Comparison of three tracer gases for determining ventilation effectiveness and capture efficiency

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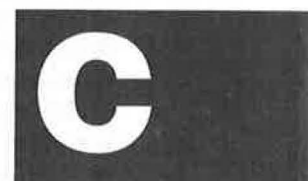
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Introduction

Many different chemical tracers and various measuring apparatuses are used for ventilation studies. A desirable tracer gas has the following characteristics (1): density and diffusion properties similar to those of air, nonexplosive, nontoxic, odorless, unreactive with the constituent of the air or test area, detectable quantitatively at low concentrations, and not produced in the test area. No tracer gas fulfills all of these requirements. The most common tracer gases are sulphur hexafluoride, nitrous oxide, perfluorocarbons and helium (2,3). The detection of the tracer gas concentration has usually been performed with infrared absorption or with electron capture gas chromatography. A portable mass spectrograph has been used to monitor the helium concentration.

Some authors have reported comparisons between different tracer gases. The comparisons have mainly been used with the concentration decay method usually at low air change rates. Grimsrud et al. (4) measured air change rates in the range of 0.45 to 1.6 air change per hour with five different tracer gases and found that SF_6 gave slightly different values than that of N_2O, CH_4 and He. Shaw (5) performed the tracer gas measurements in a sealed room at the air change rates ranging from 0.05 to 1 ach by using CH_4, CO, CO_2, N_2O and SF_6 as tracers. The agreement between the tracer gas measurements and the measured volumetric flow rates of the exhaust fan was good for all tracer gases but the scatter of the CO_2 and SF_6 data was much greater than that for other gases. Olander (6) made a comparison between the instruments used for measuring air change rates with nitrous oxide and sulphur hexafluoride. He observed a good agreement between the two tracer gases at air change rates ranging from 2.5 to 20 ach. In the applications mentioned above, the tracer gases have been fed into the inlet air or into the room with extra mixing fans giving rise to effective mixing of the tracer gas with air.

In the measurements aimed to determine the capture efficiency of a local exhaust hood, the effectiveness of the general ventilation in removing contaminants, or the dispersion routes of contaminants, the tracer gas is released in the contaminant generation area in order to simulate contaminant emission. A prerequisite for correct simulation is that the tracer gas discharge is passive with respect to the contaminant source, i.e. the tracer gas discharge does not affect the natural velocity field of contaminants, and the behaviour of the tracer gas is similar to that of the contaminants generated. In measurements like these there is a

risk that the tracer gas released does not mix sufficiently with the flow
being investigated. A basic assumption in industrial ventilation
engineering is that, from the standpoint of contaminant dispersion, the
bulk movement of the air and the turbulent diffusion are the dominant
mechanisms whereas density differences and molecular diffusion play only a
minor role (7). On the other hand, it has been reported that
stratification phenomena due to density differences may occur in some
cases, e.g. in unventilated rooms or with specific ventilation
arrangements (8).

The purpose of this study was to compare three tracer gases with
different densities and diffusion properties for determining the mean age
of air in the test room and the capture efficiency of a local exhaust
hood. Our approach was practical one, i.e. the tests were performed in
conditions which generally occur in industrial work rooms.

Sulphur hexafluoride (relative density 5.10) served as a heavy tracer
gas whereas helium (r.d. 0.17) represented an ultralight tracer. Nitrous
oxide (r.d. 1.53) was used as the third tracer gas. The concentrations of
SF_6 and N_2O were continuously monitored with a dual-channel infrared
analyzer, and the concentration of He was measured with a portable mass
spectrograph.

Methods

Experimental set-up

The experiments for general ventilation studies were performed in a
test room with a volume of 31 m^3 (Fig.1). The inlet air was introduced
into the room through the rectangular register near the ceiling. The air
was exhausted from the opposite wall near the floor. The ventilation flow
rate, about 600 m^3/h, was kept constant during each test. The stability
of the air flow rate was controlled by an orifice flow meter. Five mixing
fans were mounted in the test room to ensure complete mixing of the room
air.

The tracer gases were injected into the inlet air duct at a distance
of more than 40 duct diameters from the inlet air register. When the
tracer gases were injected within the room, the source was located at
point 1 or point 2. Emission point 1 was on the work bench located in the
center of the test room. Emission point 2 was 0,5 m above floor level,
0,8 m from the wall with the inlet air register.

