and coefficient of variation are calculated using Equations (1) and (2), respectively.

A regression analysis was performed to investigate the relationship of variations in average velocity and variations in velocity pressure, gas temperature, and moisture measurements. The analysis shows that the highest correlation exists between average velocity and velocity pressure. The plot of the averages of the square roots of the velocity pressure $(U)^{1/2}_{avg}$ versus average velocity presented in Figure 9 illustrates the high degree of correlation. The results of the regression analysis indicate that greater than 99 percent of the variability in the average velocity determinations can be explained by the corresponding variation in velocity pressure measurements.

Variations in the measurement of flue gas temperature and moisture, even though the latter varied appreciably in some tests, do not significantly increase the amount of explained variability in the average velocity determinations.

The observed variability in the velocity determinations appears in the form of systematic differences between laboratories. If the laboratories are ranked from highest to lowest values of average velocity, about the same general patterns are observed for all tests at most sites. Furthermore, a correlation appears to exist between the magnitude of the pitot tube calibration factor (CP) and the ranking; the higher CP factors are usually correlated with higher velocity values and vice versa. The relationship suggests that a bias may be introduced by the pitot calibration procedure.

If an arbitrary pitot correction factor of 0.84 is used to calculate average velocity, the ranking of laboratories by the magnitude of the average velocity is less systematic. Variability in the measurements at Site I increases slightly, Sites II and IV variations decrease slightly, and Site

TABLE 11. STATISTICAL ANALYSIS OF VELOCITY PRESSURE, MOISTURE, AND GAS TEMPERATURE MEASUREMENTS

Site	Test Number	n	Velocity Pressure, $H_{avg.}$, in. H_2O Test Mean	Std. Dev.,	CV,%	Percent Moisture Test Mean	Std. Dev.,	CV,%	Gas Temperature, F Test Mean	Std. Dev.,	CV,%
I	2	4	0.93	0.11	11.8	7.77	2.15	27.7	277	3	1.1
	3	4	0.89	0.10	11.2	8.94	0.96	10.7	278	2	0.6
	4	4	0.90	0.05	5.6	8.63	0.58	6.7	270	9	3.3
	5	4	0.88	0.08	9.1	9.54	0.73	7.7	272	10	3.7
	6	4	0.92	0.06	6.5	9.13	0.84	9.2	269	13	4.8
	7	4	0.91	0.05	5.5	8.48	1.76	20.8	273	11	4.0
II	1	3	0.41	0.02	4.9	0.66	0.20	30.3	136	3	2.3
	2	4	0.39	0.02	5.1	1.43	0.31	21.7	158	6	3.7
	3	3	0.39	0.03	7.7	0.99	0.90	90.9	139	3	1.8
	4	3	0.40	0.02	5.0	1.35	0.18	13.3	108	3	2.4
	5	4	0.41	0.02	4.9	1.25	0.31	24.8	112	2	2.1
	6	4	0.36	0.02	5.6	0.88	0.63	71.6	165	5	3.2
	7	4	0.32	0.01	3.1	1.46	0.25	17.1	135	6	4.7
	8	4	0.34	0.01	2.9	1.65	0.33	20.0	133	4	3.0
III	1	4	3.26	0.05	1.5	6.18	0.42	6.8	325	6	1.8
	2	4	3.12	0.08	2.6	6.23	0.59	9.5	328	3	1.0
	3	4	2.90	0.05	1.7	6.43	0.19	3.0	328	3	0.8
	4	4	3.15	0.03	1.0	6.74	0.08	1.2	331	4	1.1
	5	4	3.18	0.04	1.3	7.08	1.28	18.1	333	3	0.9
	6	3	3.43	0.12	3.5	7.67	0.23	3.0	327	11	3.3
	7	3	3.39	0.07	2.1	7.84	0.41	5.2	331	3	1.0
	8	4	3.43	0.08	2.3	7.00	0.43	6.1	320	22	6.7
	9	4	3.29	0.07	2.1	6.89	0.42	6.1	321	21	6.6
	10	3	3.25	0.11	3.4	7.11	0.38	5.3	327	14	4.2
	11	4	3.32	0.08	2.4	7.57	0.34	4.5	331	15	4.4
	12	4	1.88	0.05	2.7	5.68	0.39	6.9	312	4	1.2
	13	3	2.17	0.11	5.1	7.11	0.10	1.4	329	4	1.1
	14	4	3.37	0.08	2.4	7.72	0.45	5.8	330	11	3.2
	15	4	3.39	0.03	0.9	6.94	1.22	17.6	333	9	2.8

TABLE 11. STATISTICAL ANALYSIS OF VELOCITY PRESSURE, MOISTURE, AND GAS TEMPERATURE MEASUREMENTS (Continued)

Site	Test Number	n	Velocity Pressure, $H_{avg.}$, in. H_2O Test Mean	Std. Dev.,	CV,%	Percent Moisture Test Mean	Std. Dev., σ	CV, %	Gas Temperature, F Test Mean	Std. Dev.,	CV,%
IV	1	3	1.79	0.11	6.1	5.13	0.40	7.8	360	17	4.8
	2	3	1.81	0.08	4.4	5.11	0.56	11.0	360	7	1.9
	3	4	1.67	0.28	16.8	4.89	0.31	6.3	356	6	1.7
	4	4	1.78	0.07	3.9	5.28	1.46	27.7	356	8	2.3
	5	4	1.73	0.08	4.6	4.94	0.66	13.4	368	6	1.7
	6	4	1.76	0.23	13.1	4.90	0.64	13.1	360	7	2.1
	7	4	1.83	0.08	4.4	5.24	0.52	9.9	360	4	1.1
	8	4	1.77	0.07	4.0	5.68	0.88	15.5	357	14	3.9
	9	4	1.21	0.04	3.3	6.10	1.16	19.0	367	12	3.3
	10	4	1.19	0.01	0.8	5.88	1.31	22.3	378	11	2.9
	11	4	1.18	0.03	2.5	6.59	1.61	24.4	380	14	3.8
	12	4	1.19	0.02	1.7	4.41	2.02	45.8	353	13	4.0
	13	4	1.37	0.05	3.6	5.69	1.53	26.9	382	8	2.1
	14	4	1.35	0.03	2.2	5.45	1.15	21.1	382	9	2.4

