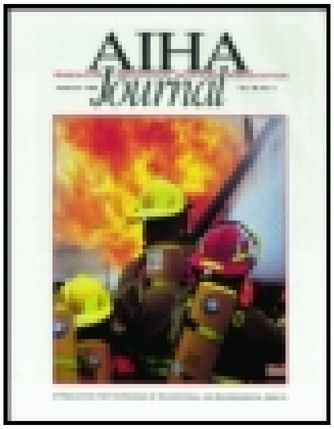

American Industrial Hygiene Association Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/aiha20

Comparison of Pitot Traverses Taken at Varying Distances Downstream of Obstructions

Steven E. Guffey [a] & Derrick W. Booth [b]

[a] University of Washington, School of Public Health and Community Medicine, Department of Environmental Health, Box 357234, Seattle, WA 98195-7234

[b] University of Washington, School of Engineering, Department of Civil Engineering

Published online: 04 Jun 2010.

To cite this article: Steven E. Guffey & Derrick W. Booth (1999) Comparison of Pitot Traverses Taken at Varying Distances Downstream of Obstructions, American Industrial Hygiene Association Journal, 60:2, 165-174

To link to this article: http://dx.doi.org/10.1080/00028899908984431

Authors
Steven E. Guffey[a]
Derrick W. Booth Sr.[b]

[a]University of Washington School of Public Health and Community Medicine, Department of Environmental Health, Box 357234, Seattle, WA 98195–7234;
[b]University of Washington School of Engineering, Department of Civil Engineering

Comparison of Pitot Traverses Taken at Varying Distances Downstream of Obstructions

This study determined the deviations between pitot traverses taken under "ideal" conditions—at least seven duct diameter's lengths (i.e., distance=7D) from obstructions, elbows, junction fittings, and other disturbances to flows—with those taken downstream from commonplace disturbances. Two perpendicular 10-point, log-linear velocity pressure traverses were taken at various distances downstream of tested upstream conditions. Upstream conditions included a plain duct opening, a junction fitting, a single 90° elbow, and two elbows rotated 90° from each other into two orthogonal planes. Airflows determined from those values were compared with the values measured more than 40D downstream of the same obstructions under ideal conditions. The ideal measurements were taken on three traverse diameters in the same plane separated by 120° in honed drawn-over-mandrel tubing. In all cases the pitot tubes were held in place by devices that effectively eliminated alignment errors and insertion depth errors. Duct velocities ranged from 1500 to 4500 ft/min. Results were surprisingly good if one employed two perpendicular traverses. When the averages of two perpendicular traverses was taken, deviations from ideal value were 6% or less even for traverses taken as close as 2D distance from the upstream disturbances. At 3D distance, deviations seldom exceeded 5%. With single diameter traverses, errors seldom exceeded 5% at 6D or more downstream from the disturbance. Interestingly, percentage deviations were about the same at high and low velocities. This study demonstrated that two perpendicular pitot traverses can be taken as close as 3D from these disturbances with acceptable (≤5%) deviations from measurements taken under ideal conditions.

Keywords: pitot traverses, ventilation

Accurate airflow determinations are important in industrial exhaust ventilation for three common tasks: (1) ensuring that the specified airflow has been provided to hoods, (2) modeling systems for redesign,[1] and (3) making troubleshooting comparisons.[2] Traverses done using a pitot tube and a pressure sensor are still the most practical and reliable way to determine airflows in industrial ventilation ducts, despite the tediousness of the task using current measurement methods.[3]

Under laboratory conditions, the calibration factor for a hemispherical-nosed pitot tube has been determined[4] to be between 1.000 and 0.995 with a standard deviation in both cases within ±0.001. Besides errors attributable to the pressure sensor, there are several potential sources of error for the pitot tube under field conditions, including misalignment of the probe with the duct, failure to insert the probe to correct distances along the diameter sampled, use of unnecessarily large pitot tubes, and lack of alignment of the airflow with the duct.[4,5]

All but the latter present little practical difficulty. Instrument errors can be reduced by using tubes for velocity determination only at velocity pressures high enough for the manometer to measure accurately. Other problems can be minimized by aligning the probe with the duct during traverses, marking insertion depths carefully, and using tubes with stems less than 1/30 of the duct diameter.[4] For example, misalignment of

Funding for this study was provided by the National Institute for Occupational Safety and Health in grant number 1 RO1 OH03165.

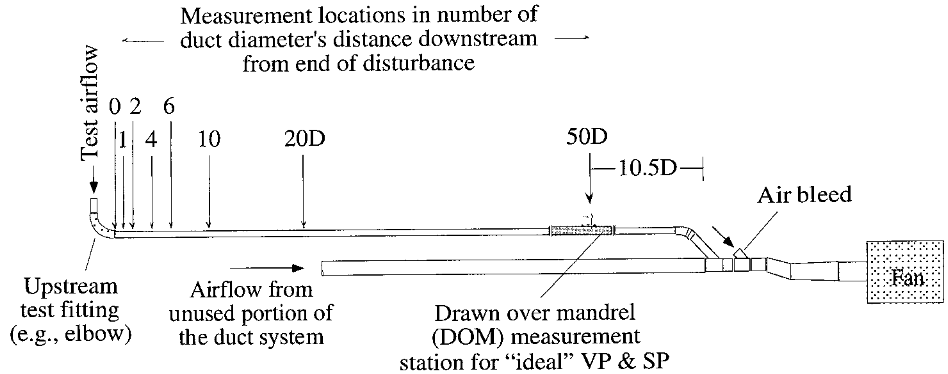

FIGURE 1. Ventilation system used in study

the probe with the airstream produces somewhat less than a 3% velocity error for yaws less than 5 degrees.[3] Thus, one should either hold the tube carefully in the hand or use a device designed to hold tubes to correct alignment and insertion depths.[3]

Taking measurements only where airflow should be aligned with the duct is more difficult. To avoid conditions where the flow is not parallel to the duct, some references[4–9] specify that traverses be done a minimum of 8.5 diameters (D) of straight duct length (L) downstream and 1.5 diameters (i.e., 1.5D) upstream from elbows, junctions, dampers, obstructions, and all other disturbances to flow. *Industrial Ventilation*[6] recommends that pitot traverses be taken at least 7 duct diameters (7D) of distance downstream from disturbances. It also recommends that the average of two perpendicular traverses be employed to improve accuracy when conditions are less than ideal.

