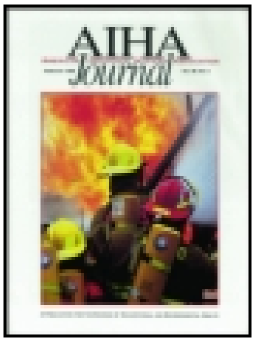

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Use of Tracer Gas Technique for Industrial Exhaust Hood Efficiency Evaluation — Where to Sample?*

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A tracer gas technique using sulfur hexafluoride (SF_6) was developed for the evaluation of industrial exhaust hood efficiency. In addition to other parameters, accuracy of this method depends on proper location of the sampling probe. The sampling probe should be located in the duct at a minimum distance from the investigated hood where the SF_6 is dispersed uniformly across the duct cross section. To determine the minimum sampling distance, the SF_6 dispersion in the duct in fully developed turbulent flow was studied at four duct configurations frequently found in industry: straight duct, straight duct-side branch, straight duct-one elbow, and straight duct-two elbows combinations. Based on the established SF_6 dispersion factor, the minimum sampling distances were determined as follows: for straight duct, at least 50 duct diameters; for straight duct-side branch combination, at least 25 duct diameters; for straight duct-one elbow combination, 7 duct diameters; and for straight duct-two elbow combination, 4 duct diameters. Sampling at (or beyond) these distances minimizes the error caused by the non-homogenous dispersion of SF_6 in the duct and contributes to the accuracy of the tracer gas technique.

Introduction

One of the most commonly used controls of harmful industrial contaminants is a local exhaust hood. The efficiency of this system is defined as the ratio of air contaminant quantity captured by the system per unit time to the total contaminant quantity produced by the process per unit time. Two of the following measurements are required for the efficiency determination: 1) total contaminant generation rate; 2) hood capture rate of contaminants; or 3) total contaminant rate escaping the hood. Measurement of the capture rate can be accomplished by contaminant sampling in the duct; however, measurement of the total contaminant generation rate or the hood escape rate is extremely difficult or even impossible without a complete enclosure of the process area. To overcome these problems, a tracer gas technique has been suggested to evaluate single hood performance. This technique provides information which cannot be obtained readily in any other manner.

The tracer method, employing gaseous or particulate tracers, has been used for performance evaluation of fume hoods.[1-4] Recently, Ellenbecker *et al.*[5] used particulate tracer for the evaluation of industrial local exhaust. Its use, however, may be impractical in some cases because of the inability to differentiate tracer and industrial process particulates. Therefore, a tracer gas method using sulfur hexafluoride (SF_6) was developed to estimate the efficiency of hoods controlling gaseous and vaporous emissions.[6] First, SF_6 is discharged at a known constant rate into the industrial process generation area. Then, by comparing this quantity to that captured by the exhaust system (as measured in the exhaust duct), hood efficiency is estimated at the point of tracer gas generation. Accuracy of this method is determined partially by the accuracy of SF_6 concentration estimation. Since SF_6 is detected in the duct, the correct estimation of SF_6 requires a sampling probe to be located in the duct at a distance from the exhaust hood where SF_6 is dispersed uniformly across the duct cross section. If the sampling probe is located at a shorter distance, a significant error may be introduced into this method.

In addition to molecular and turbulent diffusion, the gas dispersion in the duct is affected by duct air velocity and duct configuration. Therefore, SF_6 dispersion in fully developed turbulent airflow was studied as a function of the duct velocity and duct configuration frequently used in industry. The purpose of this research was to determine the minimum sampling distance from the exhaust hood at which the sampling probe should be located to minimize error caused by the non-homogenous dispersion of SF_6 in the duct.

Methodology

An experimental installation shown in Figure 1 was used for the study. Sulfur hexafluoride was discharged into the duct