The experimental design for testing the capture efficiency of the
local exhaust hood is shown in Fig.2. The rectangular flanged hood rested
on a flat surface. The tracer gas source was located on the flat surface
0,3m from the hood face. The capture velocity at the point of emission
ranged from 0,2 to 0,5 m/s. A fan was used to generate a controlled cross
draft perpendicularly to the hood axis. When the fan was in operation, it
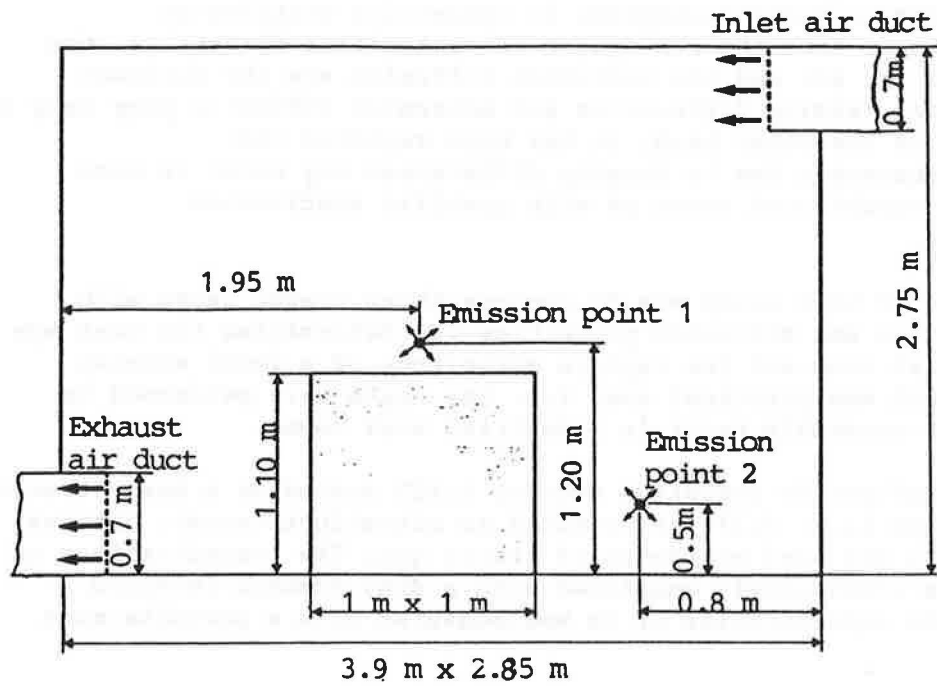produced the cross draft of 0,7 m/s at the point of injection.

Inlet air duct

0.7m

2.75 m

1.95 m

Emission point 1

Exhaust
air duct

0.7 m

1.10 m

1.20 m

Emission
point 2

0.5m

1 m x 1 m

0.8 m

3.9 m x 2.85 m

Fig. 1. The test room for the general ventilation studies.