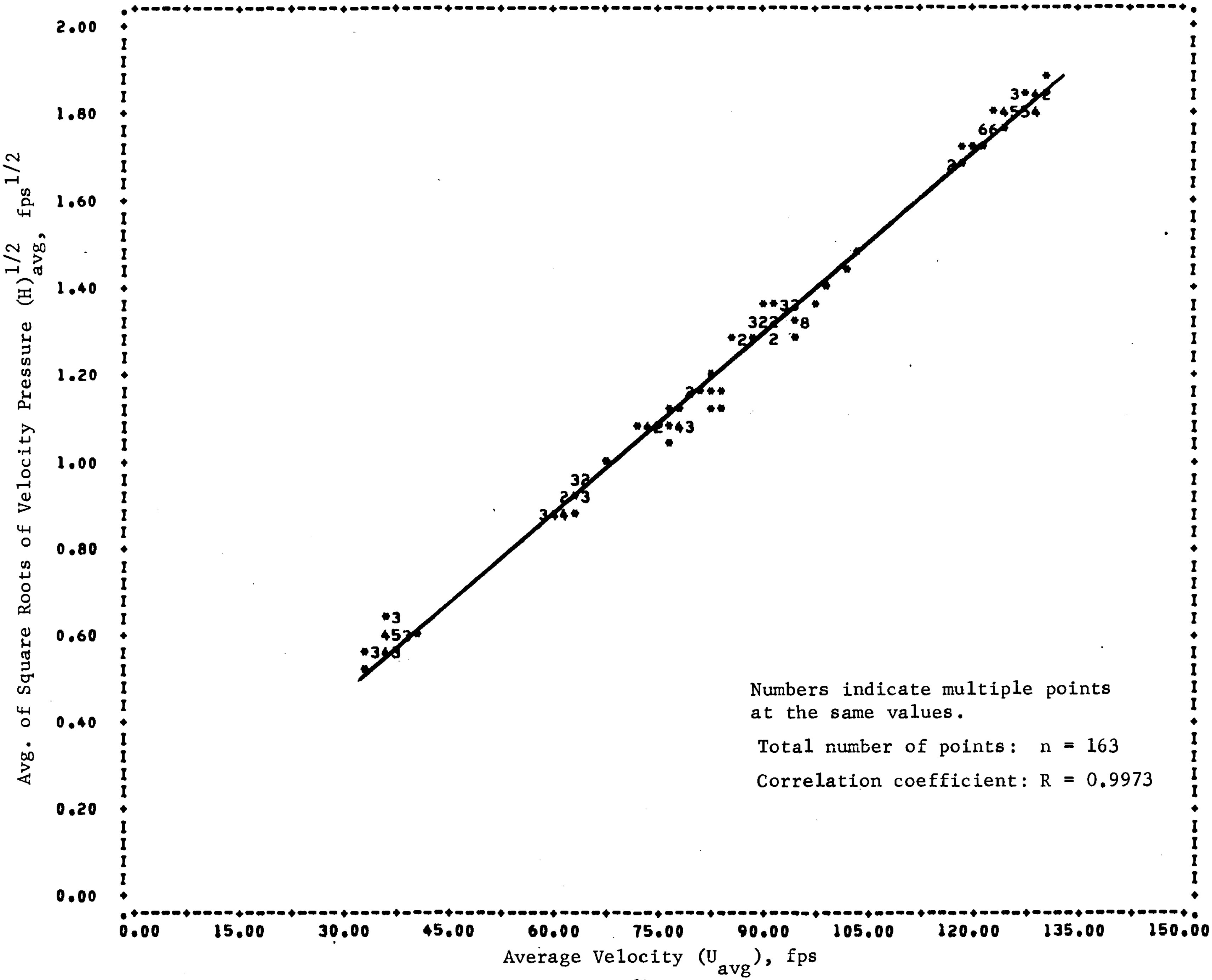


FIGURE 9. SCATTERGRAM SHOWING CORRELATION BETWEEN VELOCITY PRESSURE AND AVERAGE VELOCITY

III data are not significantly affected. In general, however, the standard deviations of all tests and the resultant statistical conclusions drawn from this study are not altered significantly.

The intrinsic relationship between velocity pressure and the pitot factor makes it impossible to definitively isolate the separate effects of tube calibration and errors due to estimation of the velocity pressure reading which also might be systematic in nature. Although the results suggest that the variability observed in this study may contain a component due to pitot tube calibration, the net effect of this component does not appear to significantly increase the magnitude of the between-laboratory variations.

DISCUSSION AND CONCLUSIONS

The standard error for average velocity measurements, in the range 30 to 130 fps, made with a Type "S" pitot tube in accordance with ASTM Method D 3154-72 may be estimated by the equation:

$$S_T(\text{between-laboratory}) = 0.21\sqrt{m} ,$$

where, S_T, the standard error and, m, the mean velocity are in feet per second.

A practical application of the standard error estimate is the construction of confidence limits of measurements obtained using the Test Method. If it is assumed that a laboratory's measurement of the average velocity by this method is unbiased, and further that the distribution of this measurement by various laboratories follows a normal distribution, then a 95 percent confidence limit for a single laboratory's measurement can be determined as the observed measurement, $m \pm 1.96\ S_T$, where S_T is calculated as $S_T = 0.21\sqrt{m}$. If a large number of laboratories were to make simultaneous measurements of this average velocity, we would expect approximately 95 percent of these simultaneous measurements to lie within this confidence interval. Alternatively, realizing that between laboratory variability exists, this 95 percent confidence interval represents a reasonable estimate of the range in which any single measurement of the average velocity will fall.

The most significant source of variability in the velocity measurement is that associated with the determination of the velocity pressure. Consequently, the following factors which affect velocity pressure readings can be expected to have a significant bearing on the accuracy and precision of average velocity measurements.

- Manometer zero and level
- Technique used to read manometer liquid level
- Use of a capillary to damp flucuations
- Pitot tube calibration
- Length of lines between the pitot tube and manometer
- Plugging of pitot tube by particulates in gas stream
- Leaks in lines or connections
- Departures from steady-state flow conditions.

The study results show that, in general, normal variations in the measurement of other parameters associated with the determination of average velocity have a much less significant effect on precision.

RECOMMENDATIONS

The results of this study demonstrate that no major modifications are required to the overall procedure described in ASTM Method D 3154-72 to produce precise measures of average velocity. However, minor changes and additions to the procedure and the official text are suggested.

(1) Paragraph 7.5.1 should be rewritten to include the determination of moisture content by use of a desiccant trap following the condenser. This method is commonly used in current particulate sampling procedures.

(2) A precaution should be added that accuracy and precision can be affected by higher dust loading. Frequent purging of the lines with a positive displacement pump should be recommended to alleviate errors caused by clogging of the pitot tube.

(3) A precaution should be added concerning the buildup of a static charge on the pitot tube, particularly when measuring velocity in a flue following an electrostatic precipitator. Grounding of the pitot tube to eliminate the shock hazard should be recommended.

(4) The following typographical errors are noted in the official text of the method.

Paragraph 7.4.

(a) The static pressure should be identified as P_s' in Equation (1).

(b) The prime (') notation has been omitted in the definition of the terms in Equation (1).

(c) Check is mispelled.

Paragraph 8.2.

The constant referred to in this paragraph is calculated in Paragraph 7.6.

Paragraph 9.2.

Paragraph 8.1.4 concludes the discussion of traverse point selection.

Paragraph 9.3.4.

Traverse points may be calculated by referring to Equation (7).

<u>Paragraph 9.5.</u>

Words are missing in third sentence. "Opening" is misspelled in the fourth sentence.

(5) A statement of precision based on this interlaboratory study should be included in the method.

The following additional revisions are recommended based on review of the method by the cooperating laboratories.

1. It is suggested that the method consistently refer to "ducts" rather than "stacks", "flues" or "breechings".
2. Draft gauges should be consistently called "manometers".
3. Section 4.2 should state that this method (D 3154) is likewise applicable to measurement of unsteady state velocities, however, certain precautions must be taken as stated in Section 9.6.
4. Section 6.1.2. A correction factor of 0.99 for a standard Pitot tube ("3/8 inch") should be noted.
5. Section 6.1.3. We disagree with the statement, "However, use of the standard pitot tube, where feasible, will give additional accuracy" Higher readings result from use of a Type S pitot tube and therefore resolution is more easily obtained with a Type "S" pitot tube.
6. Placing U gauges at an angle is an inaccurate method of measurement and its mention should be removed from the text of Section 6.2.1.
7. Section 6.3 should read "Thermocouple - A device which generates a small voltage whenever two junctions of two dissimilar metals in an electric circuit are at different temperature levels.
8. The title of Section 7 should be "Elements of Velocity Measurement".
9. The requirement of using an inclined manometer which reads to within one percent of the highest reading <u>expected</u> as stated in Section 7.1 is an unnecessarily stringent requirement which was not adhered to during the field testing of Project Threshold; and further, requires field equipment which is not available.
10. Remove the word "log" from the last sentence of Section 7.1. Its use there is redundant.
11. Remove the words "standard metal" from the first sentence of Section 7.3. They are redundant.

12. In section 7.3.1, "small" flues should be defined as "less than or equal to 2-feet effective diameter".

13. Section 7.4. - Use of an Type "S" Pitot tube to measure static pressure should not be discouraged by mentioning significant errors. For most stack static pressures even a 20 percent deviation results in an insignificant deviation of the absolute pressure measurements.

14. Section 7.4. - "Atmospheric pressure" should be replaced by "barometric pressure" for consistency of terminology.

15. Equation 3 in Section 7.5.1.2 is only applicable in a sampling train where the meter is at the same pressure as that in the condenser, which is not true for the ASTM sampling train. The equation should read:

$$V_w = V_m \frac{(\ Pwc\ )}{(\ Pc\ )} ,$$

where P_c is the pressure of the condenser. This term, V_w, can be ignored if silica gel is used in the final impinger and its weight increase added to the condensate volume. Using this procedure simplifies equation 4. We suggest the use of silica gel be incorporated in the method for moisture determination thus eliminating the need to measure the condenser temperature and pressure.