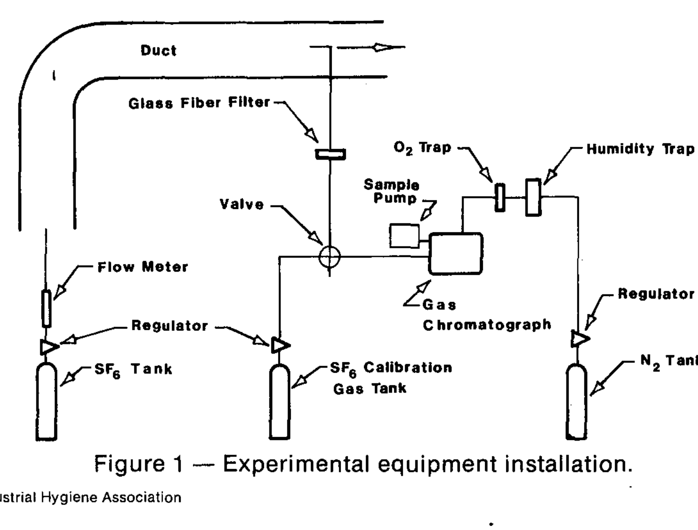

Figure 1 — Experimental equipment installation.

*Mention of company names or products does not constitute endorsement by the National Institute for Occupational Safety and Health.

and detected at different distances from the discharge point or disturbance source in the duct. An 0.25% SF_6 - air mixture (AIRCO Industrial Gases) discharged at a steady rate from a cylinder was used as a tracer source. The discharge flow rate was controlled by a flowmeter with an accuracy of ±3%.

For SF_6 detection, a gas chromatograph (Baseline Industries, Inc., Model 1030A) equipped with an electron capture detector was used. The chromatographic column was a 183 cm (6 ft) long, 0.32 cm (1/8 inch) OD stainless steel tubing with Molesieve 5A 60/80. A built-in microprocessor provided automatic repetition of sampling cycle. High-purity nitrogen was used as a carrier gas (AIRCO Industrial Gases). The sampling line was provided with a glass fiber filter to avoid contamination of the gas chromatographic column by the particulate emissions. The carrier gas and air sample flow rates were maintained constantly at 50 mL/min.

For calibration, SF_6-air mixtures with various concentrations of SF_6 were used. The mixtures were commercially available with a guaranteed analysis of the SF_6 content in ppb range with accuracy of ±5% (Scott-Marrin, Inc.).

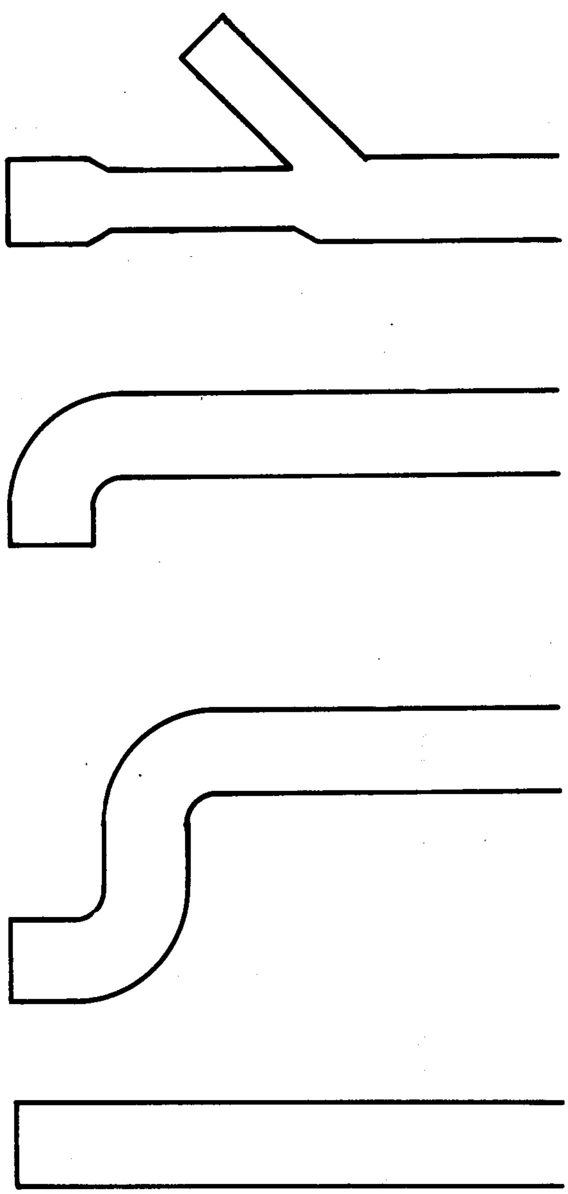

Figure 2 — Investigated duct configurations.