Unfortunately, the ducts in industrial systems often do not provide the recommended 7D to 8.5D of uninterrupted straight length due to the realities of system installation. The inaccuracy due to these often unavoidable "poor" measurement locations is not well documented in the literature, nor is it clear how much benefit a second traverse would bring for either good or poor traverse locations.

Thus, although research has shown that the accuracy of mean velocities determined from pitot traverses are within 2% under good conditions,[5,7–10] the accuracy of pitot traverses under relatively poor conditions is not known. This study determined the deviations between pitot traverses taken under "ideal" conditions and those taken at various distances from various commonplace disturbances. In addition, the reductions in deviations gained by averaging two perpendicular traverses was analyzed. Since all the measurements employed pitot tubes, this study addresses consistency with readings at a good measurement location rather than accuracy.

APPARATUS

All measurements were taken on an industrial exhaust ventilation system constructed from spiral-wound, 22-gauge, galvanized ducts. The system, which was located in the first author's ventilation laboratory, and the measurement devices have been described in detail in previous studies.[11,12] The system had two 127-mm (5-inch) diameter branches, one 152-mm (6-inch) branch, and two 178-mm (7-inch) diameter branches. For this study only one duct was employed for the tests (see Figure 1); air was allowed to flow freely through the other ducts as dictated by their relative resistances to flow (i.e., the other ducts were not disturbed or altered during the study). The test duct was one of the 178-mm

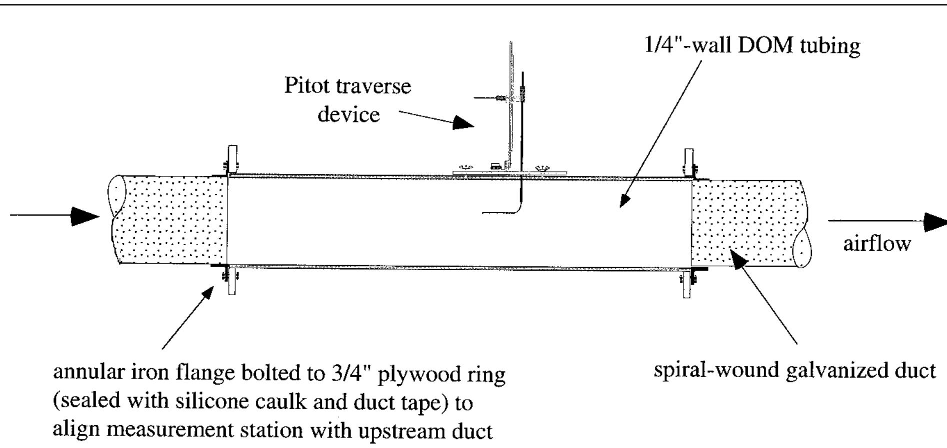

FIGURE 2. Ideal airflow measurement station

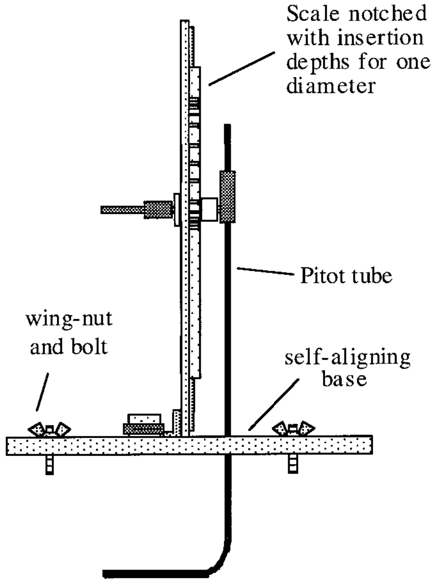

FIGURE 3. Pitot traverse device

(7-inch) branch ducts (see Figure 1). Air flowed into plain duct openings without flanges or transitions for all the branches in the system.

The system airflow was provided by a Buffalo Forge size 40MW Industrial Exhauster powered by a 20 hp motor. Fan rotation rate was relatively constant at 1201 rpm. Airflow levels through the test duct sometimes were varied by bleeding in air downstream of the ideal measurement station (see Figure 1).

Measurement Stations

The "ideal condition" velocity pressure and static pressure measurements were taken at a measurement station (Figure 2) made from drawn-over-mandrel (DOM) tubing and located at the downstream end of the duct at a distance of about 50D from any upstream disturbance. The DOM tubing had an inner bore that had been precision-honed to the nominal duct size and perfect circularity.

The upstream disturbed conditions ("test") static pressure and velocity pressure values were taken through 3/16-inch holes drilled into the spiral-wound duct at distances from disturbances varying from 1D to 20D.

Measurement Devices

For the ideal location, static and velocity pressures were measured with traverse devices[3] mounted to the DOM tubing using wing nuts that were tightened on bolts glued to the DOM tubing (see Figure 3). For the nonideal conditions, the traverse devices were attached to the galvanized duct using adjustable straps that were looped through a D-ring and held in place with lock and tag strips. The pitot tubes were ANSI/ASHRAE Standard 41.2-1987 devices[13] with hemispherical heads and 32-mm (⅛-inch) stem diameters.