16. The comma is misplaced in the definition of W in Section 7.5.2.1. The comma should follow "gas", not "volume".

17. Rankine temperatures should be noted at all mention of stack and meter temperatures. (Sections 7.5.1.1., 7.6, 8.2)

18. Section 7.6. The second portion of this section is concerned with multi-point velocity averaging. It should be mentioned in Section 8.2.

19. Sections 8.1.-8.1.4 do not specify an exact procedure for the determination of the number of traverse and/or sampling points. The method should propose an exact procedure in order to assure reproducible and representative results.

20. In Section 8.2, the definition of Cp should be "average pitot tube correction factor, dimensionless" and the definition of T_s should be "average absolute temperature in duct, deg".

21. Figure 7 gives two inconsistent indications of the number of sampling points to be chosen. Rather than presenting the lower table, we suggest the enclosure of the more versatile Table 1.1 of the proposed ASTM particulate sampling method.
22. We disagree with the statement in Section 8.1.4 "Where sampling sites are less than two diameters downstream from flow disturbance, reasonable accuracy with pitot tube measurements cannot be expected." When sampling at a sufficient number of points, especially in a large diameter duct (greater than eight feet effective diameter) or in a duct with low velocity pressure (approximately 0.2 inch of water or less) an accurate representation of the flow rate is attained. We note that velocity traverse data at Site I of Project Threshold were collected in a curved section of ductwork.
23. Section 8.2. After defining terms in equation (8) the following statement should appear, in place of the second portion of Section 7.6. "This equation should be used in the case that stack temperatures do not vary by more than ten percent. However, if stack temperatures at the various points vary by more than ten percent, the square root of the product of the velocity pressure and stack temperature at each point should be averaged and then multiplied by 85.4 $Cp(P_sM_s)^{-1/2}$ to determine the average velocity.
24. The fourth sentence of Section 9.4 should say "ports" instead of "parts".
25. Delete the incomplete sentence "The differential should fluid stabilizes" of Section 9.5.
26. Section 9.6 is well-written and offers helpful suggestions.
27. The method should include a detailed description of the pitot tube calibration procedure.

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(12) "Use of the Terms Precision and Accuracy as Applied to Measurement of a Property of a Material", ASTM Method E 177.

APPENDIX A

REPRINT OF ASTM

STANDARD METHOD OF TEST FOR AVERAGE VELOCITY IN A DUCT (PITOT TUBE METHOD)

ASTM Designation: D 3154-72

Designation: D 3154 - 72

Standard Method of Test 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.

1. Scope

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

2. Applicable Documents

2.1 *ASTM Standards:*

D 1356 Definitions of Terms Relating to Atmospheric Sampling and Analysis[2]

D 2928 Sampling Stacks for Particulate Matter[2]

E 337 Determining Relative Humidity by Wet- and Dry-Bulb Psychrometer[3]

3. Summary of Method

3.1 This method covers the 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.

4. Significance

4.1 The material being presented here is available, in part, in Method D 2928, as well as ASME Methods (**1,2**),[4] the Federal Register (**3**) and other publications (**4**). Many times the title of the publication does not indicate that it includes procedures for velocity measurement. Therefore, this method is being made available as a separate reference.

4.2 The method presented is basically oriented to steady-state flow and constant fluid properties. It is recognized that deviations from steady state do occur. This method discusses and indicates the relative effect of deviations from steady state, for the various factors that contribute to the calculation of an average velocity.

5. Definitions

5.1 For definitions of terms used in this method, refer to Definitions D 1356.

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 is shown in Fig. 1. Details are shown in Fig. 2.

6.1.1 To minimize the stem effect caused when the physical dimensions of the pitot tube are too large with respect to the flow scale, the diameter of the pitot tube barrel should not exceed $\frac{1}{30}$ the size of the duct diameter.

6.1.2 At locations where the standard pitot tube cannot be inserted into the flue, or where dust or moisture or both are present which might clog the small holes in this instrument, a Staubscheibe pitot tube, commonly called a Type "S" pitot tube, shown in Fig. 3 should be used. For this latter case, it is necessary to apply a correction factor to compensate for the inherent high reading given by the Type "S"

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[1] This method is under the jurisdiction of ASTM Committee D-22 on Sampling and Analysis of Atmospheres.

Current edition approved Dec. 29, 1972. Published March 1973.

[2] *Annual Book of ASTM Standards*, Part 23.

[3] *Annual Book of ASTM Standards*, Parts 15, 24, and 30.

[4] The boldface numbers in parenthesis refer to the list of references at the end of this method.

pitot tube. The correction factor may be determined by comparing readings taken with a Type "S" pitot tube and with a standard pitot tube. Every Type "S" pitot tube must be calibrated since the correction factor as stated by the manufacturer for these instruments may be inaccurate. The correction factor is usually in the order of 0.85 ± 0.02. The calibration should be made in a velocity-calibrated gas stream and must be made over the velocity range of interest.

6.1.3 The Type "S" pitot tube may be used in all applications. However, use of the standard pitot tube, where feasible, will give addiional accuracy.

6.2 *Manometer*—The manometer is a simple and useful instrument for measuring small values of differences in pressure. In its simplest form, the manometer consists of a U-shaped glass tube partially filled with a liquid. A difference in height of the two fluid columns denotes a difference in pressure on the two legs, which is proportional to the difference in height.

6.2.1 *Draft Gage*—For measuring pressure differences of a few inches of water or less, U-gages are often set at an angle for scale amplification. In many gages of this type, commonly termed draft gages or inclined manometers, only one tube of small bore is used and the other leg is replaced by a reservoir.

6.3 *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 *Potentiometer*—An instrument for measuring small voltages, or for comparing small voltages with a known voltage.

7. Single-Point Velocity Measurement

7.1 The pitot tube is used to sense the difference between the total and static pressures in a moving gas stream. This pressure differential is equal to the velocity head and is read on a suitable manometer or draft gage in inches of water. The accuracy of the velocity reading depends on the type of manometer and for this reason an inclined manometer that reads to within 1 % of the highest reading expected should be used. Before use, level, zero and leak test a draft gage in accordance with 9.4. Check the zero reading before and after each set of readings. Record the readings on a gas velocity data log sheet.

7.2 *Velocity*—A standard pitot tube and inclined manometer are satisfactory for measuring velocity pressures of 0.01 in. (0.25 mm) of water (equivalent to 10 ft/s at 70 (3 m/s at 21.1 C)) or greater. Measure the velocity at specific points within the flue in accordance with a plan determined by flue size. Marks placed on the pitot tube aid in locating the sampling points at which the velocity is to be measured.

7.3 *Temperature*—Measure the gas temperature with a standard metal thermocouple and a potentiometer. In larger flues, measure the temperature at various points as is done in measuring velocites. If possible, take temperature and velocity traverses simultaneously. Unshielded thermocouples may be used to a temperature of about 700 F (370 C). For higher temperatures, use a high-velocity gas-aspirated shielded thermocouple selected in accordance with reference (**3**).

7.3.1 In small flues a standard mercury bulb thermometer inserted into the flue 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 a reading is taken. If there are frequent variations of the gas temperature with time due to process changes, a continuous recording of the temperature will prove useful.

7.4 *Static Pressure*—Measure the static pressure by connecting the static pressure tap of a standard pitot tube to one side of a water gage manometer leaving the other leg open to the atmosphere. A ¼-in. (6.4 mm) tap in the wall of the flue may also be used if it is not near any obstructions. If high static pressures are expected, use a vertical U-tube manometer calibrated to be read in inches of water. An alternative method, not generally recommended because its precision is only ± 20%, is to insert the Type "S" pitot tube into the duct and rotate it 90 deg to the direction of the gas flow, then connect either leg to a manometer and read the static pressure. The absolute pressure in the flue is equal to the atmospheric pressure plus or minus the static pressure in the flue depending on whether it is under vacuum or pressure.

$$P_s = P_b \pm (p'_s/13.6) \quad (1)$$

where:

P_s = absolute pressure in flue, in. Hg,
P_b = barometric pressure, in. Hg, and
P_s = static pressure in flue, in. water

7.4.1 The static pressure need only be determined at a single point in the flue in most cases. Chick this pressure occasionally throughout the test period.