TABLE I
Summary of Investigated Parameters

Duct Configuration	Velocities	Discharge Method	Sampling Distances	Sampling Points
Straight duct	1	1 point	4	20
	3	4 point	4	12
Side branch	2	4 point	4	12
One elbo	2	4 point	4	12
Two elbows	2	4 point	4	12

To investigate the SF_6 concentration across the duct area, a 6- or 10-point traverse method was used. This method is a standard method for evaluation of the duct air velocity.[7] The measurements were taken in both vertical and horizontal directions. At each point, five or more samples were taken in 5-min intervals.

Investigated Variables

Effects of the following variables on SF_6 dispersion uniformity were investigated: duct air velocity; duct configuration; and sampling distance from the SF_6 discharge (or the last flow disturbance source in the duct).

Galvanized ducts with diameters of 25.4 cm (10 in) and 35.6 cm (14 in) were used for experiments. The selected velocities ranged from 508 cm/sec to 2033 cm/sec (1000 ft/min to 4000 ft/min), which covers the range of the velocities generally used in industry. The duct air velocity was measured by the standard traverse method.[7] Since these velocities may correspond to different airflow rates in the ducts with different diameters, the velocity parameter was expressed as a function of Reynolds number, Re, which includes both velocity and duct size. Two systems are said to be dynamically similar if the Reynolds number is the same. The three selected velocities corresponded to the following Reynolds numbers: 120 000; 200 000; and 300 000. A majority of industrial ducts usually operate at Re above 100 000. Of 55 industrial ducts investigated, only 14% of ducts were operating considerably under 100 000 Re.

The duct configuration effect was studied at four different configurations frequently found in industrial ventilation systems: straight duct; straight duct in combination with side branch; straight duct with one 90° elbow; and straight duct with two 90° elbows. These are shown schematically in Figure 2.

Sampling distance was expressed in duct diameters to include effect of the duct size. The distance between the sampling probe and the SF_6 discharge or last disturbance source ranged from 2.5 to 25 duct diameters. A summary of investigated parameters is presented in Table I.

The SF_6 was discharged from a four-point source. The four-point source was a simple ring located around the periphery of the duct. This ring was provided with four equally-spaced holes with diameters of 0.2 cm (0.08 inch). Sulfur hexafluoride was discharged perpendicularly to the duct airflow; however, for comparison, SF_6 also was dis-

TABLE II
Overall Mean and Standard Deviation of SF_6 Concentration (ppb) Across Duct Cross Section at Different Sampling Distances

Duct Configuration	Distance (duct diameter)	SF_6 concentration (ppb) Overall Mean Re = 1.2 × 10^5	Overall Mean Re = 2.0 × 10^5	Overall Mean Re = 3.0 × 10^5	± Standard Deviation Re = 1.2 × 10^5	± Standard Deviation Re = 2.0 × 10^5	± Standard Deviation Re = 3.0 × 10^5	Remarks
Straight duct	5.0	3.45			4.43			
	10.0	4.64			2.74			1-point discharge
	15.0	4.39			1.80			
	25.0	4.65			0.32			
Straight duct	5.0	6.12	5.00	5.51	3.89	2.97	3.21	
	10.0	5.29	5.26	5.00	1.02	1.61	1.21	
	15.0	5.53	5.15	5.81	1.29	0.98	0.78	
	25.0	5.49	5.06	5.10	0.65	0.75	0.54	
Side branch	5.0	5.32	NM[A]		0.82	NM[A]		
	10.0	5.62	5.03		0.62	0.83		
	15.0	5.28	5.34		0.43	0.73		4-point discharge
	25.0	4.90	5.12		0.22	0.41		
1 elbow	2.5	6.18	4.25		1.46	0.78		
	5.0	5.30	4.31		0.47	0.28		
	10.0	5.32	4.28		0.07	0.07		
	15.0	5.59	4.29		0.11	0.04		
2 elbows	2.5	4.38	4.26		0.25	0.22		
	5.0	4.63	4.61		0.21	0.14		
	10.0	4.92	4.73		0.11	0.18		
	15.0	4.86	4.81		0.13	0.03		

[A]NM = Not measured.

charged from a 1-point source represented by a tubing located parallel to the duct airflow, in the straight duct configuration only.

The SF_6 concentration data found at individual traverse points in vertical and horizontal directions were averaged. Then an overall mean SF_6 concentration across the entire duct cross section was calculated for each sampling distance. These data are shown in Table II.

