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CHARACTERIZATION OF GAS MIXING IN AN EXHAUST STACK

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A typical ventilation exhaust stack has been studied for gas mixing and uniformity of flow. A test gas, sulfur hexafluoride (SF_6), was introduced into a rectangular duct entering the 30.5-cm (12 inch) interior diameter stack at 45°. Cross sectional air samples were drawn through a multipoint sampling probe from two perpendicular directions at three stack levels. A photoacoustic infrared spectrometer measured SF_6 concentrations. Gas distributions were quite nonuniform at 1.5 stack diameters from the last disturbance. When introduced at duct center, the gas was well mixed (relative standard deviation $\leq$ 0.05) by 10 stack diameters from the last disturbance. This agrees with Environmental Protection Agency and American National Standards Institute "rules of thumb." Comparisons with another experimental study using SF_6 indicate that the angle of entry of the air into a stack or duct determines the distance required for mixing. Mixing was reduced at off-center injection, but apparently unchanged at halved air flow.

"Representative particle samples from ducts and large stacks can be assured only by careful selection of the sampling point, with attention given to the design of the probe and sampler arrangement."(1) Sampling location(s) within a ventilation stack or duct are three dimensional: (1) distance along the center line from some defined point and (2) coordinates within a two-dimensional cross sectional plane.

The number of sampling probes or sampling positions of a single probe required in this cross section depends on the uniformity of the air flow and, particularly, on the completeness of mixing of particulates or gases from the source. Transitions, such as changes in duct sizes and/or angular intersections of ducts, and bends, such as elbows, are present in nearly all ventilation systems. These have the effects of disturbing airflow, creating eddies, cross currents, and dead flow spaces. On the other hand, such disturbances have the positive effect of enhancing mixing of gases or particulates.

Identification of the point along a stack or duct where airflow is adequately uniform and mixing is adequately complete is valuable. The rate of sampling appropriate to the type of sampler used can be easily selected and maintained. Also, the need for multiple samplers or multiple sampling locations would be obviated. The objective of this report is to present additional data and analysis to move toward prediction of this ideal sampling point.

BACKGROUND

The American National Standards Institutes, Inc. (ANSI), *Guide to Sampling Airborne Radioactive Materials in Nuclear Facilities* states: "Generally, the distance from the transition or elbow to the point of sampling should be a minimum of five and preferably ten or more diameters downstream. In some cases this distance may be inadequate."(1)

The U.S. Environmental Protection Agency (EPA) has recommended an "eight- and two-diameter rule," which states that sampling should be performed at locations at least eight stack diameters downstream and two diameters upstream from any flow disturbance.(2)

Hampl et al. studied gas mixing in four duct configurations.(3) They used sulfur hexafluoride (SF_6) discharged from a symmetrical four-point (in one case also a one-point) source. Dispersion factors (D = RSD, the relative standard deviation of cross section measurements) were measured at selected sampling distances along the ducts. They made extrapolations of dispersion factors on log-log plots to D = 0.05, where mixing was considered complete, to arrive at these minimum sampling distances: 50 duct diameters for a straight duct; 25 duct diameters for a straight duct, 45° side branch combination with flow through both branches; 7 duct diameters for a straight duct, one-elbow combination; and 4 duct diameters for a straight duct, two-elbow combination. These conclusions suggest that the ANSI and EPA rules-of-thumb may be inadequate.

EXPERIMENTAL

Gas mixing studies have been done with a ventilation stack in actual use at the Los Alamos National Laboratory. The stack followed ducting, a HEPA filter bank, and a centrifugal fan in a system dedicated to the general ventilation of two large rooms. Figure 1 shows the design and dimensions of the circular stack of 30 cm (12 inches) inner diameter and the rectangular duct of 28 cm (11 inches) wide × 33 cm (13 inches) high connecting it to the fan from the south direction.

Air flow (approximately 102 m^3/min or 3600 ft^3/min) was maintained by a computerized controller (SMART II from Staefa Control System, Inc., San Diego, Calif.). However, variations in total air flow rate occurred as a result of doors to the rooms being opened and sometimes left open. For one set of studies air flow was adjusted to half the normal flow.