7.5 *Gas Density*—Gas density depends on the temperature, the absolute pressure, the moisture content, and on the composition of the gas stream.

7.5.1 *Moisture Content*—Determine the water content of the gas stream by passing a known volume of the gas stream through an ice-bath condenser. The volume of water condensed should be measured in a standard graduated cylinder, or other volumetric mass determination, that will give accuracy within 5 % when using Method D 2928. Use the condensed water volume and the temperature of the gas leaving the condenser to determine the total moisture content. An explanation of these calculations follows:

7.5.1.1 Determine the equivalent vapor volume of the condensate at the meter:

$$V_c = (C_w/453.6)(387/18)(T_m/530)(29.92/P_m)$$

$$V_c = 0.00268\,(C_w)(T_m/P_m) \quad (2)$$

where:

V_c = equivalent vapor volume of condensate at meter conditions, ft³,
C_w = volume of condensate in condenser, ml,
T_m = absolute temperature at meter, deg, and
P_m = absolute pressure at meter, in. Hg.

7.5.1.2 Determine amount of water remaining in gas stream after condenser:

$$V_w = (V_m/P_m)(P_{wc}) \quad (3)$$

where:

V_w = volume of water vapor remaining in meter volume, ft³,
V_m = gas sampled at meter conditions, ft³,
P_{wc} = vapor pressure of water vapor at condenser exit temperature, in. Hg, and
P_m = absolute pressure at meter, in. Hg.

7.5.1.3 Actual percent moisture in flue gas:

$$W = [(V_c + V_w)/(V_c + V_m)](100) \quad (4)$$

where:

W = moisture in flue gas, volume %
V_c = equivalent vapor volume of condensate at meter conditions, ft³,
V_w = volume of water vapor remaining in meter volume, ft³, and
V_m = gas volume sampled at meter conditions, ft³.

7.5.1.4 For preliminary work where a lower level of accuracy is required, wet- and dry-bulb temperatures may also be used to measure moisture content if the wet-bulb thermometer can be kept wet continuously and heavy dust loading does not interfere with the moisture equilibrium. The procedure presented in Method E 337, specifies that gas flow over the wet bulb must be at least 16 ft/s (5 m/s). Refer to a psychrometric chart to find the moisture content of the gas stream (see Fig. 4 and 4A).

7.5.2 *Gas Composition, Combustion Processes*—An accurate determination of flue gas flow requires a knowledge of its chemical composition in addition to its moisture content. For most fuel combustion processes, determine the carbon dioxide (CO_2), carbon monoxide (CO), and the oxygen (O_2) content of the gas stream. Determine the nitrogen (N_2) by difference. If the sulfur dioxide (SO_2) content of the gas stream is above 1 %, include in the analysis. Use an Orsat or equivalent apparatus to determine chemical composition. Simpler devices may be used for measuring CO_2 and O_2 in combustion gas, which are not as accurate as an Orsat, hut which will determine the approximate molecular weight rapidly in the field. All methods must yield a gas analysis on a dry basis.

7.5.2.1 Determine the specific gravity of the gas or the molecular weight or both for a typical combustion process as follows (**3**):

$$(\%\,CO_2)(0.44) =$$
$$(\%\,CO)(0.28) =$$
$$(\%\,O_2)(0.32) =$$
$$(\%\,N_2)(0.28) =$$
$$(\%\,SO_2)(0.64) =$$
$$\text{sum} = M_d$$

$$M_s = M_d(100 - W)/100 + (0.18)(W)$$

where:

M_s = average molecular weight of the flue gas at flue conditions, lb/lb mol,
M_d = average molecular weight of flue gas, dry basis, lb/lb mol, and
W = moisture in flue gas volume, %.

7.5.3 *Gas Composition, Noncombustion*

Processes—If there is reason to believe that the molecular weight of the flue gas may differ from that of air, then the molecular weight of the gas must be determined by composition analysis, the particular analysis depending on the process.

7.5.4 If the composition of the gas stream to be sampled varies with time, perform gas analysis at various time intervals to determine changes in gas composition. An integrated gas sample may be collected in a glass container or plastic bag during the test period and a single analysis performed on the collected sample.

7.6 *Stable Flow Conditions*—After the various parameters have been determined, calculate the gas velocity in feet per second from the following:

$$u_n = (2.90)(C_p)\cdot[(29.92/P_s)(28.95/M_s)(p_n)(T_s)]^{1/2} \quad (6)$$

where:

u_n = flue gas velocity at *n*th sampling point, ft/s,
C_p = pitot tube correction factor, dimensionless,
P_s = absolute pressure in flue, in. Hg,
M_s = average molecular weight of flue gas at flue conditions, lb/lb mol,
P_n = velocity pressure at *n*th sampling point, in. water, and
T_s = absolute temperature in the flue, deg.

If the various flue gas parameters, such as temperature, vary greatly from point to point in the duct, make a separate velocity calculation for each point and use the arithmetic average of these velocities as the average velocity. Usually only the velocity pressure varies from point to point. In that case, factor out the other parameters in order to simplify the calculations.

8. Average Velocity Measurements

8.1 To determine the average velocity in a stack it is necessary to make several velocity measurements. This is true even if the flow does not vary with time. Velocities in any flue cannot be assumed to be uniform across any large cross-sectional area. However, in any single subarea, one may assume a constant rate of change of velocity over the area with average velocity at the centroid of this area. Determination of the number of points at which velocities are to be measured, and their locations are made in accordance with commonly accepted practices when gas flow patterns are essentially uniform. In all cases, divide the effective inside area into a number of equal areas, and measure the gas velocity at the centroid of each of these areas.

8.1.1 In rectangular flues, divide the cross-sectional area into equal rectangular subareas as shown in Fig. 5. The number of areas to be used depends on the flow pattern and flue size. Use Fig. 7 to find the minimum number of areas when sampling at least eight equivalent diameters downstream and 2 equivalent diameters upstream from the nearest flow disturbance. The equivalent diameter = 2 (length × width)/(length + width). 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 8.1.4.

8.1.2 In circular flues divide the area concentrically as shown in Fig. 6. The minimum number of areas to use and the distance to the test point is shown in Fig. 7 or may be calculated as follows:

$$r_n = D_s\sqrt{(2n-1)/4N} \quad (7)$$

where:

D_s = internal diameter of flue, in.,
r_n = radial distance from center of flue to *n*th sampling point, in.,
n = *n*th sampling point from center of flue, and
N = number of sampling points across a diameter.

Conduct traverses along two diameters 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 used as indicated below.

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

8.1.4 Though no exact rules are available, it is good practice to 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 will have to be determined on its own merits in the field. Where sampling sites are less than two diameters downstream from any flow disturbances, reasonahle accuracy with pitot tube measurements can not be expected and another method for stack gas quantitation should be sought.

8.2 *Average Velocity*—Average flue gas velocity is equal to the constant calculated in 6.6 multiplied by the average of the square roots of the velocity pressures as in Eq 8. (It is important to note that the average of the square roots of the velocity pressures is used. The velocity pressures cannot first be averaged and then the square root taken.)

$$u_{avg} = (2.90)(C_p)\cdot[(29.92/P_s)(28.95/M_s)(T_s)]^{1/2}\sqrt{(p)}avg \quad (8)$$

where:

u_{avg} = average flue gas velocity, during preliminary stable run, ft/s,
C_D = pitot tube correction factor, dimensionless,
P_s = absolute pressure in flue, in. Hg,
M_s = average molecular weight of flue gas at flue conditions, lb/mol,
T_s = absolute temperature in flue, deg, and
$\sqrt{(p)}_{avg}$ = average of square roots of velocity pressure.