Results

As mentioned previously, magnitude of the tracer method accuracy depends on the degree of the SF_6 dispersion uniformity in the duct. To characterize this degree, a dispersion factor was established and defined as a relative standard deviation of SF_6 concentrations estimated at each sampling location as follows:

TABLE III
The Dispersion Factors at Different Sampling Distances

Duct Configuration	Distance (duct diameter)	Dispersion Factor Re = 1.2 × 10^5	Re = 2.0 × 10^5	Re = 3.0 × 10^5	Remarks
Straight duct	5.0	1.29			
	10.0	0.59			
	15.0	0.41			1-point discharge
	25.0	0.07			
Straight duct	5.0	0.64	0.59	0.58	
	10.0	0.19	0.31	0.24	
	15.0	0.23	0.19	0.14	
	25.0	0.12	0.15	0.11	
Side branch	5.0	0.16	NM[A]		
	10.0	0.11	0.17		
	15.0	0.08	0.14		
	25.0	0.05	0.08		4-point discharge
1 elbow	2.5	0.24	0.18		
	5.0	0.09	0.06		
	10.0	0.01	0.02		
	15.0	0.02	0.01		
2 elbows	2.5	0.06	0.05		
	5.0	0.05	0.03		
	10.0	0.02	0.04		
	15.0	0.03	0.01		

[A]NM = Not measured

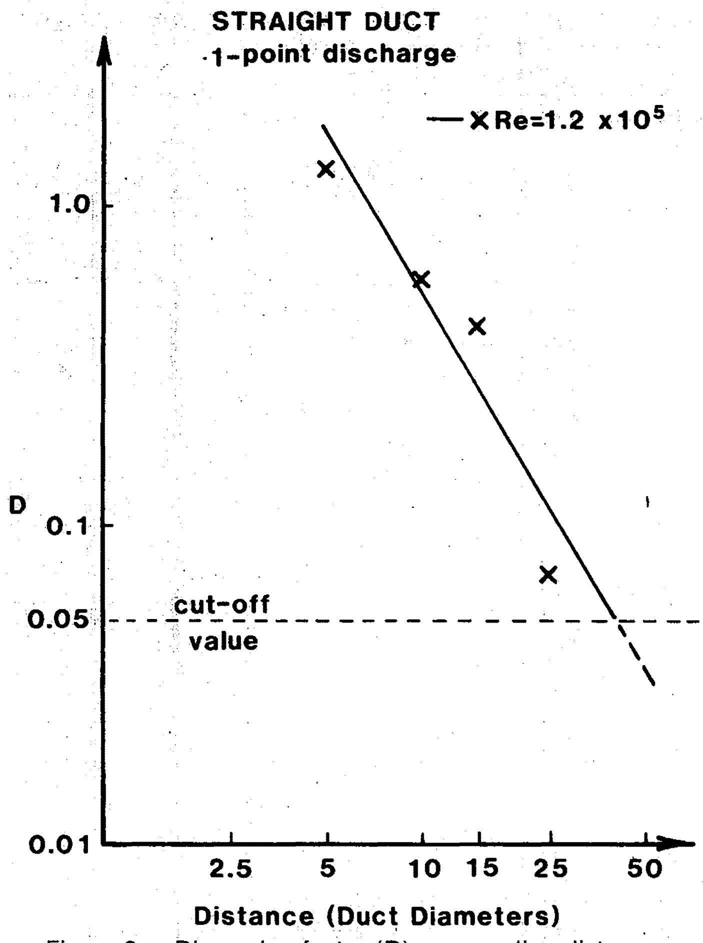

Figure 3 — Dispersion factor (D) *vs.* sampling distance.

$$D = \frac{1}{\bar{C}}\sqrt{\frac{\sum^{n}(C_i - \bar{C})^2}{n-1}} \quad (1)$$

where D = dispersion factor;
$\bar{C}$ = overall mean SF_6 concentration across the duct cross section at individual sampling distance;
C_i = mean SF_6 concentration at individual traverse points;
n = number of traverse points.