0.17 m

0.50 m

0.9 m

1.30 m

1.15 m

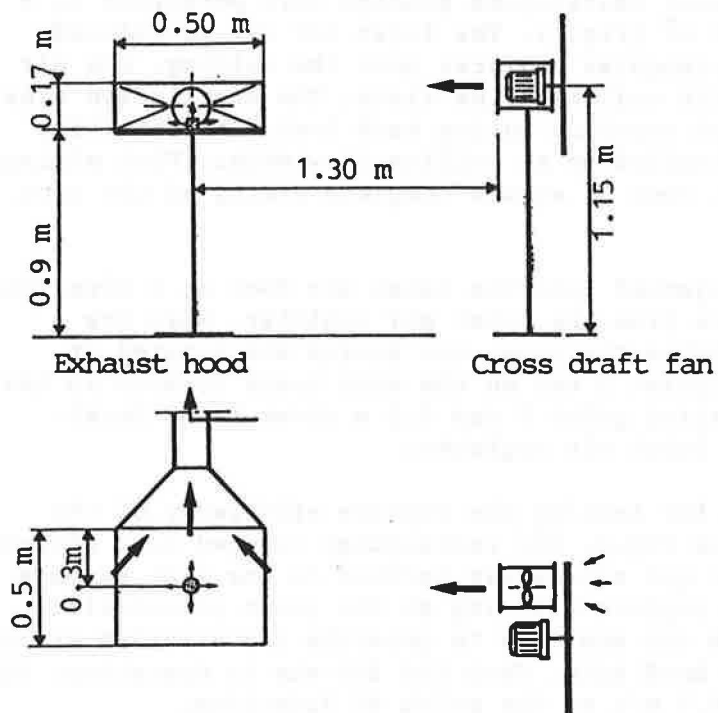Exhaust hood

Cross draft fan

0.5 m

0.3m

Fig. 2. The local exhaust system.

The basic construction of the injection device consisted of a cylinder and a diffuser (Fig.3). Three tracer gases were fed into the cylinder through the separate inlets at the bottom of the cylinder. There was also a fourth inlet allowing pumping of extra air. Three perforated plates were installed in the cylinder to accelerate mixing of the tracer gases. The tracer gases were discharged through the sintered diffuser at an emission velocity of about 0,3 m/s. This basic construction was used in the tests for the general ventilation studies and partly in the capture efficiency measurements of the local exhaust hood. In addition to this basic version of the injection device, two modifications were used in the capture efficiency studies. In the first modification, the sintered diffuser was replaced by the ring producing a jet of air upwards at the emission velocity of 2,5 m/s. In the second one, a miniature mixing fan was installed in the cylinder to enhance mixing of the tracer gases.
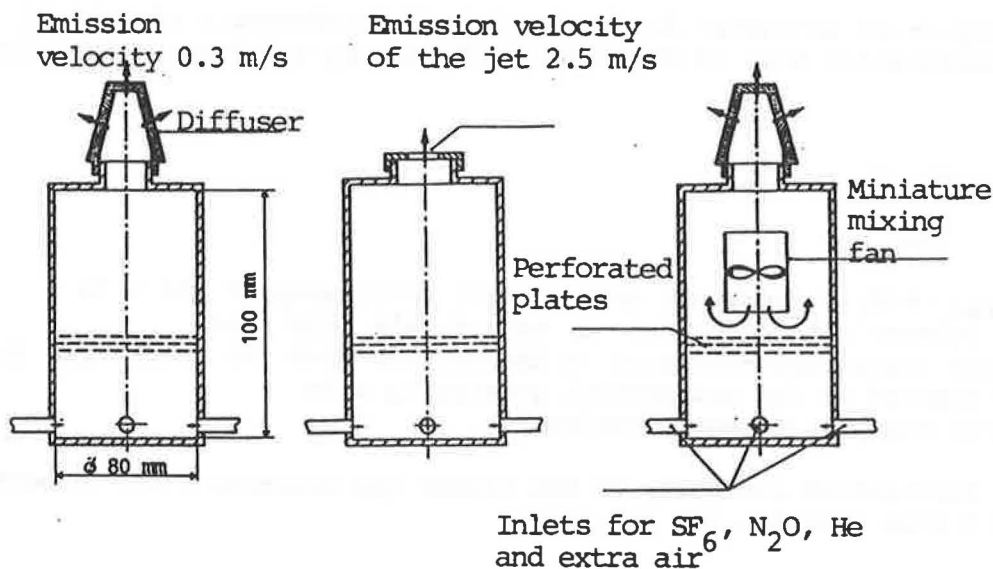
Emission velocity 0.3 m/s

Diffuser

Emission velocity of the jet 2.5 m/s

Perforated plates

Miniature mixing fan

100 mm

ø 80 mm

Inlets for SF_6, N_2O, He and extra air

Fig.3. The tracer gas injection devices.

Measurement Parameters

A key parameter for expressing of the ventilation effectiveness is the mean residence time of air or contaminant molecules. The parameter can be experimentally obtained for instance from step-up or step-down tests. Equation 1 gives the mean residence time A_θ, also called the mean exit age, when the step-up procedure is used (3):

$$(1) \quad A_e = \int_0^\infty (1 - \frac{C_e(t)}{C_e(\infty)}) \, dt$$

where = $C_e(t)$ = the concentration of tracer gas in the exhaust
$C_e(\infty)$ = the steady state concentration

For the step-down procedure the following equation is valid;

$$(2) \quad A_e = \int_0^\infty \frac{C_e(t)}{C_e(0)} dt$$

where, $C_e(0)$ = the concentration of tracer gas in the exhaust air when the release was stopped. In the case of fluctuating concentrations the steady state concentrations $C(\infty)$ or $C(0)$ were determined by taking average concentration during a time interval of about 10 minutes.