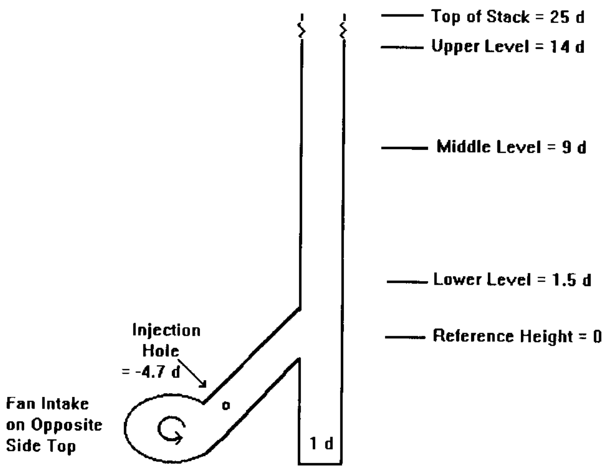

FIGURE 1. Dimensions (not to scale) of the test stack, duct, and fan. Distances in d = 30.5 cm (12 inches) were measured from the upper intersection of the duct and stack. The view is from the east.

SF_6 gas (Commercial grade, Air Products, Inc., Tamaqua, Penn.) was used as the tracer. Its flow was controlled by a Multipoint Sampler and Doser (Type 1303, Bruel & Kjaer, Naerum, Denmark) at a flow rate measured to be 51 ± 0.5 mL/min for 276 kPa (40 psi) supply pressure. The SF_6 was introduced perpendicular to air flow through a 3-mm (1/8-inch) outside diameter copper tube inserted through a hole in the east side of the duct between the stack and the fan (Figure 1). The tube was inserted to selected distances and bent, if necessary, to inject gas perpendicular to air flow at various locations in the duct cross section. For some reference measurements SF_6 was introduced into the ventilation system in the duct preceding the fan to ensure complete mixing.

A multipoint probe (Figure 2) was used to take samples at 0, 5.1, 10.2, 15.2, 25.4, and 30.5 cm (0, 2, 4, 6, 10 and 12 inches) from the farthest inner wall along diameters of the stack. The B&K Multipoint Sampler and Doser instrument drew samples at 1.8 L/min through six 1.6-mm (1/16 inch) outside diameter sampling lines and introduced them sequentially at 1-minute intervals into the analyzer. The sample line at 20.3 cm was not used, since the sampler could handle only six samples. Threaded 10-mm (3/8-inch) holes were drilled into the stack from two directions for insertion of the probe at three levels: lower level 9.1 m (30 feet) above ground level, south and west; middle level 11.4 m (37. 5 feet), south and west; upper level 13.0 m (42.7 feet), north and west. Holes were plugged when not being used. These three axial distances up the stack were used because the holes already had been drilled by someone else previously measuring velocities.

In one test, SF_6 samples were taken sequentially from the stack centers at the three sampling levels and analyzed. The gas injection location was the east duct wall.

SF_6 concentrations were measured by a supplier-calibrated photoacoustic infrared spectrometer (Multi-gas Monitor, Type 1302, Bruel & Kjaer). Water vapor concentrations were also measured, for which interferences were automatically corrected. Measured concentration data (mg/m^3) were transferred to a computer controlling both B&K instruments and subsequently analyzed on a spreadsheet. Sampling and analysis at 1-minute intervals was cycled through the six traverse points for about 90 minutes.

Stack air flow measurements were taken at the three levels according to EPA Method 2[(4)] using an Electronic Digital Micromanometer (Model EDM-I, Neotronics, Norwalk, Conn.). The same sampling holes described above were used. Pitot tube locations were at 1.3, 2.5, 4.6, 6.9, 10.4, 20.1, 23.6, 25.9, 27.9, and 29.2 cm from the farthest inner stack wall. Two perpendicular traverses gave a total of 20 cross section sampling points per level. Velocity pressures were converted to linear and volumetric flow rates using calibration factors traceable to the National Institute for Science and Technology and obtained at Los Alamos, N.M.

Table I summarizes the gas injection locations and stack levels at which concentrations were measured. These measurements were made over a period of 52 days. Duplicate measurements made on different days for one middle level traverse were in good agreement (means of 4.51 vs. 4.28 mg/m^3 with standard deviations of 0.24 and 0.14, respectively).