The dispersion factor data were calculated for each sampling distance and each duct configuration (see Table III). These data were plotted *vs.* sampling distance as shown in Figures 3-7. Straight lines were calculated by the least squares method. Theoretically, the sampling distance at which the straight line crosses the X-axis (D=0) should be a distance at which SF_6 should be uniformly dispersed. Consequently, this should be the minimum distance for locating the sampling probe; however, the dispersion factor, D, will not be zero (even if SF_6 is uniformly dispersed) because the standard deviation is affected by factors other than non-uniformity of SF_6 dispersion — such as sampling and analytical errors, fluctuation in SF_6 flow. Therefore, a cut-off value of D was introduced to establish the necessary minimum sampling distance.

To calculate the cut-off values, one-way analysis of variance was used to test (statistically) the homogeneity of the SF_6 dispersion at each sampling distance.[8] A significance level of 0.05 was used. The results are shown in Table IV along with the critical F-test values for rejection. The F-test values lower than the critical F-test values for rejection are

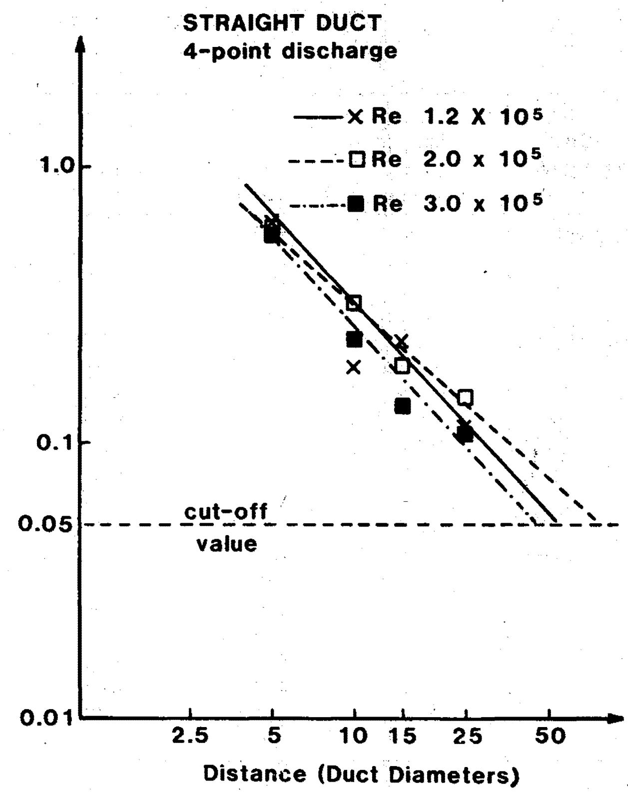

Figure 4 — Dispersion factor (D) *vs.* sampling distance.

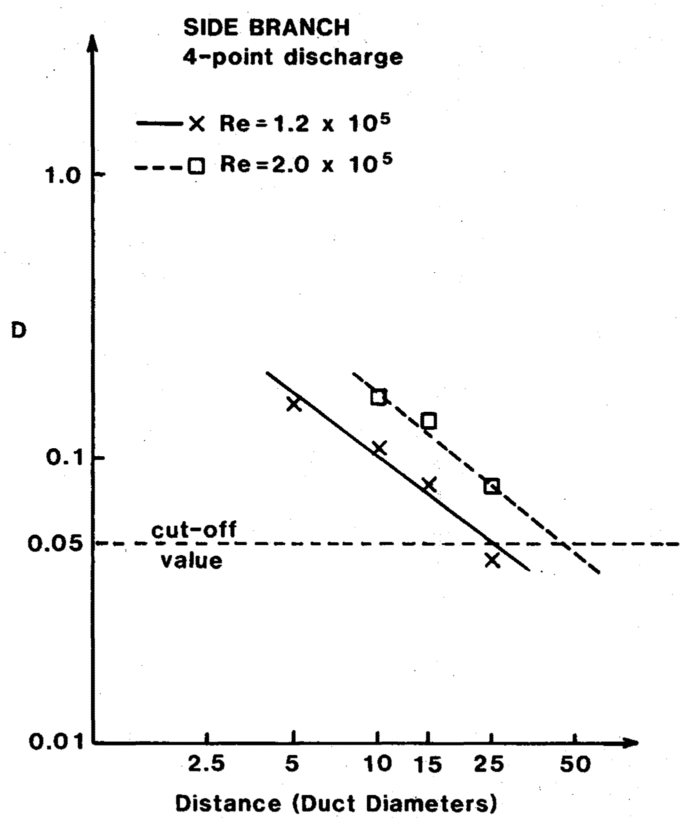

Figure 5 — Dispersion factor (D) *vs.* sampling distance.