An important parameter for evaluating the performance of a local exhaust ventilation hood is the capture efficiency η, given by equation 3

$$(3) \quad \eta = \frac{C_x - C_b}{C_{ref} - C_b} \times 100 \text{ %}$$

where, $C_{ref} = m/Q_e$ corresponds to a capture efficiency of 100 % (m constant release rate of tracer, Q_e exhaust air flow rate)
C_x = the tracer concentration in the exhaust when the tracer gas is released on the contaminant generation site
C_b = the background concentration

The fluctuation intensity of the tracer gas concentration, I, was calculated from equation (4)

$$(4) \quad I = \delta/M \times 100 \text{ %}$$

where δ=standard deviation of the concentration
M=arithmetic mean

Injection Strategy of the Tracer Gases

Three tracer gases, i.e. sulphur hexafluoride, nitrous oxide and helium were used in the present study. Table 1 shows the pertinent characteristics of these tracer gases (9).

Table 1. Characteristics of the tracer gases used

Gas	Density compared air at NPT	Diffusion coefficient in air m^2/sec	Concentration range ppm	Measuring apparatus
Sulphur hexafluoride	5.10	8.2×10^{-6}	0-200	IR-analyzer, Binos 4b. Leybold-Heraeus
Nitrous oxide	1.53	13.2×10^{-6}	0-200	"
Helium	0.17	59.7×10^{-6}	0-200	Mass spectrograph Ultratest UL 100 Leybold-Heraeus
Air	–	17.5×10^{-6}	–	

It is worth observing that the turbulent diffusion coefficient of the air under the actual test conditions was about $15 \cdot 10^{-4}$ m^2/s, i.e. 100-fold the molecular diffusion coefficients given in Table 1. The tracer gases were injected at the constant flow rates into the injection device constructed for this study. Because of the flow meters available and the measurement ranges of tracer concentrations, the release flow rates of the gases were 0.7 l/min for SF_6, 1.4 l/min for N_2O and 1.0 l/min for He in the tests for general ventilation studies. The relative density of the gas mixture was then 1.9 presupposing completely homogeneous mixing. In the case of the capture efficiency measurements, the release flow rates were 1,3 l/min for SF_6, 1,0 l/min for N_2O and 2,0 l/min for He, resulting in the same relative density of the mixture as in the general ventilation tests.

The stability of the He flow rate was controlled by a mass flow meter (Bronkhurst High-Tech, F201) whereas the flow rates of SF_6 and N_2O were controlled by conventional float rotameters. The mass flow meter regulated the He flow with a stability better than one % whereas the estimated stability of the rotameters was ±5 %. The duration of the release period in the general ventilation varied between 20 and 36 min. The measurement of the concentrations was continued for 40 to 70 min after the release was stopped.

Measurement of the Concentrations

The sample air was continuously pumped from the exhaust air duct at a flow rate of 2.0 l/min. The sampling point was located 40 duct diameters from the exhaust terminals. The concentration of each tracer gas was simultaneously detected. The concentrations of SF_6 and N_2O were measured by a non-dispersive, dual-cell IR-analyzer (Binos 4b, Leybold-Heraeus) with a time constant of 3 sec. The output voltages of the IR-analyzer units were recorded every 15 sec by a data acquisition system controlled by a Hewlett Packard 71B hand-held computer. The concentration of He was measured by a portable mass spectrograph (Ultratest UL 100, Leybold-Heraeus) with a time constant less than one sec. The concentration signal of He was recorded by a PC (Compaq Portable II) controlled data

acquisition system once per sec and in addition by the HP71 controlled system once every 15 sec. The concentration curves were displayed in real time on the screens of the computers during the tests. At the end of the measurement the results were stored and the concentration curves were plotted. Each test was repeated at least three times. Each test was repeated at least three times.