The flue gas flow rate in cubic feet per minute is then equal to the product of the inside cross-sectional area of the flue and the average velocity.

$$Q_s = (u_{avg})(A_s) \times 60 \quad (9)$$

where:

Q_s = flue gas flow rate at flue conditions, ft^3/min,
u_{avg} = average flue gas velocity, during preliminary stable run, ft/s, and
A_s = effective area of flue, ft^2.

Determine the flue gas flow rate at standard conditions:

$$Q_{stp} = (Q_s)(530/T_s)(P_s/29.92) \quad (10)$$

where:

Q_{stp} = flue gas flow rate at standard conditions, standard ft^3/min,
Q_s = flue gas flow rate at flue conditions, ft^3/min,
T_s = absolute temperature in the flue, deg R, and
P_s = absolute pressure in flue, in. Hg.

8.3 *Changing Flow Conditions*—If the flow rate changes moderately during the test period, monitor this change continuously by measuring the flow at a single point and relating this flow to the total stack flow obtained during a fairly stable period. Determine the point of average velocity during stable flow conditions and locate a fixed pitot tube at this point for reference during the period of changing flow. The average velocity across a flue is equal to the average velocity at the reference point multiplied by the ratio of the average velocity across the flue during the stable run divided by the average velocity at the reference point during the stable run.

$$u_{avg} = (u_r)(u)_{avg}/(u_r)_{avg} \quad (11)$$

where:

u_{avg} = average flue gas velocity, during preliminary stable run, ft/s,
r_r = flue gas velocity at reference point, ft/s, and
$(u_r)_{avg}$ = average velocity at reference point during preliminary stable run, ft/s.

9. Set-up Procedures

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

9.1.1 If the above is impractical, a site should be selected that comes as close as possible to meeting the above conditions.

9.2 *Number of Traverse Points*—Select traverse points as indicated in 8.1.1 through 8.1.5.

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

9.3.1 Slide the pitot tube all the way into the sampling port, normally a 3-in. pipe size coupling, until the tip touches the far wall of the flue 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.

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

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

9.3.4 Mark the traverse points on the pitot tube after referring to Fig. 7 or use Eq 1. (It is advisable to mark the traverse points in one manner and the centerline and end points in a different manner.)

9.3.5 Take velocity readings 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.

9.4 *Assembling Equipment*—Blow through each leg of the pitot tube alternately blocking and opening the other ports to ensure that the tube is not plugged. If simultaneous temperature measurements are to be taken (this is advisable), attach a thermocouple or other suitable temperature-measuring device to the pitot tube at a point near but not beyond the end of the pitot tube. Choose a manometer that is appropriate for the velocity head range of the sample gas stream. The manometer must be leveled and zeroed with the pressure parts shielded from drafts. 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 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.

9.5 *Insertion*—Pinch off the tubing as the pitot tube is inserted into the sample stream to preserve the manometer fluid. Release the tubes at the pitot tube. This differential should fluid stabilizes. Align the pitot tube so that the opeining faces upstream, or in the case of the "S" type so that one opening faces upstream and the other faces downstream and the manometer gives a positive reading. Seal the breach around the tube to prevent air from leaking into or out of the duct. The pitot tube assembly can now be moved to each point on the traverse plan.

9.6 *Measurement*—Measure the velocity head and the temperature where applicable at each traverse point. Determine the static pressure as noted in 7.4. Fluctuations in the level of the manometer fluid during the measurement period can be damped by inserting a piece of capillary tubing about 1 in. (25 mm) in length in the line connecting the pitot tube to the manometer or a pinch clamp on a hose.

9.7 *Recording*—Figure 8 shows a form used to record the data of each traverse point that will be needed to calculate the velocity head in the stack. Be sure to record the barometric pressure at the sampling port.

10. Precision and Accuracy

10.1 Precision and accuracy data for this method will not be available until the completion of Phase II of ASTM "Project Threshold."

REFERENCES

(1) ASME Power Test Codes; PTC 19.5; 3-1965, Fluid Velocity Measurement.

(2) Cohen, P., Corey, R. C., Meyers, J. W., "Methods and Instrumentation for Furnace Heat-Absorption Studies of Temperature and Composition of Gases at Furnace Outlet", *Transaction's ASME*, November 1949, pp. 965-978.

(3) *Federal Register* Vol 36, Dec. 23, 1971, p. 24875.

(4) Bulletin WP-50, Western Precipitation Division, Joy Manufacturing Co., "Methods for Determination of Velocity, Volume, Dust and Mist Content of Gases."

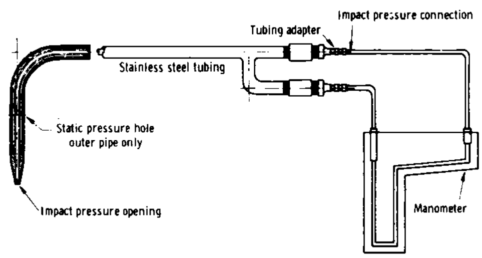


FIG. 1 Pitot Tube

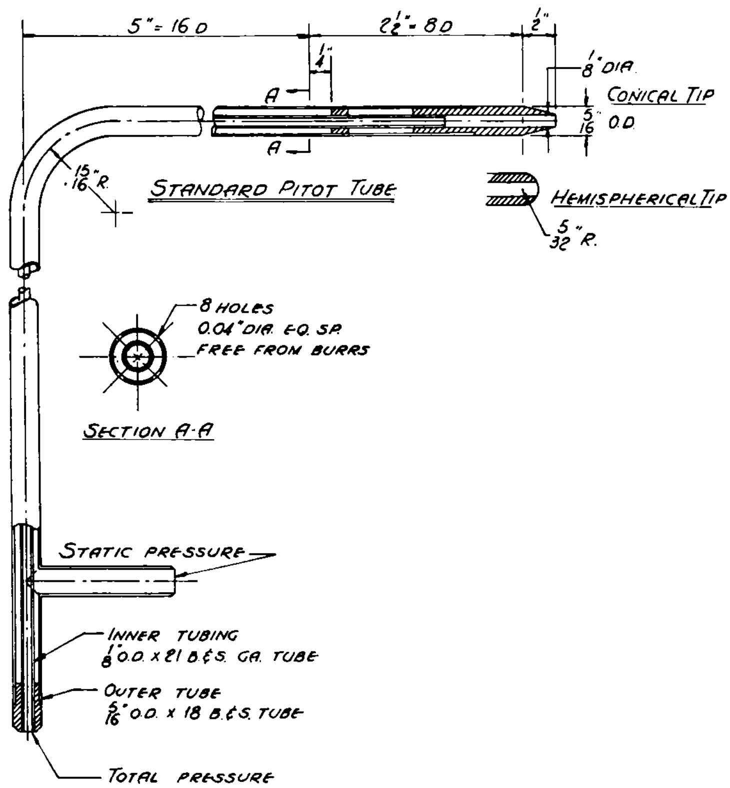
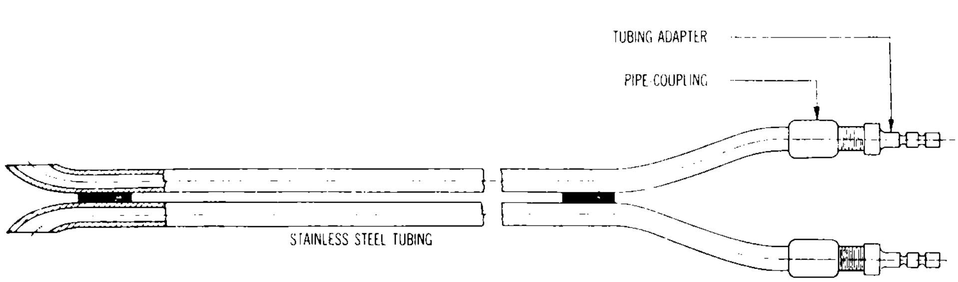


FIG. 2 Standard Pitot Tube Details



TYPE S PITOT TUBE (SPECIAL)

FIG. 3 Type S Pitot Tube (Special)