Pressure measurements were taken using a Merriam Instruments Model 40HE35WM inclined manometer, which was calibrated with a Dwyer hook gage (Dwyer Instruments, Inc., Series 1425) having a resolution of 0.25 Pa (0.001-inch water gage). The manometer was inclined to produce a maximum of 4-inch water gage and had a reading resolution of 1.25 Pa (0.005-inch w.g.).

Wet and dry bulb temperatures in the laboratory were recorded for every round of data using a Cole-Parmer Psychro Dyne and a

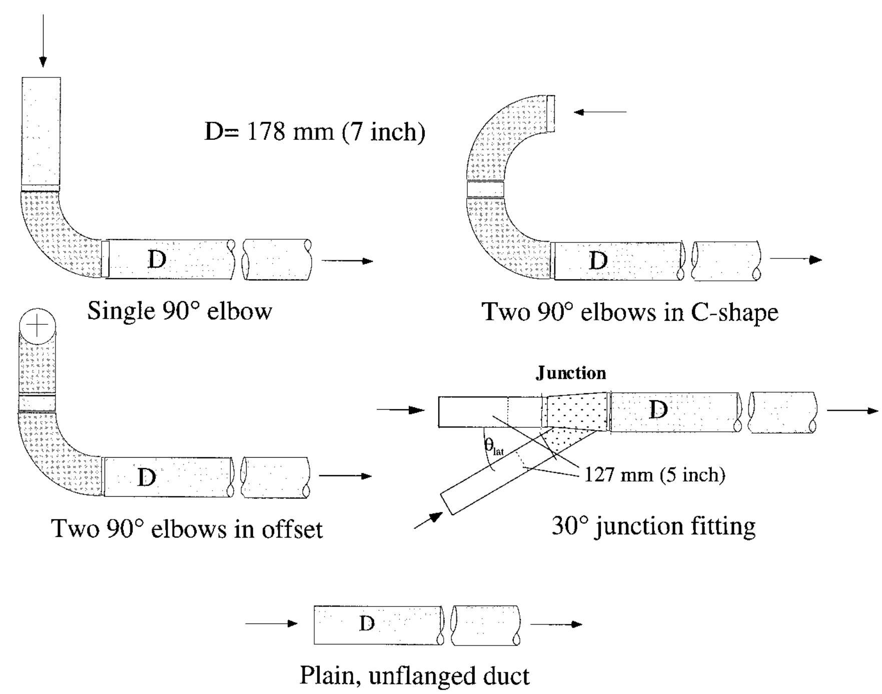

FIGURE 4. Upstream test disturbances

TABLE I. Study Design

Upstream Component Tested	Upstream of Test Component	Number of Cases at Each Distance[A]						Median Velocity[C]
		1D	2D	4D	6D	10D	50D[B]	
Plain duct	nothing	2	2	2	2	2	2	3473
One elbow	nothing	2	2	2	2	2	2	3391
One elbow	3D of straight duct	1	1	1	1	1	1	3741
Two elbows, C-shape	nothing	4	4	4	4	4	4	2807
Two elbows, offset	nothing	3	4	3	3	4	8	4021
Junction 755	collinear and lateral ducts	2	2	2	1	0	3	3835
Junction 755	collinear duct inlet partially blocked	0	0	1	0	0	1	3895
Junction 755	lateral duct inlet partially blocked	0	0	1	0	0	1	4044

[A]Number of duct diameters distance downstream from the test section
[B]"Ideal" measurement location
[C]Velocity in ft/min