The analyzing cells of the IR instrument were calibrated with the certified mixture of "span" gases of 200 ppm. The mass spectrometer was calibrated with the certified gas of 50 or 100 ppm ($\pm$ 1%). In addition, the zero-levels of all three instruments were checked before and after each test by using pure room air.

Results

General ventilation

Typical concentration curves of three tracer gases used are shown in Fig. 4. Notable concentration fluctuations occurred when the tracer gases were injected into the test room without artificial mixing.
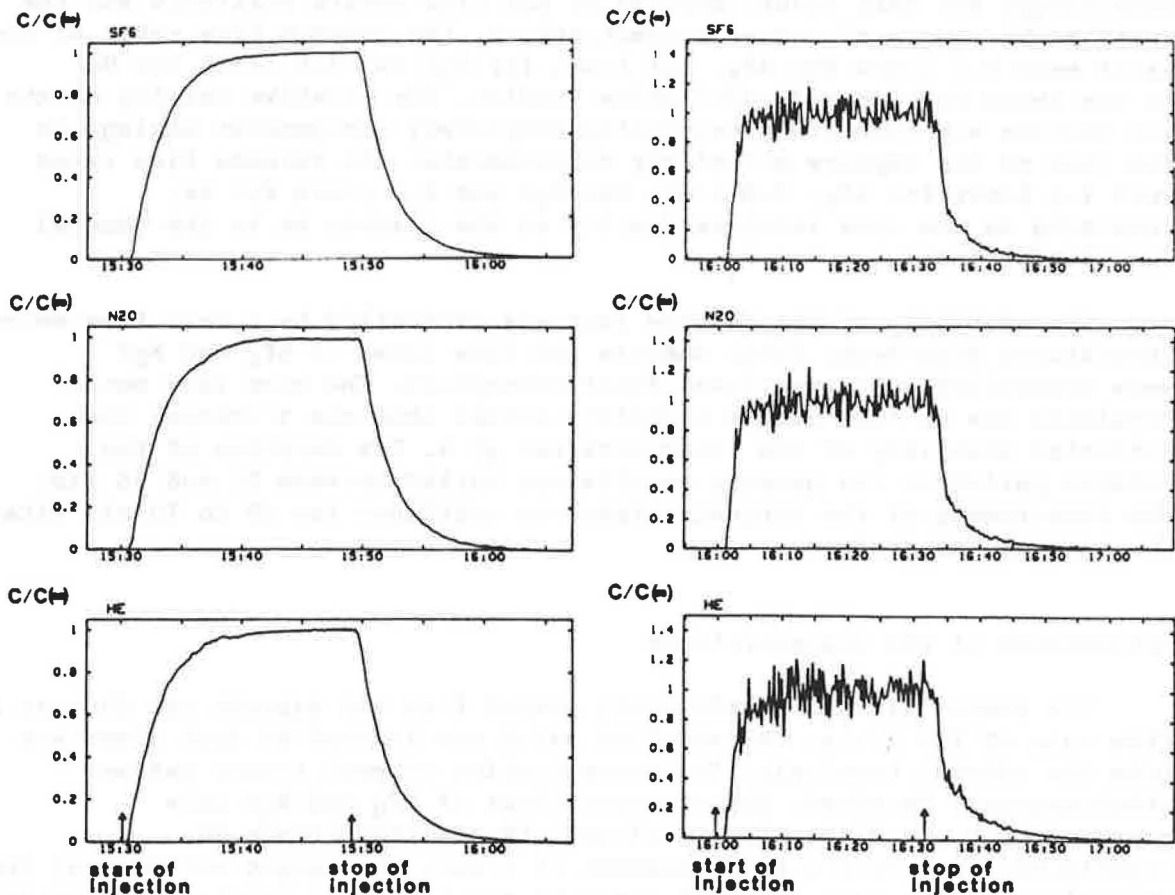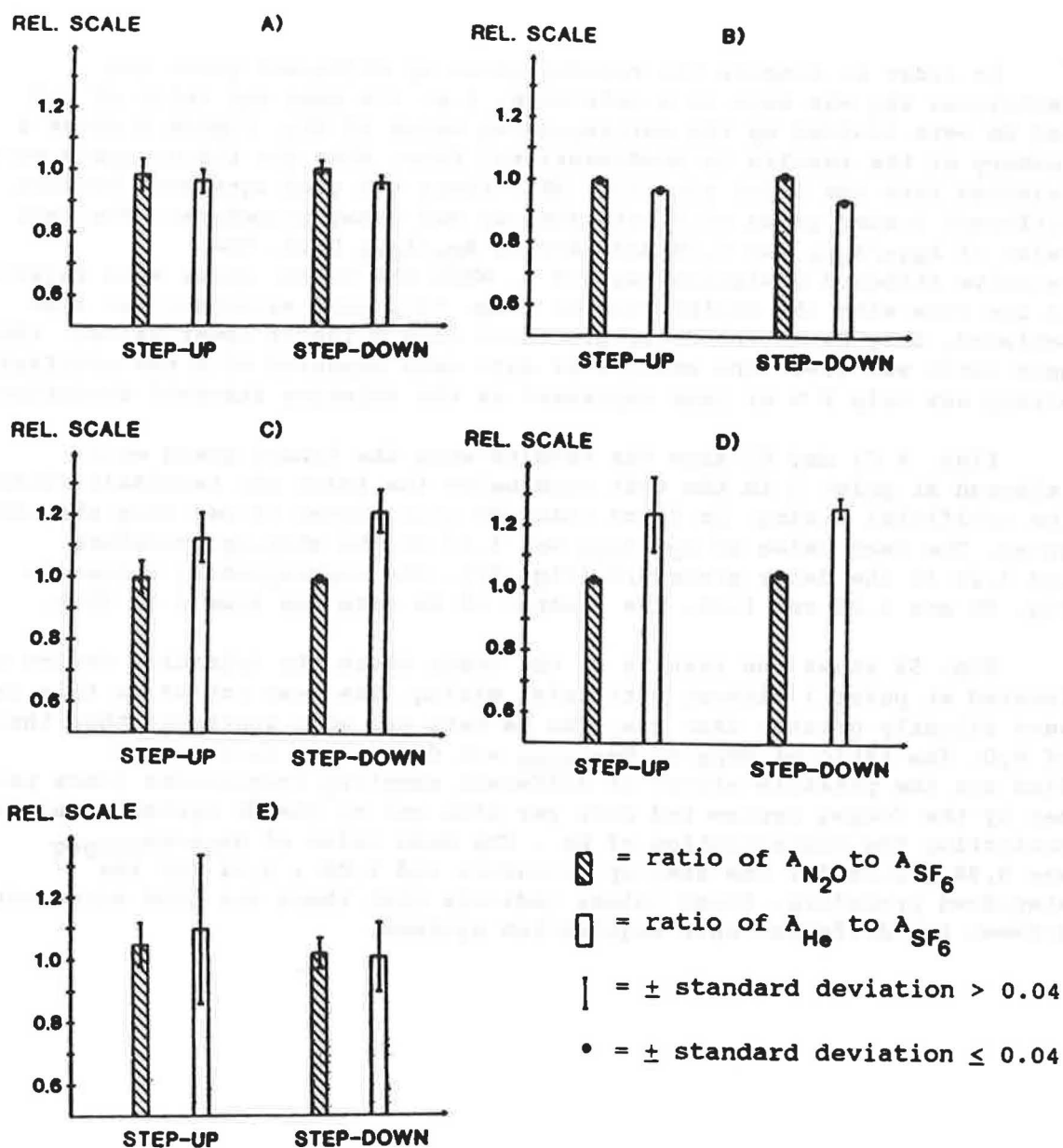