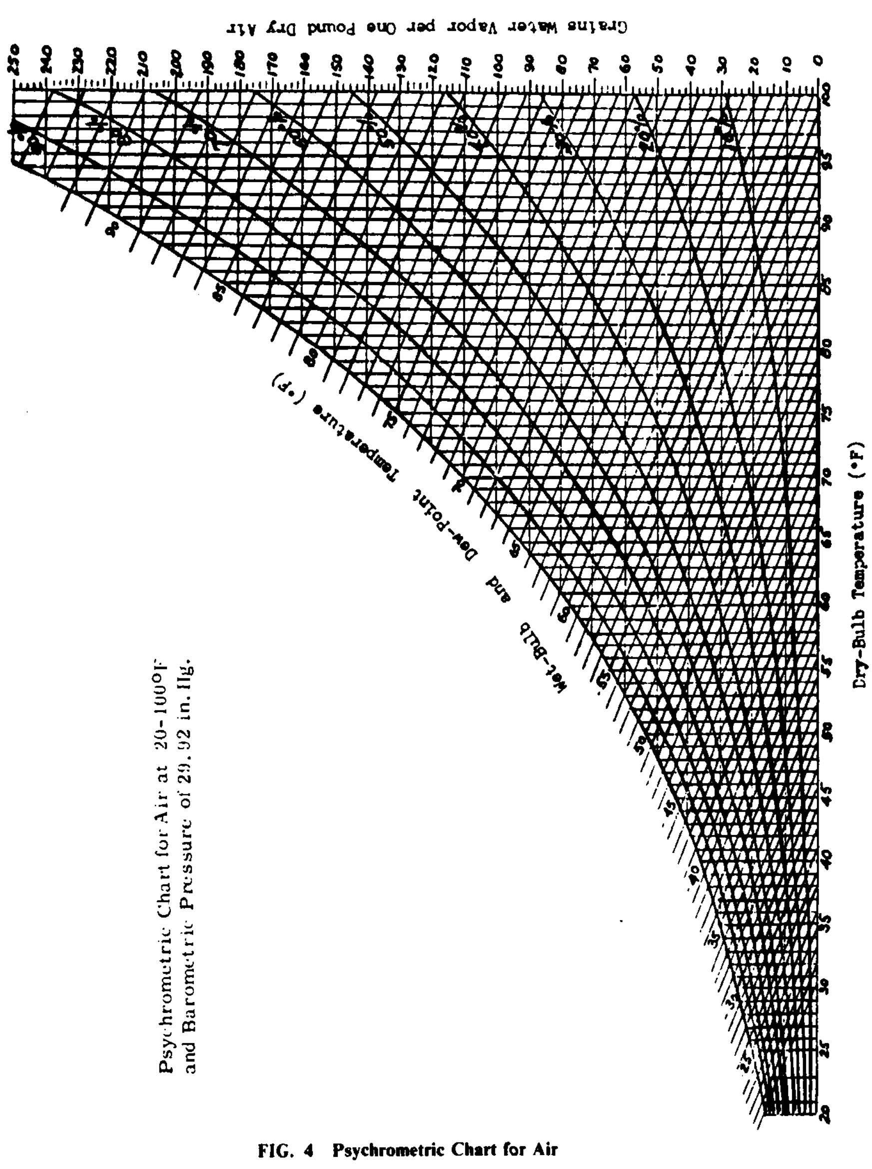


FIG. 4 Psychrometric Chart for Air

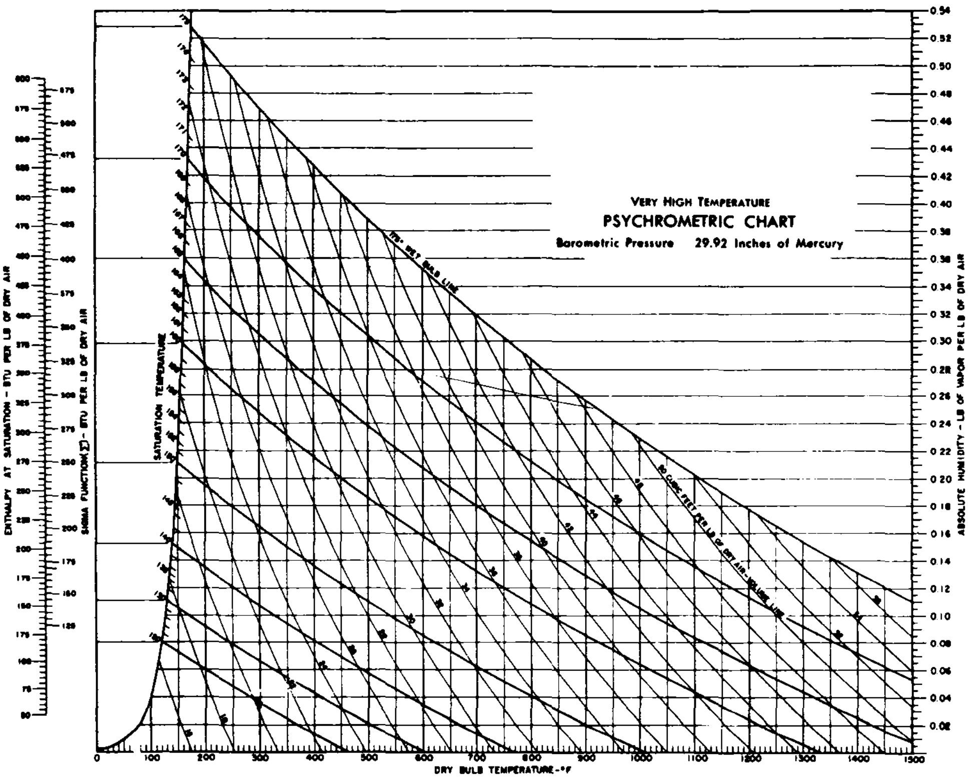
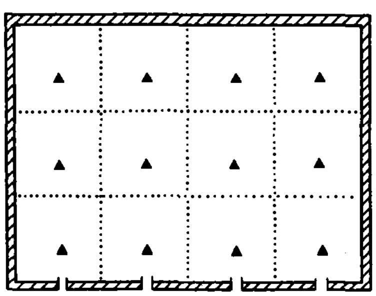


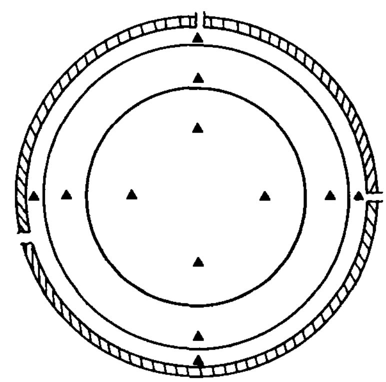
FIG. 4A Psychrometric Chart, (Very High Temperature)

TRAVERSE POSITIONS TRAVERSE POSITIONS



RECTANGULAR FLUE

FIG. 5 Traverse Positions and Rectangular Flue



ROUND FLUE

FIG. 6 Traverse Positions and Round Flue

MINIMUM NUMBER OF MEASUREMENTS
FOR RECTANGULAR SAMPLING-SITES

Cross sectional area of sampling-site, ft^2	Number of measurements
Less than 2	4
2 to 25	12
Greater than 25	20