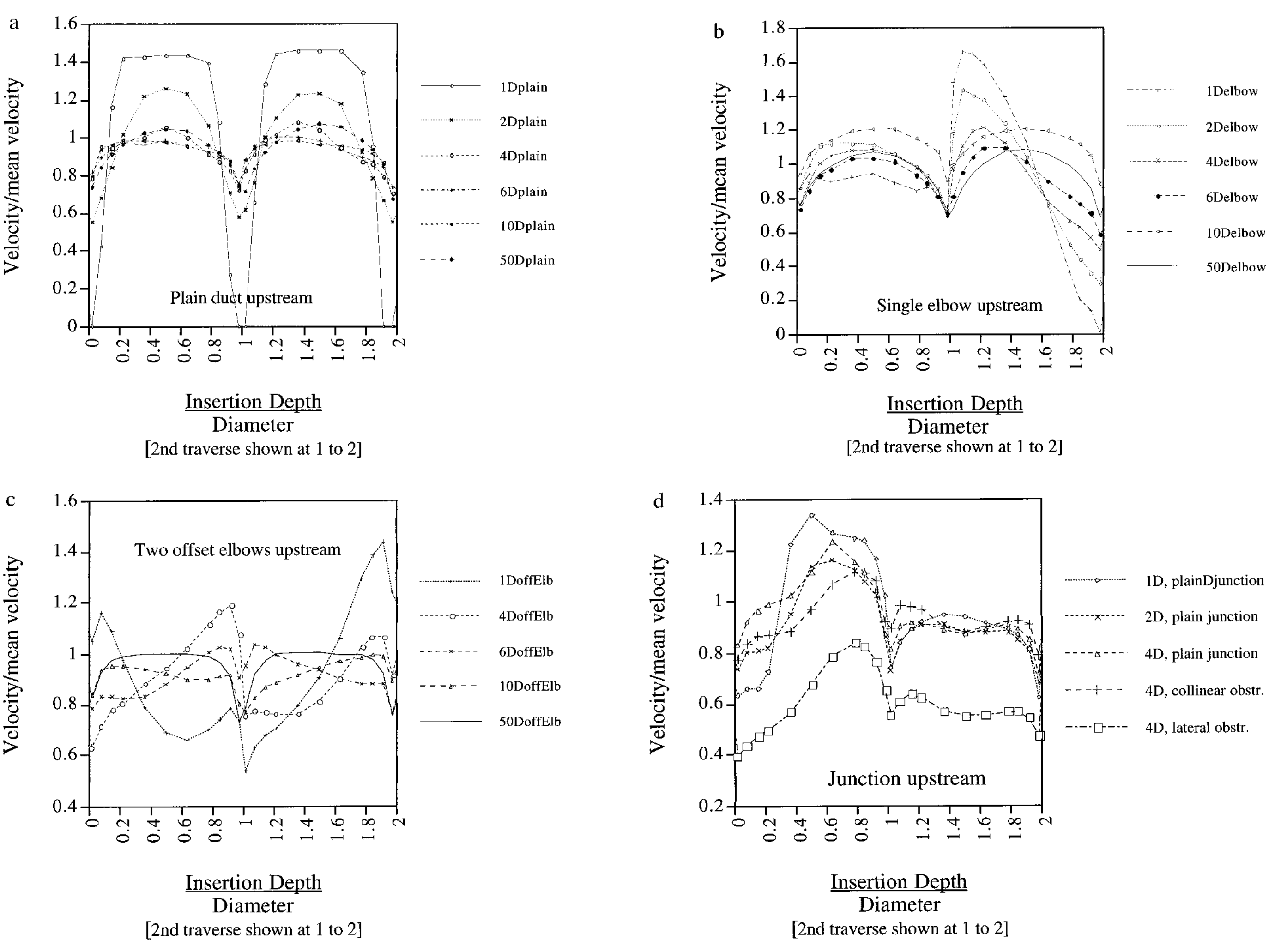

FIGURE 5. a: Velocity contours, plain; b: velocity contours, single elbow; c: velocity contours, offset elbows; d: velocity contours, junction

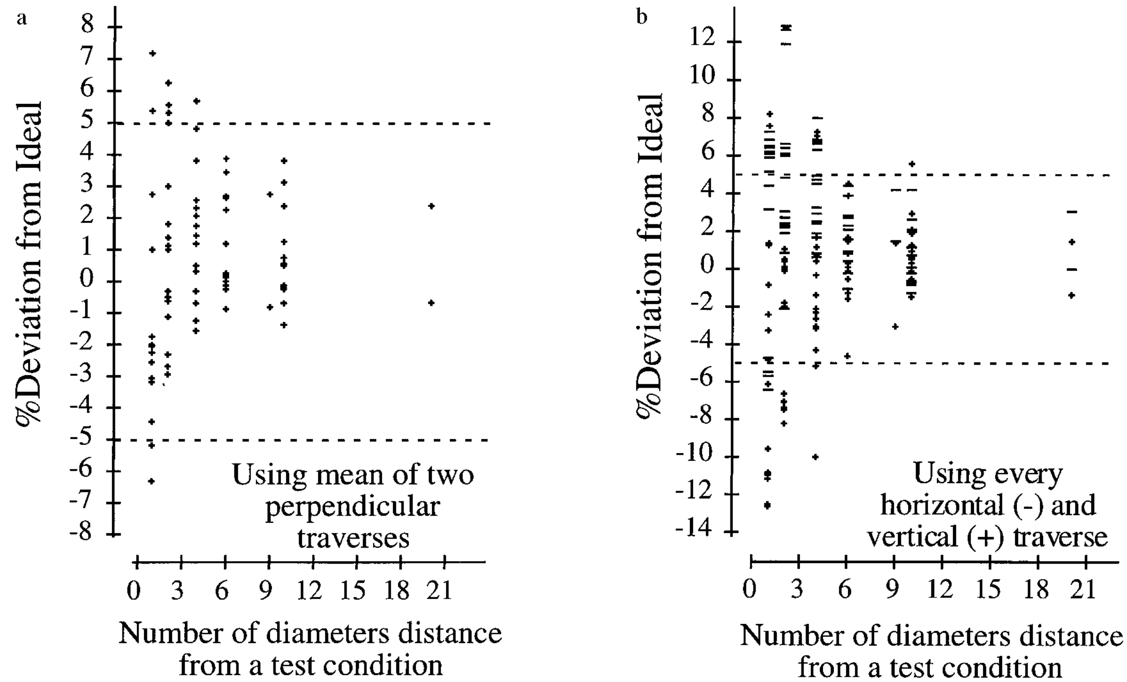

FIGURE 6. a: Double traverse errors; b: Single traverse errors

National Institute of Standards and Technology-certified thermometer. Relative humidity was estimated from a standard psychometric chart. While wet bulb temperatures varied by as much as 5°C from day to day, room temperature was always between 19 and 20.5°C. Duct temperature was always within one degree of room temperature. Barometric pressure was recorded each day using a standard mercury barometer.

Upstream Test Disturbances

The upstream conditions for various tests (see Figure 4) were a plain duct opening, a junction fitting, a single elbow, and two elbows close-coupled in series. For the plain duct, air entered directly into the unflanged open end of the straight, 22-gauge, spiral-wound duct, which continued uninterrupted by elbows or junctions to the DOM tubing at the end of the branch duct. That is, incoming air passed through only plain straight duct on its way to the upstream (test) and downstream (ideal) traverse locations. When elbows or the junction fitting were the test condition, the elbows or the junction fitting were attached to the previously open end of the spiral duct.

Each elbow was stamped from 20-gauge sheet metal in a smooth full 90° turn. One elbow had a radius-to-diameter ratio of 1.5; the other had a radius-to-diameter ratio of 2.0. The former was used as the single elbow and as the downstream elbow when two elbows were close coupled. The latter was the upstream elbow when two elbows were used close-coupled in series. When two elbows were present, in some tests they completed a 180° turn in one plane (C-shape elbows). In other tests, they were rotated 90° into two orthogonal planes (see Figure 4, offset). For most tests with elbows, air entered directly into the open end of the upstream elbows. Since it is more typical that elbows have at least some straight duct upstream, for other cases air first passed through an additional 3D straight section of spiral duct attached upstream of the elbows.