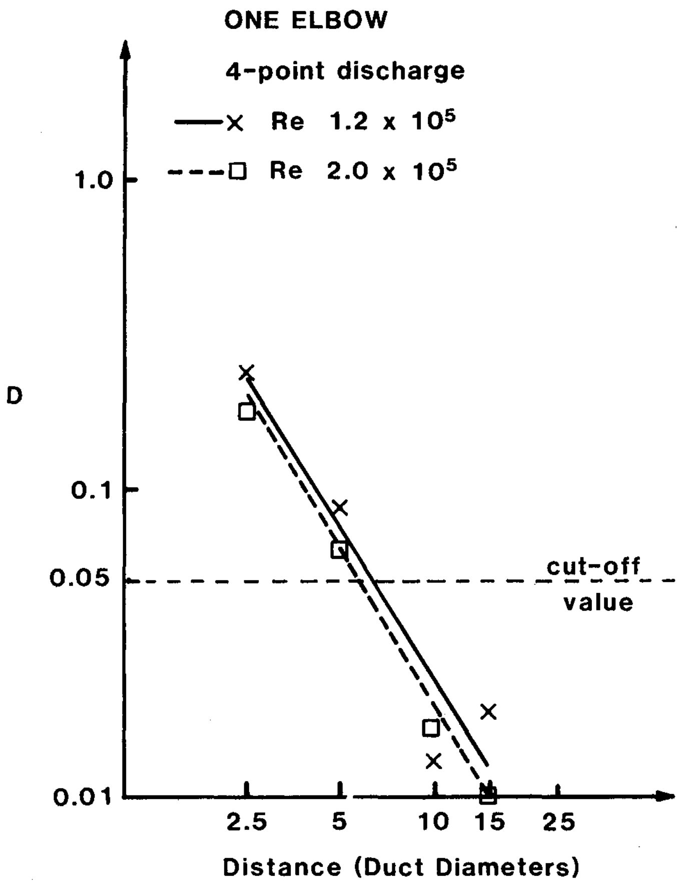

Figure 6 — Dispersion factor (D) *vs.* sampling distance.

underlined. By comparing the underlined data to the dispersion factors shown in Table III, it can be seen that the underlined F-test values are related to the dispersion factors equal or less than 0.05. Therefore, the dispersion factor value 0.05, which fulfills the statistical criteria for SF_6 dispersion uniformity, was determined as the cut-off point. Based on these cut-off points (see Figures 3-7), the minimum distances for sampling probe were estimated. At these distances or beyond, SF_6 is considered to be dispersed uniformly across the duct cross-section and sampling may be conducted at any depth in the duct. Sampling at shorter distances than minimum ones will result in increase of error caused by the SF_6 non-uniformity in the duct.

Discussion

For the straight duct (Figures 3-4), the minimum distance was approximately 50 duct diameters, whether SF_6 was discharged from the 1-point or 4-point source. This agreed with a theoretical study by Jordan[9] which showed that at least 50 duct diameters are required for a uniform gas dispersion in smooth-walled straight ducts in fully developed airflow. The straight duct-side branch combination (Figure 5) somewhat accelerated the SF_6 dispersion and reduced the minimum sampling distance to 25 and 40 duct diameters at Re = 120 000 and 200 000, respectively. The combination of the straight duct with one elbow significantly reduced the minimum distance to 7 duct diameters (Figure 6). The minimum distance of approximately 4 duct diameters was found for the combination of straight duct with two elbows (Figure 7).

As can be seen in Figures 4-7, the Re effect on the minimum sampling distance is small (straight duct, combination of straight duct with one elbow) or below the cut-off dispersion factor value (combination of straight duct with two elbows). Only at the straight duct-side branch combination, the dispersion factor data indicate a somewhat larger effect of the Re on the sampling distance; however, explanation of this would require additional research.