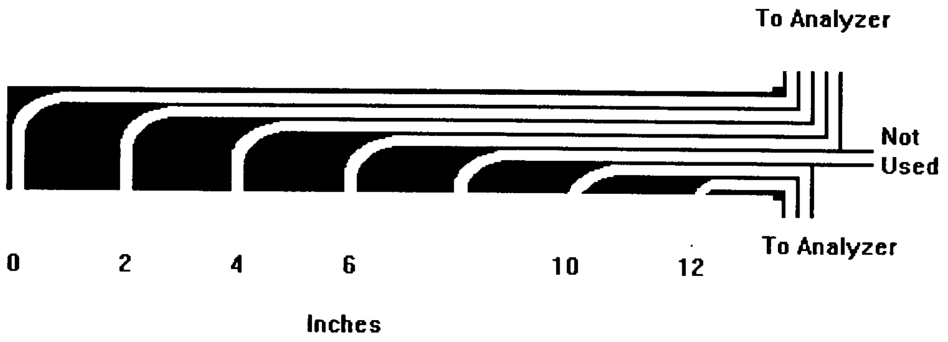

FIGURE 2. Multipoint sampling probe for gases (not to scale). Probe was 9.5-mm ($^3/_8$ inch) outside diameter copper; seven tubes were 1.6-mm (1/16 inch) outside diameter by 46 cm (18 inches) long stainless steel.

DATA ANALYSIS

Slow drifts in average concentrations were observed and attributed to activities in the rooms being ventilated and ambient temperature changes during the day. Such variations required taking many samples over periods of

TABLE I. Dispersion Factors Across the Stack

	Relative Standard Deviation Stack Measurement Level		
Injection Point in the Duct	*Lower*	*Middle*	*Upper*
Center	0.26	0.06	0.03
West wall			
Full flow	0.56	0.11	0.05
Half flow	0.50	0.19	
East wall		0.10	
Top wall		0.14	
Bottom wall		0.17	
Before fan	0.02[A]	0.01	0.03[A]
Distance from injection (diameters):	6.2	13.7	18.7
Distance from last disturbance (diameters):	1.5	9	14

[A] one traverse only

hours. Concentrations at each sampling location and level for a selected injection point on a given day were averaged. Then these averages for all traverses were normalized to the overall average for all measurements at one stack level and injection point. A relative standard deviation (dispersion factor of Hampl et al.) was then computed for the 12 (or in one case 18) normalized concentrations.

Velocity measurements at each stack level also were averaged, and a relative standard deviation for 20 points was calculated.

Three-dimensional (3-D) plots of both the SF_6 concentration distributions and the velocity distributions were made using SURFER (Golden Software, Inc., Golden, Colo.). First, the data were fit to a 36 × 36 grid. Then the surface outside a 15-cm radius was blanked out to simulate the round stack. This software draws the flat base at the lowest value inside the 15-cm radius to show the range of values, which may not be obvious if out of sight of the direction of view.

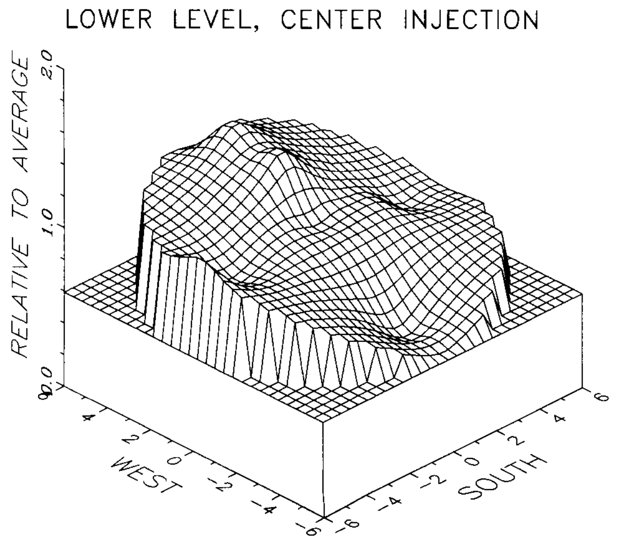

FIGURE 3. Normalized SF_6 concentration profile at the lower level when the gas was injected at duct center