The junction fitting had two 127-mm (5-inch) upstream connections and a 254-mm (10-inch) long tapered body with a 178-mm (7-inch) discharge that connected to the plain duct opening (see Figure 4, junction fitting). A different 7D-long section of spiral duct was connected to each of the upstream connections. The lateral duct joined the center of the taper at its midpoint at an angle of 30 degrees. For some tests the lateral duct was partially blocked at the duct opening to vary the relative flow through the two upstream ducts.

METHODS

Prior to data collection the 178-mm (7-inch) diameter duct used for all tests was examined for leaks by capping off all branches and using Draeger smoke tubes to detect any flow into seams or joints in the ductwork. Silicon caulk and duct tape were used to seal leaks. At the completion of data collection, identical smoke tests indicated that no leaks had developed during the study.

For each combination of airflow and test condition, two perpendicular 10-point log-linear traverses were taken at various distances downstream of the test disturbance (1D, 2D, 4D, 6D, 10D), and three traverses 120° apart were taken at the DOM tubing at a distance of 50D from the test disturbances. The latter is referred to hereafter as the ideal location. In addition, the centerline velocity pressure was measured for each 10-point traverse taken. The density of the air was computed from the barometric pressure, the appropriate duct static pressure, and room temperature and humidity. The airflow for the upstream test measurements was estimated using each traverse separately and by using

TABLE IIA. ANOVA of Deviations Between Individual Upstream Test Traverses and the Mean of the Far Downstream (Ideal) Traverses

Source of Variability	df	Sum Sq.	Mean Sq.	F-ratio	Prob.
Constant	1	84.3490	84.3490	4.6450	0.0328
Axis of traverse	1	643.240	643.240	35.423	≤0.0001
Distance from disturbance	6	160.406	26.7344	1.4722	0.1917
Type of disturbance	2	165.548	82.7741	4.5583	0.0120
Error	144	2614.89	18.1590		
Total	153	3577.99			

the average of the two traverses. The airflow for the ideal conditions was computed from the average of all three equally spaced traverses.

Since the static pressures at the two locations were somewhat different, the actual airflows should be somewhat different. For that reason, both airflows were converted to the values they would have had at 20C and 760 mm Hg to allow relevant comparisons between upstream test measurements and downstream ideal measurements.

Study Design

Complete characterization of pressures and flows in the test duct was made for the eight sets of test configurations shown in Table I. In addition, some minor variations were tested, such as slightly misaligning the downstream end of the junction fitting for some junction tests. Note that velocities varied for different conditions due to the effects of their different resistances to flow and to differing amounts of air bled in downstream of the test duct. In particular, the C-shaped elbows condition was tested at 1500, 2300, 3000, and 3300 ft/min duct velocities and the plain condition was tested at 3000 and 3500 ft/min velocities.

One dependent variable was the percentage difference between airflow (standardized to 20°C and 760 mmHg) determined from traverses at varying distances downstream of the test condition (Q_{test}) and the airflow computed from averaging the mean velocities at the ideal location far downstream (Q_{ideal}):

$$\%\ \text{deviation from ideal} = \left(\frac{Q_{test} - Q_{ideal}}{Q_{ideal}}\right) \cdot 100 \qquad (1)$$

Another outcome of interest was the difference between airflows determined from horizontal (Q_H) and vertical (Q_V) traverses:

$$\%\ \text{difference between perpendicular traverses} = \left(\frac{Q_H - Q_V}{(Q_H + Q_V)/2}\right) \cdot 100 \qquad (2)$$

Finally, it would be convenient if one could estimate the mean duct velocity from a single velocity measurement. In the authors' experience, practitioners commonly estimate mean velocity using the centerline velocity multiplied by an assumed pipe factor (ratio of mean velocity to centerline velocity; PF) of 0.90. The relative efficacy of that approach can be estimated from Equation 1 and:

$$PF\ Q_{test} = 0.9\ (V_{cl})(A) \qquad (3)$$

where V_{cl} = centerline velocity and A = duct cross-sectional area.

Independent variables that were expected to affect deviations from ideal downstream values were (1) the upstream test conditions, (2) the number of diameters distance downstream from the condition to the measurement location, (3) whether a horizontal (H) or vertical (V) traverse was employed, and (4) whether the average velocity was determined with a single traverse or the mean of the horizontal and vertical traverses.

RESULTS AND DISCUSSION

The three traverses used to compute the reference (i.e., ideal or gold-standard) airflow showed good agreement among themselves with a standard deviation of the differences of 0.8%. Hence the mean value of the three traverses should vary by less than 1% for repeated measurements. Since test and ideal values were taken on the same day, day-to-day variability in fan output should have had no affect on their relative values. However, it is possible that airflows varied *within* a given day so that the difference in time of day could have affected the relative values of upstream (test) and downstream (ideal) measurements. Thus, fluctuations with time could have somewhat inflated the "errors" due to use of nonideal measurement conditions.

All of the experimental variables were important except duct velocity, but the importance of a given variable varied with changes to other variables (i.e., the effects were interactive).