MINIMUM NUMBER AND LOCATION OF MEASUREMENTS
BASED UPON SAMPLING ALONG TWO PERPENDICULAR
DIAMETERS OF A CIRCULAR DUCT

Sampling site diameter, inches	Minimum number of equal annular areas	Minimum number of meas-urements	Distance from sampling port to sampling point, inches											
			No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No. 12
8	2	8	1/2	2	4	7 1/2								
10	2	8	5/8	2 1/2	7 1/2	9 3/8								
12	3	12	1/2	1 3/4	3 1/2	8 1/2	10 1/4	11 1/2						
14	3	12	5/8	2	4 1/8	9 7/8	12	13 3/8						
18	3	12	5/8	2 1/8	4 1/2	10 1/2	12 3/8	14 3/8						
16	3	12	3/4	2 3/8	4 3/4	11 1/4	13 2/8	15 1/4						
18	5	12	3/4	2 5/8	5 1/4	12 3/4	18 3/8	17 1/4						
20	4	18	5/8	2 1/8	3 7/8	6 3/8	13 5/8	16 1/8	17 7/8	19 5/8				
22	4	18	3/4	2 3/8	4 1/4	7 1/8	14 7/8	17 3/4	19 5/8	21 1/4				
24	4	18	3/4	2 1/2	4 5/8	7 3/4	18 1/4	18 3/8	21 1/2	23 1/4				
28	4	16	7/8	2 3/4	5	8 3/8	17 8/8	21	23 1/4	25 1/8				
28	4	18	7/8	3	5 3/8	9	18	22 5/8	25	27 1/8				
30	5	20	3/4	2 1/2	4 5/8	6 3/4	10 3/8	18 5/8	23 1/4	25 5/8	27 1/2	29 1/4		
32	5	20	5/4	[illegible]	4 5/8	7 1/4	11	21 [illegible]	24 3/4	27 3/8	29 3/8	31 1/4		
36	5	20	7/8	3	5 1/4	8 1/8	12 3/8	28 5/8	27 7/8	30 3/4	33	35 1/8		
42	5	20	1 1/8	3 1/2	7 1/8	10 1/2	15 1/2	27 1/2	28 1/2	32 7/8	38 1/2	40 7/8		
48	8	24	1	3 1/4	5 2/8	8 1/2	12	17	31	58	38 1/8	48 8/8	44 3/4	47
54	6	24	1 1/8	3 3/4	6 3/8	9 1/2	15 1/2	19 1/2	34 1/2	40 1/2	44 1/5	47 5/8	50 1/4	52 7/8
60	6	24	1 1/4	4 1/8	7 1/8	10 2/8	12	21 1/4	38 3/4	42	49 5/8	52 7/8	55 7/8	58 3/4
68	8	24	1 3/8	4 1/2	7 3/4	11 2/8	16 1/2	23 3/8	42 2/8	49 1/2	54 2/8	58 1/4	61 1/2	64 5/8
72	8	24	1 1/2	4 3/4	8 1/2	12 3/4	18	25 1/2	46 1/2	54	58 1/4	83 1/2	67 1/4	70 1/8
78	6	24	1 5/8	5 1/8	9 1/8	13 3/4	19 1/2	27 5/8	50 3/8	28 1/2	84 1/4	88 7/8	72 7/2	78 3/8
84	6	24	1 5/8	5 5/8	9 7/8	14 7/8	21	29 3/4	53 1/4	63	68 1/8	73 1/8	78 3/8	81 3/8
80	6	24	1 3/4	8	10 2/8	15 7/8	22 1/2	31 7/8	58 1/8	67 1/2	74 1/8	79 3/8	84	88 1/4
96	8	24	2	8 3/8	11 5/8	17	24	34	82	72	79	84 2/8	89 5/8	94
108	8	24	2 1/4	7 1/4	12 3/4	19 1/8	27	38 8/8	89 2/8	81	88 7/8	92 1/4	100 3/4	102 2/4
120	8	24	2 1/2	8	14 1/8	21 1/4	30	42 5/8	77 3/8	90	98 3/4	105 7/8	112	117 1/2
152	8	24	2 3/4	8 7/8	15 5/4	25 3/8	35	46 7/8	85 1/8	99	108 5/8	118 1/4	123 1/8	128 1/4
144	6	24	3	9 5/8	17	35 1/2	38	51 1/8	92 7/8	108	118 1/2	127	134 3/8	141

FIG. 7 Minimnn Number of Measurements for Rectangular Sampling-Sites

VELOCITY TRAVERSE DATA

CLIENT ______________________ PAGE ______ OF ______

Location of Test ______________________ DATE OF TEST ______

Conditions ______________________ TEST NO. ______

Personnel ______________________ JOB NO. ______

Ba. ______ " Hg AMBIENT TEMP. ______ °F STACK AREA ______ SQ. FT.

MOLECULAR WGT. ______ #/CU. FT.

$$u_n = 2.90 \times C_p \sqrt{\frac{29.92}{P_s} \times \frac{28.95}{M_s} \times P_n \times T_s}$$

$C_p = 1.0$ for STD. Pitot Tube
$C_p = 0.83$ for Type "S" Pitot Tube

$$K = \_\_\_\_\_\_ \sqrt{\frac{29.92}{\_\_\_\_} \times \frac{28.95}{\_\_\_\_}} = \_\_\_\_\_\_$$

POINT NO.	STACK TEMP. °F	STACK TEMP. $T_s = F + 460$	STATIC PRESS. Abs (P_s)	K	P_n	$P_n \times T_s$	$\sqrt{P_n \times T_s}$	U_n Ft/Sec.
TOTAL								
READINGS								
AVE.								

FIG. 8 Velocity Traverse Data

APPENDIXES

X1. DISCUSSION OF SOME ERRORS INHERENT IN THE PITOT TUBE VELOCITY MEASURING TECHNIQUE

X1.1 *Errors Due to Turbulence*—Turbulence, when applied to a dynamic device such as the standard pitot tube will introduce a series of basic errors in the interpreted readings. The first is mathematical in that the reading produced by the pitot is a "head" or $u^2/2g$ while the result required is the velocity or u. First, when measuring a turbulent or fluctuating velocity, the head measured will be the RMS value of the wave form and will always be higher than the head produced by the "average" velocity. Secondly, this problem is complicated by the flow dynamics of the resistance of the small size pressure taps and tubing, the compressibility of air in the tubes, and the inertia of the indicating fluid. These two effects are additive such that in turbulent flow fields, when using fluid dynamics devices, the velocity as read will always be higher than the actual velocity being measured. The problem of flow resistance can be partially corrected by using large sensing holes in the probe, close coupling of the probe to the manometer and using a manometer or other readout device of low displacement volume and inertia.

X1.2 *Errors Due to Vorticity*—The effect of flow stream vorticity has just the opposite effect on the velocity readout. Vorticity represents a well-ordered flow field of significant curvature. Figure A1 shows that a very definite pressure gradient exists in curved flow fields. If the radius of curvative of the flow streamline is of the same order of magnitude as the measuring device, the device will not be measuring either the correct dynamic or static pressure. Vorticity of small scale (L) and high intensity ($\bar{u}/u$) can, therefore contain a significant amount of dynamic energy that will not be read if the measuring device is physically too large with respect to L. Unfortunately, there is no way to evaluate the effect of vorticity on dynamic flow measurement. Therefore, vorticity should be minimized or eliminated by "egg crates" or screens if no other flow traversing station, without vorticity, is available.

X1.3 *Turbulence, Defined*—Flow turbulence is usually considered to be a random but isotropic process. This is done mainly to simplify the energy calculations. Typically, flow in industrial flues produces two distinct turbulence characteristics such as are shown in Fig. A2. Many installations include sharp corners and other abrupt discontinuities which will produce turbulent roll. This roll is characterized by fluctuating velocity components $\bar{u}$ and $\bar{v}$ in the plane of the paper as drawn. A third component $\bar{w}$ is perpendicular to the plane shown and is usually of smaller magnitude. Isotropic turbulence is defined as $\bar{u} = \bar{v} = w$ and is difficult to find in industrial work. Turbulence is characterized, where possible, by the combined values of intensity, frequency and scale.

X1.4 *Vorticity, Defined*—The vortex flow can be produced by stack entrance and fan discharges. It can also be produced by two roll turbulence patterns intersecting at an angle. As noted in Fig. A2, it is difficult to characterize the vortex component in the linear vector notation.

X2. Principle of Operation of Pitot Tube

X2.1 *Bernoulli's Equation*—Bernoulli's equation for steady flow of a frictionless, compressible fluid of unit weight is:

$$gz + (v^2/2) + \int(dp/\rho) = \text{constant} \quad (12)$$

where:

g = gravity, ft/s²,
z = height, ft,
v = velocity, ft/s,
p = pressure, lb/ft², and
ρ = density, slug/ft³.

If the fluid is assumed to be imcompressible, Bernoulli's equation is:

$$gz + (p/\rho) + (v^2/2) = \text{constant} \quad (13)$$

Or, dividing by g

$$z + (p/\gamma) + (v^2 + (v^2/2\,g) = C \quad (14)$$

where:

γ = specific weight, lb/ft³.