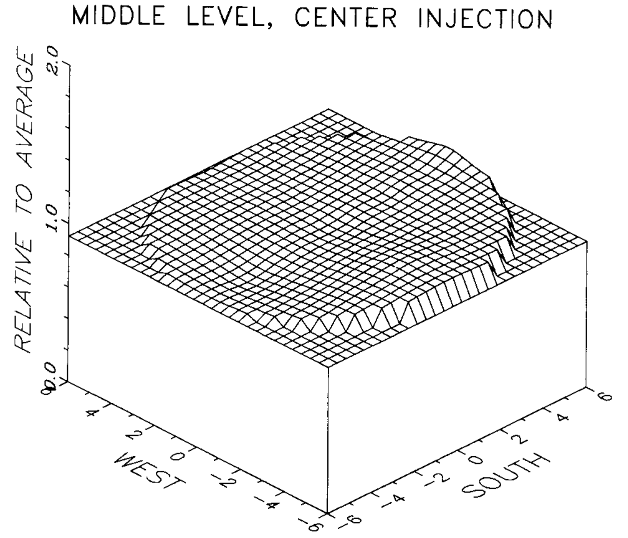

FIGURE 4. Normalized SF_6 concentration profile at the middle level when the gas was injected at duct center

RESULTS

The 3-D plots of SF_6 concentration profiles provide qualitative descriptions of mixing. Figures 3–5 show the progression of the

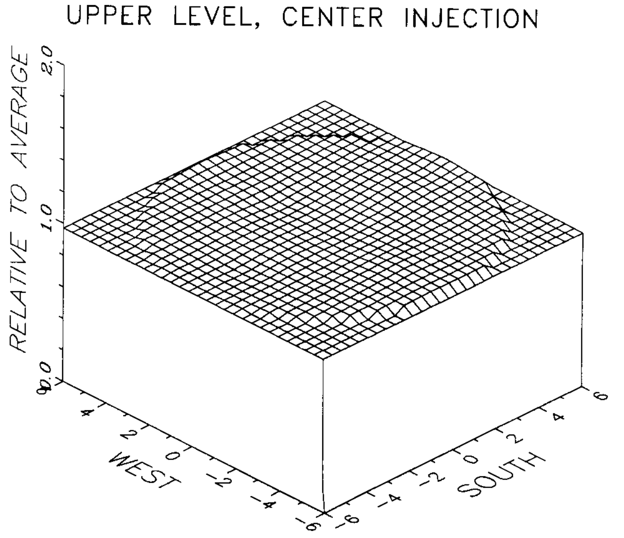

FIGURE 5. Normalized SF_6 concentration profile at the upper level when the gas was injected at duct center

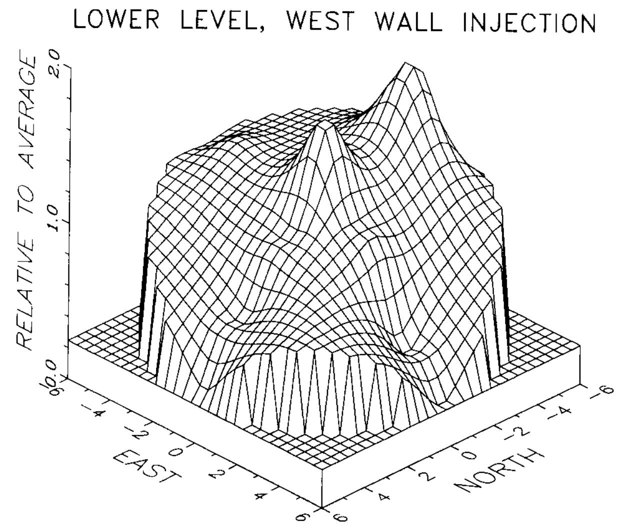

FIGURE 6. Normalized SF_6 concentration profile at the lower level when the gas was injected at duct west wall. Note that the view is 180° from those of the other surface plots to better show the concentration dips at the north and east sides.

profile toward flatness further up the stack for gas injection at duct center. The profile at the upper level (Figure 5) was nearly that of complete mixing obtained when the gas was injected into the system before the fan.

Figure 6 shows the lower level profile when the gas injection was at the west side duct wall, instead of center. Both extreme peaks and valleys, which cannot be explained at this time, can be seen in the concentration profile. Note that the view is 180° from those of the other surface plots to better show the concentration dips at the north and east sides. In this case the gas was less well mixed, even at the upper level (not shown).