Velocity Contours

As shown in Figures 5a through 5d (left traverse is vertical, right traverse is horizontal), velocity contours were highly skewed for many conditions. At 50D distance (i.e., at the ideal station far downstream of the test components), velocity contours were highly symmetric (e.g., see 50D line in Figures 5a, 5b, and 5c). For the plain and single elbow conditions, velocity contours gradually approached those found for ideal condition traverses, especially at

TABLE IIB. ANOVA of Absolute Values of Deviations Between Individual Upstream Test Traverses and the Mean of the Far Downstream (Ideal) Traverses

Source of Variability	df	Sum Sq.	Mean Sq.	F-ratio	Prob.
Constant	1	2080.22	2080.22	310.45	≤0.0001
Axis of traverse	1	0.42254	0.42254	0.0631	0.8021
Distance from disturbance	6	503.688	83.9479	12.528	≤0.0001
Type of disturbance	2	123.146	61.5731	9.1891	0.0002
Error	144	964.895	6.70066		
Total	153	1582.12			

TABLE III. Mean of Absolute Values of Percentage Deviations by Disturbance

Disturbance	Individual Axes		Avg. Both Axes	
	Mean (%)	Count	Mean (%)	Count
Overall category				
elbow	2.942	108	2.313	54
junction	4.786	22	0.9699	11
plain	1.368	24	2.223	12
Elbows				
3D upstream	0.513	10	0.0727	5
C_elbow	3.181	40	0.7716	20
one 90° elbow	1.836	20	1.190	10
offset	4.144	38	3.834	19
Junctions				
misaligned	4.605	12	1.075	6
unmodified	5.969	6	1.423	3
wood in collinear	1.191	2	0.9906	1
wood in lateral	4.189	2	1.474	1

6D and further. However, for traverses taken downstream of offset elbows and junction, velocity contours at even 10D were far from symmetrical or smooth.

One could suspect that most irregular velocity contours would be associated with the highest deviations from ideal condition values. As discussed below, that expectation was correct.

Number of Diameters and Number of Axes Used

The effect of distance (L) between the tested component and the traverse location varied with type of component (e.g., plain duct, junction, or elbow) and whether one or both traverses were used to compute the mean velocity upstream. Deviations from the ideal values (Equation 1) decreased substantially if two perpendicular traverses were averaged, and deviations decreased with increasing values of L (see Figures 6a and 6b, which plot all data).

Comparison of Figures 6a and 6b shows a striking reduction of errors when the two perpendicular traverse values were averaged rather than used separately. The results when the horizontal (H) and vertical (V) traverses were averaged together were acceptable (i.e., errors $\leq$5%) even when they were taken relatively close to the upstream component. At L$\leq$4D the deviations were less than 4% for all but one observation. Even at 2D double traverse mean values deviated by less than 6% from ideal values. Surprisingly, even at the very close distance of 1D the greatest deviation was still less than 6.5% for all but one double traverse whose deviation was 7.2%.

The results computed using a single diameter traverse were not as good (see Figure 6b). To obtain deviations consistently less than 5% required measurements at distances 6D or greater.

The variance seen in the figures reflects differing errors for differing upstream test conditions, not just replication differences for the same measurement condition. Examination of the data (see Table I for study design) would show that the deviations from ideal conditions for double traverses taken at the same location for the same upstream test condition all were within 3% of each other. The same was true for single traverses taken at more than 4D length from test conditions. Thus, if one were more interested in the change in airflows (e.g., for troubleshooting) than the actual values, these data suggest that one could generally expect repeatability within 3% under the tested conditions.

If there are no leaks between them the mass flows at the upstream and downstream locations should be the same. Instead, when the mass flows were computed for each based on their respective mean velocities and densities, the mass flows were about 1% higher upstream than downstream. Since the downstream traverses were always done before the upstream traverses on a given day (instead of in randomized order), it is possible that the small differences are attributable to systematic changes in airflow over the course of each day of measurements.

Statistical Significance of Major Variables

Analysis of variance (ANOVA) was performed with a commercial statistics software package, Datadesk (Version 5.0, Datadesk of Cornell, N.Y.). As shown in Table I, different numbers of replications were performed for different test conditions, and some conditions had no replications. Thus, the error term in following ANOVA analyses may not truly represent all conditions. To improve the power of comparisons, the number of categories of test disturbances were reduced to three by lumping all elbow conditions into one group and all junction conditions into a second group. The third type of disturbance was plain opening.

Duct velocities were varied for two test conditions (plain opening and C-shaped elbow), but velocity proved nonsignificant ($p>0.40$) for all analyses. For that reason, all analyses presented here ignore velocity as a variable.

As shown in Table IIA, the axis of the test traverse (Axis) and type of test disturbance (i.e., plain opening, elbow, and junction) were significant at $p<0.05$. Distance from disturbance to the test measurement location (Distance) was not significant. The latter occurred because the effects of under- and overestimations were nearly equal at each measurement location.

The distance from the component (L) was not significant at $p=0.2$, casting some doubt that distances of 6D or greater provided more reliable accuracy. However, the variances were quite different at each distance, making inferences about the effects of distance problematic.

As will be shown later, deviations from ideal values were both positive and negative at the same location. Since practitioners seldom take repeated traverses of the same cross section and average their values, the effects of positive and negative deviations would not cancel out for a single traverse of a given duct. For that reason, the magnitude of the deviations is perhaps of greater interest than their signs.