Each of the terms of Bernoulli's equation can be considered as a form of energy:

z is the potential energy of the fluid per unit weight based on some arbitrary datum.

p/γ corresponds to the "flow work" and applies to steady flow conditions and is called pressure energy.

$v^2/2g$ is the kinetic energy and is called the "velocity head."

Briefly then Bernoulli's equation states that the sum of the potential energy, pressure energy, and kinetic energy remains constant for a frictionless fluid at steady flow along a streamline.

The simple pitot tube is used to measure the total pressure.

The tube opening is directed upstream so that the fluid flows into the opening until the pressure intensity builds up within the tube sufficiently to withstand the impact of velocity against it. The stream line through point 1 leads to point 2, called the stagnation point where the fluid at that point is at rest. The pressure at point 2 is known from the liquid column within the tube or $h_0 + \Delta h_i$. According to Bernoulli's equation:

$$z_1 + (p_1/\gamma) + (v^2/2g) = z_2 + (p_2/\gamma) + 0$$

Since z_1 and z_2 are at the same elevation, then

$$(p_1/\gamma) + (v^2/2g) = (p_2/\gamma) = h_o + \Delta h \quad (15)$$

But $p_1/\gamma = h_o$. Therefore the equation reduces to:

$$v^2/2g = \Delta h$$

or

$$v = (2g\Delta h)^{½} \quad (16)$$

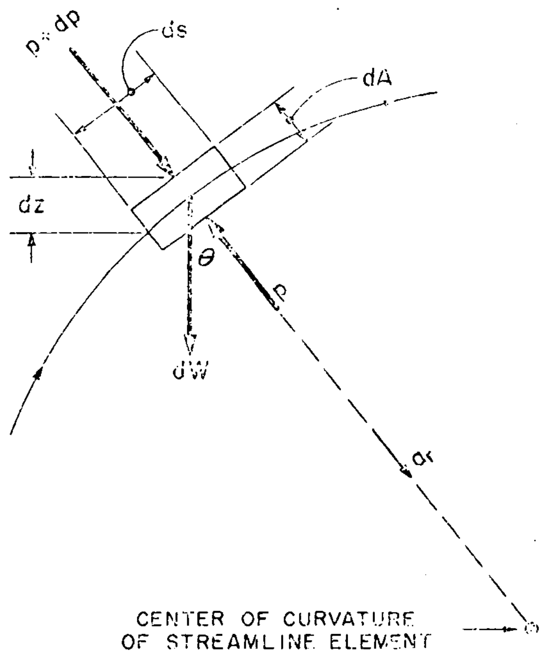
By combining the static pressure measurement and the total pressure measurement into one instrument called the pitot static tube, that is, measuring each and connecting to opposite ends of a manometer, the dynamic pressure head is obtained.

The velocity obtained from equation is the theoretical value. The ratio of the actual velocity V_a to the theoretical velocity V_t is called the velocity coefficient C_v, that is:

$$C_v = V_a/V_t$$

hence

$$V_a = C_v(2gh)^{½} \quad (17)$$



$$\frac{d}{dr}\left(\frac{p}{\gamma} + z\right) = \frac{V^2}{gr}$$

FIG A1 Curved Flow Field.

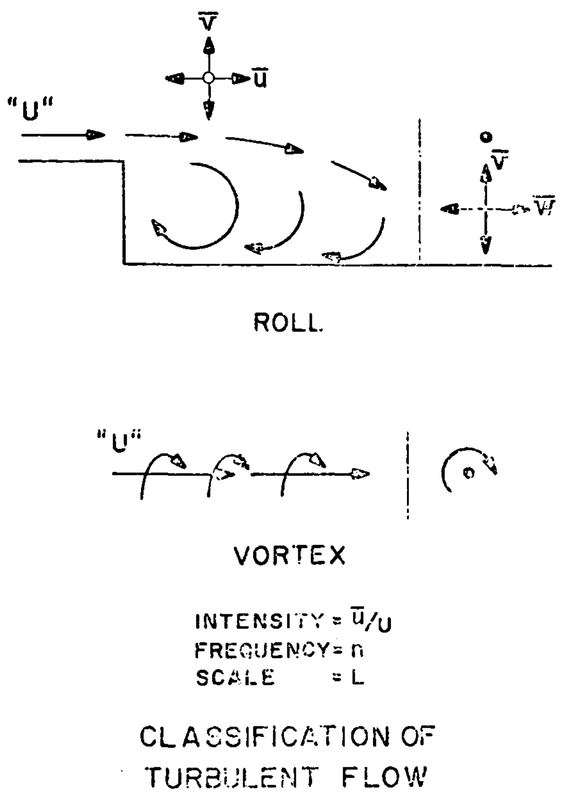


FIG A2 Classification of Turbulent Flow.

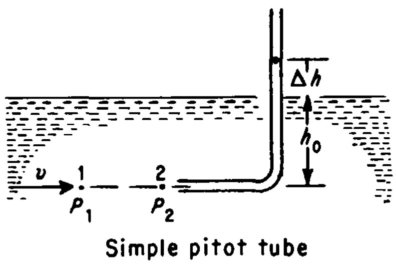


FIG A3 Simple Pitot Tube.

APPENDIX B

NBS CALIBRATION DATA FOR TYPE "S" PITOT TUBE

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

Date: January 10, 1973

Reply to Attn of: 213.08

Subject: Wind Tunnel Calibration of Type "S" Pitot Tube Per Interdivision Work Order No. 5072, Project 3105570.

To: Dr. R. H. Johns
310.05
B320 Chemistry

Calibration data for the type "S" Pitot tube submitted are tabulated below:

Reynolds number per foot V/ν, ft^{-1}	Air speed, V, fps	K	Uncertainty, %	CP*
34,000	5.6	1.415	7.0	0.841
48,000	8.1	1.405	4.6	0.844
59,000	9.7	1.414	3.0	0.841
72,000	11.9	1.422	2.1	0.839
83,000	13.8	1.429	2.0	0.837
169,000	28.2	1.428	1.8	0.837
302,000	50.3	1.414	1.1	0.841
476,000	79.7	1.423	0.7	0.838
604,000	101.3	1.416	0.4	0.840
741,000	125.6	1.422	0.3	0.839
903,000	155.0	1.424	0.3	0.838

The calibration was performed in the five-foot by seven-foot rectangular test section of the NBS closed-circuit dual test section wind tunnel. The "S" tube was inserted into the air stream through a hole in the tunnel wall placing the sensing holes of the "S" tube 30 inches above the tunnel floor and on the tunnel vertical centerline. The end of the "S" tube containing the right-angle bends where the manometer pressure tubes were attached was positioned so that the bent portion of the "S" tube faced downstream relative to the tunnel wind direction and the common axis through the centers of the sensing holes was alined with the flow.

Calibration of the "S" tube consisted of determining the calibration factor K where K is defined as the ratio of the differential pressure indicated by the "S" tube to the differential pressure indicated by the NBS laboratory standard. This was done by means of a substitution procedure in which the "S" tube and the NBS tube were mounted successively in the same tunnel position and compared to an auxiliary Pitot-static tube.

* Pitot tube calibration factor (CP) was calculated by the equation: $CP = \sqrt{\frac{1}{K}}$

The coefficient K for a tube of this type may be dependent on the Reynolds number per unit length, V/ν, where V is the air speed, and ν is the kinematic viscosity. This parameter is therefore given in the table. The properties of the gas in which measurements are made may therefore be an important consideration. The complete isentropic flow relationship was used in determining V, and hence the effect of compressibility is included in the reported value of air speed.

The estimated overall uncertainties listed are based upon three times the estimated standard errors and an allowance of 0.05 percent for possible systematic error. The standard errors are based upon the combined individual standard errors in all of the quantities involved in the determination of K. The individual standard errors were estimated on the basis of five determinations of each such quantity, and the values of K, V/ν, and V listed in the table are the averages of five independent runs covering the range of calibration.

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