Similar plots of velocity profiles have been made (Figures 7–8). Figure 7 shows the considerable dead air region on the south side of the stack at the lower level. This is not surprising since the duct from the fan is attached to the south side of the stack at a 45° angle (Figure 1). It is useful to note that an east/west traverse alone would not have detected this dead zone or a velocity profile problem. By the middle level the velocity profile is relatively flat (Figure 8).

Lower level concentration profiles (Figures 3 and 6) and the velocity profile (Figure 7) were not identical. Also, the concentration profiles depended on gas injection point. Therefore, velocity profiles cannot be used to demonstrate gas mixing.

A quantitative description of concentration profiles is given in Table I, which lists dispersion factors (relative standard deviations) at the various stack levels and gas injection points. For center of duct gas injection the dispersion factor decreased from 0.26 at the lower level to 0.03 at the upper level. This compares to dispersion factors of 0.01 to 0.03 obtained for complete gas mixing by the fan. These latter values represent analytical uncertainties. Therefore, within measurement uncertainties the gas was essentially mixed by the upper level.

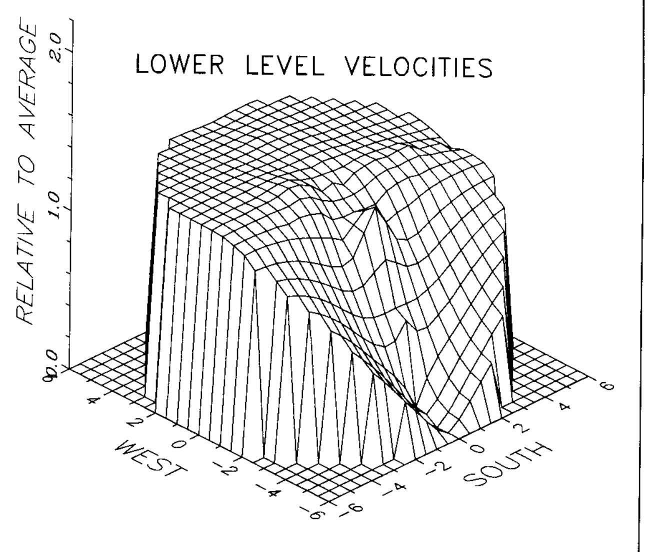

FIGURE 7. Air flow velocity profile at the lower level. The relative standard deviation of measured velocities was 0.46.

There are two ways of describing the axial distances (in duct or stack diameters): (1) distance from the point of injection and (2) distance from the point of last disturbance, in this case the upper duct wall and stack intersection. The average duct diameter $(d_1d_2)^{1/2}$ and the stack diameter were the same, 30.5 cm (12 inches). These distances also are given in Table I.

Effects of halving the air flow for west wall gas injection are shown in Figure 9. Dispersion factors were similar at both flow rates (Reynold's numbers of 3.5×10^5 and 1.7×10^5).

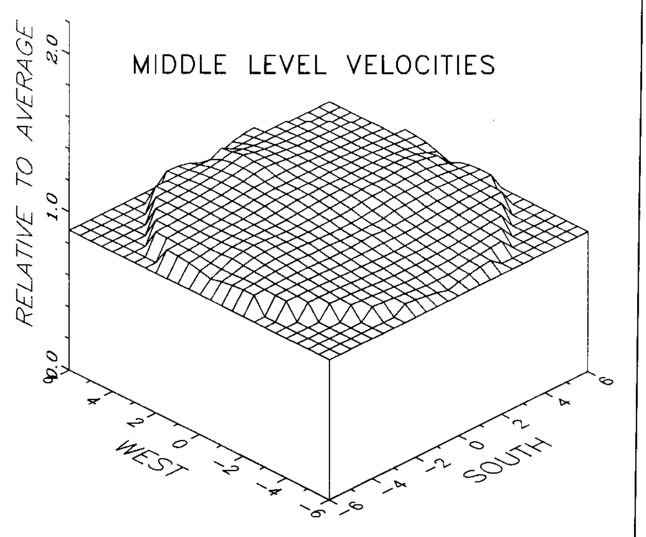

FIGURE 8. Air flow velocity profile at the middle level. The relative standard deviation of measured velocities was 0.06.