TABLE IV. ANOVA of the Absolute Value of Deviations Between the Mean of Two Perpendicular Traverses and the Mean of Three Ideal Downstream Traverses

Source of Variation	df	Sum Sq.	Mean Sq.	F-ratio	Prob.
Constant	1	357.858	375.858	141.23	≤0.0001
Distance from disturbance	6	48.8989	8.14982	3.2164	0.0077
Type of disturbance	2	14.8981	7.44907	2.9398	0.0596
Error	68	172.301	2.53384		
Total	76	232.527			

TABLE V. Percentage Difference Between Horizontal and Vertical Traverse Mean Velocities

Test Disturbance	Count	Mean (%)	Std Dev	Min (%)	Max (%)
Plain	12	−0.4	1.8	−3.6	2.4
Elbow, no inlet duct	10	−1.6	5.5	−8.7	7.9
Elbow, 3D of inlet duct	5	−1.7	3.1	−6.8	0.9
Two elbows forming C	20	−7.0	7.1	−18.7	2.4
Two offset elbows	19	−1.3	7.0	−13.8	14.0
Misaligned junction	6	−9.4	6.4	−19.4	−1.3
Junction	3	−17.0	2.8	−19.7	−14.1
Junction, collinear partially blocked	1	−5.0	·	−5.0	−5.0
Junction, lateral partially blocked	1	−11.0	·	−11.0	−11.0

If one repeats the analysis using the absolute value of the deviations (see Table IIB) the distance (L) becomes significant ($p<0.0001$) and the choice of axis becomes nonsignificant ($p=0.8$). Type of disturbance remains highly significant ($p=0.0002$). Scheffe post-hoc tests showed ($p<0.03$) that mean absolute deviations (see Table III) were greatest downstream of junction fittings (4.8%), least downstream of plain duct openings (1.4%), and in between (2.9%) for test conditions downstream of elbows. Thus, one would be most concerned about readings taken just downstream of junction fittings and least concerned about those taken just downstream of plain duct openings.

Broken down within types of disturbances (see Table III), the greatest deviations occurred downstream of the junction (mean values as high as 6%). Offset-elbows and C-elbows showed the next highest deviations. Slight modifications, such as adding 3D of duct upstream of an elbow, slightly misaligning the collinear duct of a junction fitting, or partially blocking the lateral duct of a junction fitting had no significant effect on deviations. Surprisingly, partially blocking the upstream collinear duct at a junction fitting *reduced* the mean absolute deviation from 6% to 1.2%. However, the latter findings were determined with only two tests for each condition.

When the average of the two traverses (axes H and V) was employed, the results were somewhat different. As shown on Table IV, type of disturbance was somewhat less significant. As shown on Table III, the mean magnitude of deviations was strikingly smaller for several of the conditions that had produced large deviations when only a single traverse was employed. For example, the mean deviation when an unmodified junction was the upstream test condition dropped from 6% to 1.4%. Interestingly, deviations for two offset elbows dropped marginally from 4.1% to 3.8%. Surprisingly, deviations for plain duct inlet conditions *increased* from 1.4% to 2.2%, a finding for which the authors can offer no explanation.

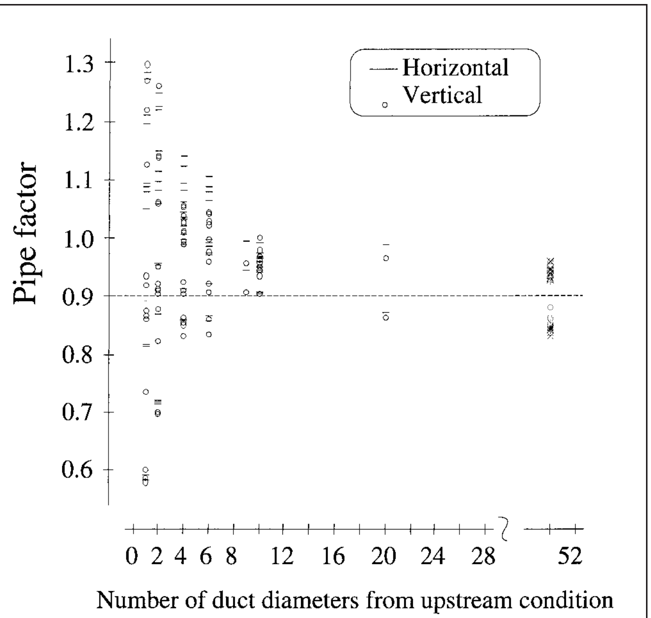

FIGURE 7. PFs for all tests

Horizontal Versus Vertical Traverse Axis

As shown in Table V, horizontal traverse values generally were lower than vertical values. However, the deviation between horizontal and vertical traverse values (Equation 2) varied with the type of test conditions. The differences between horizontal and vertical traverse values were very small for plain duct openings, as one would expect. For elbows, the difference between axes increased with increasing change in direction in the same plane. That is, the greatest difference occurred when the two elbows formed a "C" shape, the least difference occurred with elbows in both the horizontal and vertical planes (offset elbows), and in between was a single elbow. Adding three times the duct diameter of straight duct upstream of the elbow may have reduced variability by half, but the number of tested cases was low(4).

One could expect a similar pattern to occur with junction fittings, with the difference between axes increasing as the airflow through the lateral increased relative to the flow through the collinear duct (i.e., the differences in the order of partially blocked lateral, no blockage, then partially blocked collinear duct). Instead, for these data, partially blocking the collinear duct produced the least axes differences. However, only one test was done for each of the blocked conditions, making inferences highly uncertain.

Given the relatively high standard deviations of the ratio of horizontal to vertical traverse values that were associated with upstream elbows and junctions (see Table V), it would be difficult to find correction factors that would produce better estimates of average velocity using a single traverse diameter because of the high variances in the horizontal to vertical ratio.

Pipe Factor

It would be convenient if a single velocity reading could accurately estimate the mean velocity in a duct. If for example, the PF (ratio of average to centerline velocity) was a constant value for all conditions or if the PFs for conditions of interest were all known,

TABLE VI. Percentage Deviation of Observed PF from an Assumed Value of 0.9

Group	Count	Median (%)	Std Dev	Min (%)	Max (%)
Distance, L = 1D to 11D					
Elbow	108	10.3938	12.4389	−9.7392	44.1130
Junction	22	0.9187	9.2674	−18.4206	15.9824
Plain	24	−13.8224	15.9564	−35.8481	6.7350
Distance, L = 2D to 10D					
Elbow	64	9.46950	7.60868	−7.33018	26.6945
Junction	12	6.60497	5.76712	0.46213	15.9824
Plain	12	2.54835	4.94962	−7.63831	6.7350
Distance, L = 10D to 50D					
Elbow	24	7.09527	3.20468	0.28079	11.2223
Junction	2	−3.58816	0.76899	−4.13191	−3.0444
Plain	4	4.72310	0.58344	3.64842	4.9208

then the average velocity could be found by multiplying the appropriate PF by the observed centerline velocity.