Although a fundamental theory is as yet lacking, the Re effect can be explained simply in terms of a description of mass transport using an empirical turbulent diffusivity D_t (order of magnitude larger than the molecular diffusivity). The meaning of the diffusivity, D_t, is that equilibration over a distance, a (the duct radius), is approached (exponentially) requiring a time, τ, proportional to a^2/D_t. Therefore, since a concentration inhomogeneity following injection is moving downstream at the air velocity, v, the distance, ζ, required for equilibration is given proportionally by

$$\zeta \propto va^2/D_t. \qquad \textbf{(2)}$$

Dividing by the duct diameter 2a and expressing the velocity v in terms of the Reynolds number, Re, and the air kinematic viscosity, η (0.13 cm^2/sec) gives

$$\zeta/(2a) \propto \eta \, Re/D_t. \qquad \textbf{(3)}$$

The turbulent diffusivity, D_t, at high Reynolds numbers is

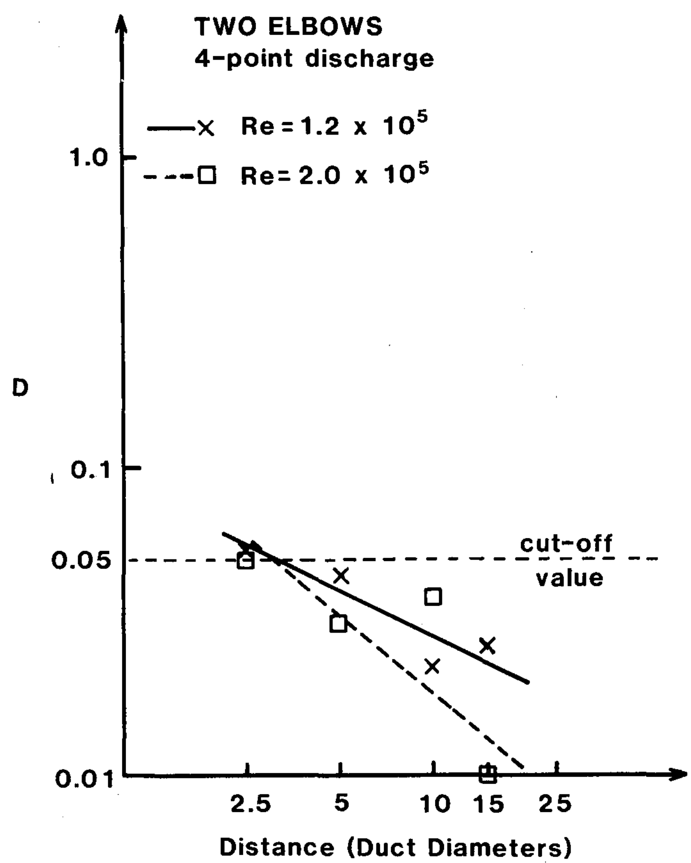

Figure 7 — Dispersion factor (D) *vs.* sampling distance.

a function of Re.[10] At the experimental Re or higher, the ratio Re/D_t approaches a constant equal to 4400 cm^2/sec (duct air at standard conditions). Therefore, the distance, $\zeta/(2a)$, measured in duct diameters simply may be considered as a constant.

The dimensionless proportionality constant implicit in Equation 3 depends on the duct geometry. With the assumption of cylindrical ducts, straightforward solution of the steady-state version of Fick's law of diffusion in the presence of convection gives

$$\zeta/(2a) = 0.017\ \eta\ Re/D_t. \tag{4}$$

The exponential approach in time following injection implies an exponential decrease in the relative standard deviation of the SF_6 concentration (dispersion factor), D, about its mean. In other words,

$$D \propto \exp(-z/\zeta), \tag{5}$$

where z = distance from injection point.

The proportionality constant implicit in Equation 5 depends on the initial concentration distribution at z = 0. Two important calculable cases are a 1-point source and a 4-point source of radius a (a very rough approximation to the 4-point discharge). Calculation gives

$$D_{1\text{-point}} = 2.5 \exp(-z/\zeta), \tag{6}$$

and

$$D_{4\text{-point}} = \exp(-z/\zeta). \tag{7}$$

The expressions of Equation 6 and 7 are plotted along with the relevant data in Figure 8. The semi-quantitative agreement between experiment and theory is consistent with what can be expected from such a crude description of turbulent mass transfer in terms of a turbulent diffusivity. The essential point is the universality of the distance (in terms of duct diameters) required for uniformity of SF_6 concentration across the duct area.

By summarizing the results, it can be seen that the minimum sampling distance is affected significantly by the duct configuration and not by Re. The duct wall surface may affect, to some degree, dispersion rate of SF_6; however, this effect was not investigated in this study.