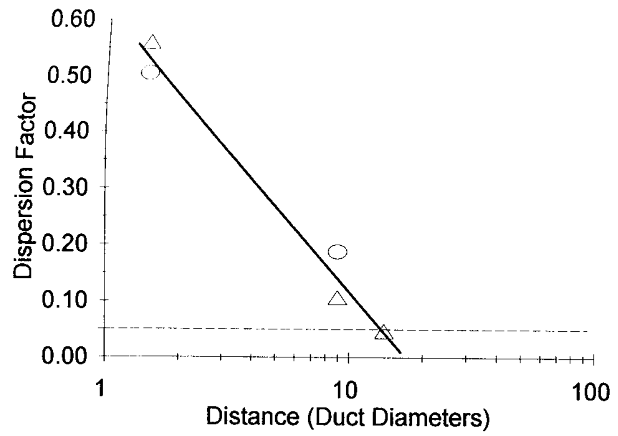

FIGURE 9. Effect of air flow rate on the dispersion factors determined for injection at the west duct wall. Full flow at a Reynold's number of 3.5×10^5 (triangles) and half flow at 1.7×10^5 (circles). The horizontal dashed line at 0.05 dispersion factor is assumed to represent complete mixing.

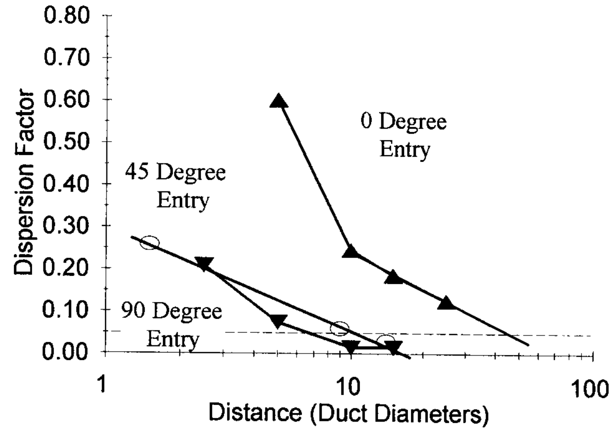

FIGURE 10. Average dispersion factors for symmetrical injections as a function of angle of entry: this work (circles); Hampl et al. work with a straight duct and one with an elbow (triangles). The horizontal dashed line at 0.05 dispersion factor is assumed to represent complete mixing.

DISCUSSION AND CONCLUSIONS

The observed lack of flow rate effects agrees with the results of Hampl et al.,(3) which showed no significant differences in mixing in either a straight duct (Reynold's numbers of 1.2×10^5 to 3.0×10^5) or ducts with one or two elbows (Reynold's numbers of 1.2×10^5 to 2.0×10^5).

Hampl et al. chose a dispersion factor of 0.05 as describing complete mixing. They used the "distance between the sampling probe and the SF_6 discharge or last disturbance source" in duct diameters as a measure, as do ANSI and EPA.(1,2) In Figure 10 Hampl's average (for all air flows) dispersion factors for 4-point discharges into a straight duct and one preceded by a 90° elbow, plotted on a semilog graph, indicate complete mixing at 45 ± 5 and 6.5 ± 0.7 duct diameters, respectively. The results in Table I for center duct gas injections and a 45° angle entry into a stack are intermediate between Hampl's, reaching a 0.05 dispersion factor in 10 ± 1 diameters.

At first it may seem that the configuration shown in Figure 1 should be compared with Hampl's branched duct. The difference is that for the latter there was air flow through both branches. Figure 11 shows how significant this difference is. Hampl's dispersion factors extrapolate to 0.05 at much larger numbers of duct diameters, 25 ± 3 and 32 ± 3 at Reynold's numbers of 1.2 ± 10^5 and 2.0 ± 10^5, respectively. Also, the mixing is clearly more efficient at the lower flow rate. These differences can be explained by stratification created by SF_6 being introduced into only one of the branches (an assumption not clearly stated in Hampl's paper). Such stratification would be compounded by the higher density of SF_6 than air and would depend on the three-dimensional arrangement of the branches. At a lower total air flow there would be more time to reduce the stratification by turbulent mixing and radial diffusion before a certain distance is reached.