The most commonly recommended value (Equation 3) for use as a PF is 0.9.[6] As shown in Figure 7, for these data the observed PF varied with distance from the test condition and with axis of traverse (i.e., horizontal or vertical). The variability of the observed values increased markedly with decreasing distance from the test condition. As shown in Table VI, estimates of average velocity using PF=0.9 produced errors as large as 44% when distances were as close as 1D. The results were not surprising, since one would expect the vena contracta at a plain inlet to produce an extremely low PF while the momentum of the flow through an elbow would produce skewed velocity profiles (see Figure 5).

When the distance was increased to 3D or greater, the very high variance associated with plain duct inlets was much reduced, and the greatest error was reduced from 36% to less than 8%. On the other hand, the greatest error associated with upstream elbows showed much less improvement, falling from a maximum of 44% to a maximum of 27%. When distance was 10D or greater the errors fell to less than 5% for cases involving upstream junctions and plain ducts, but was typically 5 to 11% off for all types of elbows.

It also would be convenient if a measure of skewness of the velocity profile were related to the measurement error. However, plotting PF against error from comparing test and downstream ideal traverses revealed no clear association between the two (not shown).

CONCLUSIONS

This study demonstrates that two perpendicular traverses can be taken closer than 7 diameter's distance (7D) from an obstruction with less than 5% deviation from results that would have been found under ideal conditions. Even at 4D few errors greater than 5% occurred for any upstream disturbance. For a single diameter traverse, the minimum of 7D distance recommended by *Industrial Ventilation* was supported. Errors were greatest when the upstream disturbance was two elbows in series or a junction fitting, and least when it was a plain duct opening.

Using the rule of thumb to estimate airflow using the PF produced large errors (>10%) for all conditions unless the measurements were taken well downstream of plain duct openings.

It should be noted that these measurements were taken using a mechanical device to hold the tubes to correct alignment and insertion depths. Although the device has been used extensively in the field by the authors and its construction specifications have been published,[3] its use is not yet widespread. It is likely that the variance of both the upstream (test) and the far downstream (ideal) readings would have been somewhat higher if the tubes had been held by hand. Future work will address this issue.

On the other hand, in some cases several hours separated the time when the test conditions were measured and the time when ideal conditions were measured. Variations due to changes in line voltage and the vagaries of fan performance thus may have inflated the observed deviations between test and ideal traverses.

ACKNOWLEDGMENTS

This study would not have been possible without the data collected by Donald A. Metzger of Seattle, Wash.

REFERENCES

1. **Guffey, S.E.:** Modeling existing ventilation systems using measured values. *Am. Ind. Hyg. Assoc. J.* 54:293–305 (1994).
2. **Guffey, S.E.:** Quantitative troubleshooting of industrial exhaust ventilation systems. *Appl. Occup. Environ. Hyg.* 9:267–280 (1994).
3. **Guffey, S.E.:** Simplifying pitot traverses. *Appl. Occup. Environ. Hyg.* 5:95–100 (1990).
4. **Ower E., and R.C. Pankhurst:** *The Measurement of Air Flow,* 5th ed. Oxford, U.K.: Pergamon Press, 1977.
5. **Howes, J.E., R.N. Pesut, and J.F. Foster:** *Final Report on Interlaboratory Study of the Precision of the Determination of the Average Velocity in a Duct (Pitot Tube Method) Using ASTM Method D 3154-72.* Philadelphia: American Society for Testing and Materials, 1974.
6. **American Conference of Governmental Industrial Hygienists (ACGIH) Committee on Industrial Ventilation:** *Industrial Ventilation: A Manual of Recommended Practice,* 23rd edition. Cincinnati, OH: ACGIH, 1998.
7. **Folsom, R.G.:** "Review of the Pitot Tube, Read before the Fluid Meters Research Committee of ASME." Nov. 1955.
8. **International Organization for Standardization (ISO):** *Measurement of Fluid Flow by Means of Orifice Plates, Nozzles and Venturi Tubes Inserted in Circular Cross-section Conduits Running Full* (ISO 5167-1980). Geneva: ISO, 1980.
9. **International Organization for Standardization (ISO):** *Measurement of Fluid Flow in Closed Conduits—Velocity Area Method Using Pitot Static Tubes* (ISO 3966-1977 (E)). Geneva: ISO, 1977.
10. **International Organization for Standardization (ISO):** *Measurement of Fluid Flow in Closed Conduits-Velocity-Area Methods of Flow*

Measurement in Swirling or Asymmetric Flow Conditions in Circular Ducts by Means of Current-Meters or Pitot Static Tubes (ISO 7194-1983 (E)). Geneva: ISO, 1983.

11. **McLoone, H.E., S.E. Guffey, and J.C. Curran:** Effects of shape, size, and air velocity on entry loss factors of suction hoods. *Am. Ind. Hyg. Assoc. J. 54*:87–94 (1993).
12. **Guffey, S.E., and J.C. Curran:** Use of power balance to model pressures in bilateral junctions for converging flow ventilation systems. *Am. Ind. Hyg. Assoc. J. 54*:102–112 (1993).
13. **American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE):** *Standard Methods for Laboratory Air-Flow Measurements* (41.2-1987). Atlanta: ASHRAE, 1993.