Conclusions

A dispersion of SF_6 in the duct was studied under fully developed duct airflow at different duct configurations, duct air velocities and sampling distances from the SF_6 injection. An equation for SF_6 dispersion degree was established, and the dispersion factor values were calculated. With the use of the statistical tests, the dispersion factor value of 0.05 was determined as a cut-off point at which SF_6 is uniformly dispersed across the duct cross section. By plotting the dispersion factor values *vs.* the sampling distance, minimum distances at which the sampling probe should be located were determined for each duct configuration. These minimum distances are summarized as follows:

TABLE IV
F-Test Data

Duct Configuration	Sampling Distance (duct diameter)	Calculated Re = 1.2 × 10^5	Calculated Re = 2.0 × 10^5	Calculated Re = 3.0 × 10^5	Critical for Rejection	Remarks
Straight duct	5.0	8.37			≥1.84	1-point discharge
	10.0	6.92			≥1.84	
	15.0	11.31			≥1.84	
	25.0	2.91			≥1.84	
Straight duct	5.0	231.27	1112.48	189.12	≥1.95	4-point discharge
	10.0	36.30	36.16	88.99	≥1.95	
	15.0	25.56	28.48	60.76	≥1.95	
	25.0	10.75	51.15	34.76	≥1.95	
Side branch	5.0	7.20	--		≥1.95	
	10.0	7.71	14.29		≥1.95	
	15.0	4.30	20.37		≥1.95	
	25.0	1.08	8.37		≥1.95	
1 elbow	2.5	66.72	77.65		≥1.95	
	5.0	39.18	6.41		≥1.95	
	10.0	0.72	0.93		≥1.95	
	15.0	0.76	0.56		≥2.81	
2 elbows	2.5	4.53	2.41		≥1.95	
	5.0	1.72	0.87		≥1.95	
	10.0	1.13	1.10		≥1.95	
	15.0	0.98	0.15		≥3.03	

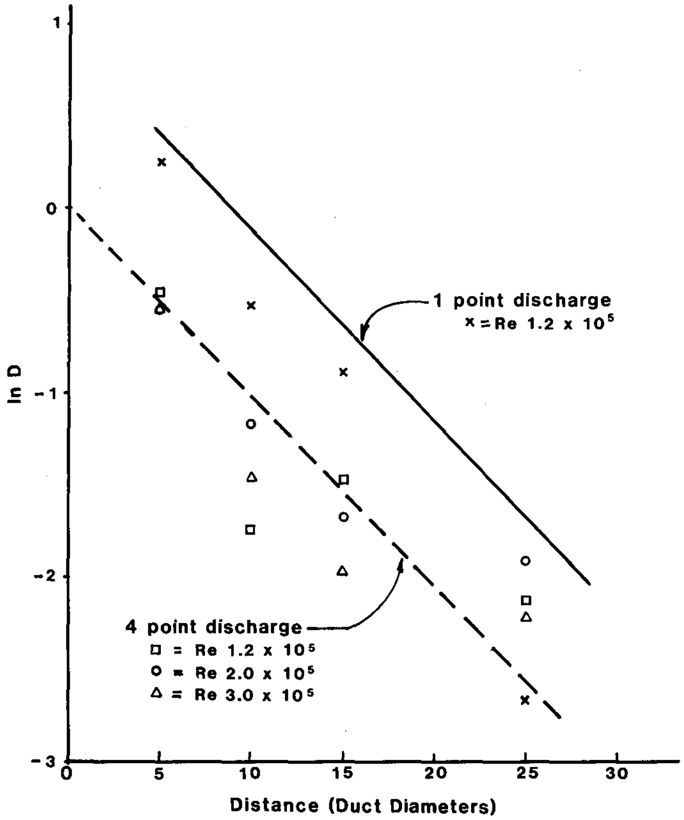

Figure 8 — Comparison of predicted and observed dispersion factors (D) *vs.* sampling distance.

Duct Configuration	Distance (in duct diameters)
straight duct	at least 50
straight duct-side branch combination	at least 25
straight duct-one elbow combination	7
straight duct-two elbows combination	4

Sampling at or beyond these distances minimizes the error caused by the non-homogenous dispersion of SF_6 in the duct and contributes to the accuracy of the tracer gas technique.

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