Table I also shows the effects of off-center gas injections. West duct wall injections produced dispersion factors about twice as large as center injections for all three sampling levels. The east wall dispersion factor at the middle level matched the west wall one (both about 14 cm, 5.5 inches, or 0.46 average duct widths from center) for middle level sampling. Top and bottom wall (about 16.5 cm, 6.5 inches, or 0.54 average duct widths from center) dispersion factors for middle level sampling were a little larger. Figure 12 is a plot of these dispersion factors

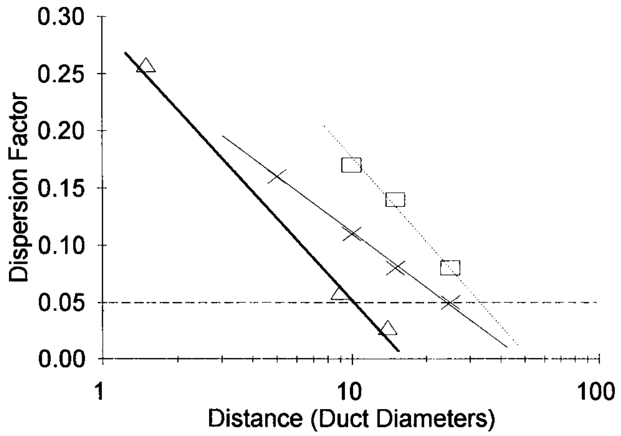

FIGURE 11. Dispersion factors for two branched flow cases: this work with a Reynold's number of 3.5×10^5 (triangles) for flow through the side branch only; Hampl et al. work with Reynold's numbers of 1.2×10^5 (Xs) and 2.0×10^5 (squares) for flow through both branches. The horizontal dashed line at 0.05 dispersion factor is assumed to represent complete mixing.

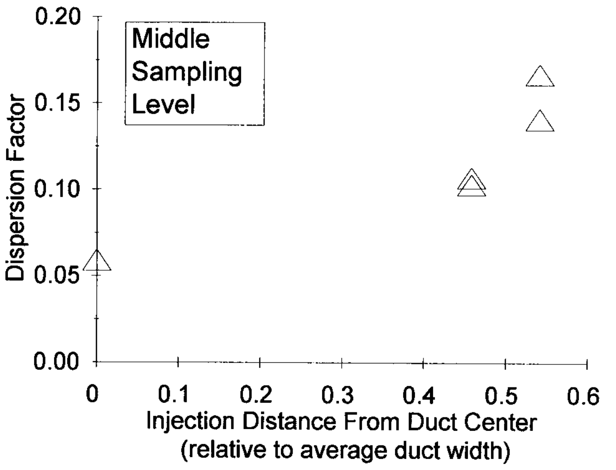

FIGURE 12. Effect of distance from duct center at which gas injection occurred on the dispersion factor measured at the middle level.

for the middle sampling level versus gas injection distance from duct center. These results show that the gas injection radial location is important, as well as the axial location. The effect shown may be as much a side wall effect as an effect of the insertion location.

For symmetrical (center of duct) gas injection and 45° entry into a stack, mixing was complete (RSD $\leq$ 0.05) by 10 stack diameters from the last flow disturbance. This is in agreement with the rules of thumb mentioned in ANSI and EPA documents.(1,2) However, comparisons with the experimental results of Hampl et al.(3) in Figure 10 show that the angle of entry of the contaminated air into the stack influences the number of stack diameters required.

Stratification of air is a likely explanation for the observation using Hampl's results that a 45° branched duct with flow through both branches required 25–32 diameters for mixing to the same extent. The flow rate effect, not seen with other geometries in this work and Hampl's, supports this conclusion.

It also was found that the point of gas injection across a duct affects the mixing achieved at a certain distance along a duct or stack. Wall effects may contribute to this. Such things must be kept in mind when measuring mixing in a system.

Two other factors that should affect completeness of mixing need to be studied: (1) the axial distance that a contaminant travels along a duct from the point of injection to the point of "last disturbance" and (2) the relative air flows in the two branches of a branched duct.

The concern of gas and particulate mixing in ducts and stacks is important for economic and regulatory reasons. More experimental and theoretical studies are needed to define the critical parameters and to develop predictive models for gas and particulate mixing.

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