Fig 4. Typical concentration curves of three tracer gases obtained from general ventilation tests.

In order to compare the results given by different gases and techniques SF_6 was kept as a reference, i.e. the mean age value of N_2O and He were divided by the corresponding value of SF_6. Figure 5 gives a summary of the results in nondimensional form. When the tracer gases were injected into the inlet air (Fig. 5A), there was good agreement between different tracer gases with both step-up and decay procedures. The mean value of A_{N2O}/A_{SF6} was 0.98 and that of A_{He}/A_{SF6} 0.96. The relative standard deviation was 4-5 %. When the tracer gases were injected in the room with the mixing fans on (Fig. 5B), good agreement was also achieved. Only He at the decay procedure gave slightly lower values, the mean ratio was 0.94. The scatter of data sets measured with the artificial mixing was only 2 % or less expressed as the relative standard deviation.

Figs. 5 C) and D) show the results when the tracer gases were released at point 2 in the test room below the inlet air terminals without the artificial mixing. In these cases He gave higher values than the other gases. The mean value of A_{He}/A_{SF6} was 1.13 at the step-up procedure and 1.22 at the decay procedure (Fig. 5C). The corresponding values in Fig. 5D are 1.24 and 1.26. The scatter of He data was from 3 to 10 %.

Fig. 5E shows the results of the tests where the injection device was located at point 1 without artificial mixing. The mean ratios in this case were slightly greater than one. The He data was more scattered than that of N_2O. The ratio of He_{HP} to He_{Compaq} was determined in order to find out the possible effect of different sampling frequencies (once per sec by the Compaq system and once per 15th sec by the HP system) used in monitoring the concentration of He . The mean value of He_{HP}/He_{Compaq} was $0,98 \pm 0,05$ for the step-up procedure and $1,00 \pm 0,02$ for the step-down procedure. These values indicate that there was good agreement between two different data acquisition systems.

Fig. 5. Comparison of three tracer gases in terms of the mean exit ages. A_{SF6} has been kept as the reference.

Capture efficiency of the local exhaust hood

Fig. 6. presents typical curves for determining the capture efficiency.
Fig. 7. gives a summary of the capture efficiency measurements as a function
of the capture velocity. In addition to these measurements given in Fig. 7,
a series of tests was conducted where extra air was pumped into the injection
device without the perturbing air flow of the cross-draft fan. A capture
efficiency of more than 99 % was achieved for all tracer gases even at the
lowest capture velocity.

For comparison of the fluctuation intensities of different tracer gases,
the scattergrams and the best linear fits of each pair of gases are depicted
in Fig. 8. There was no notable difference in the fluctuation intensity of the
He concentration between the sampling frequency of once per sec and once per
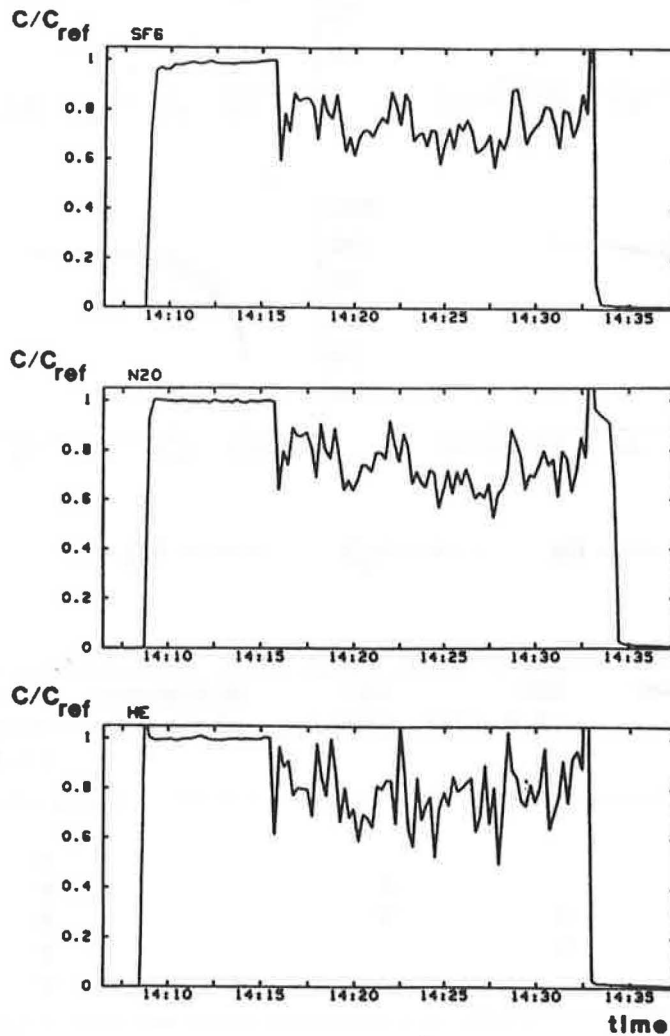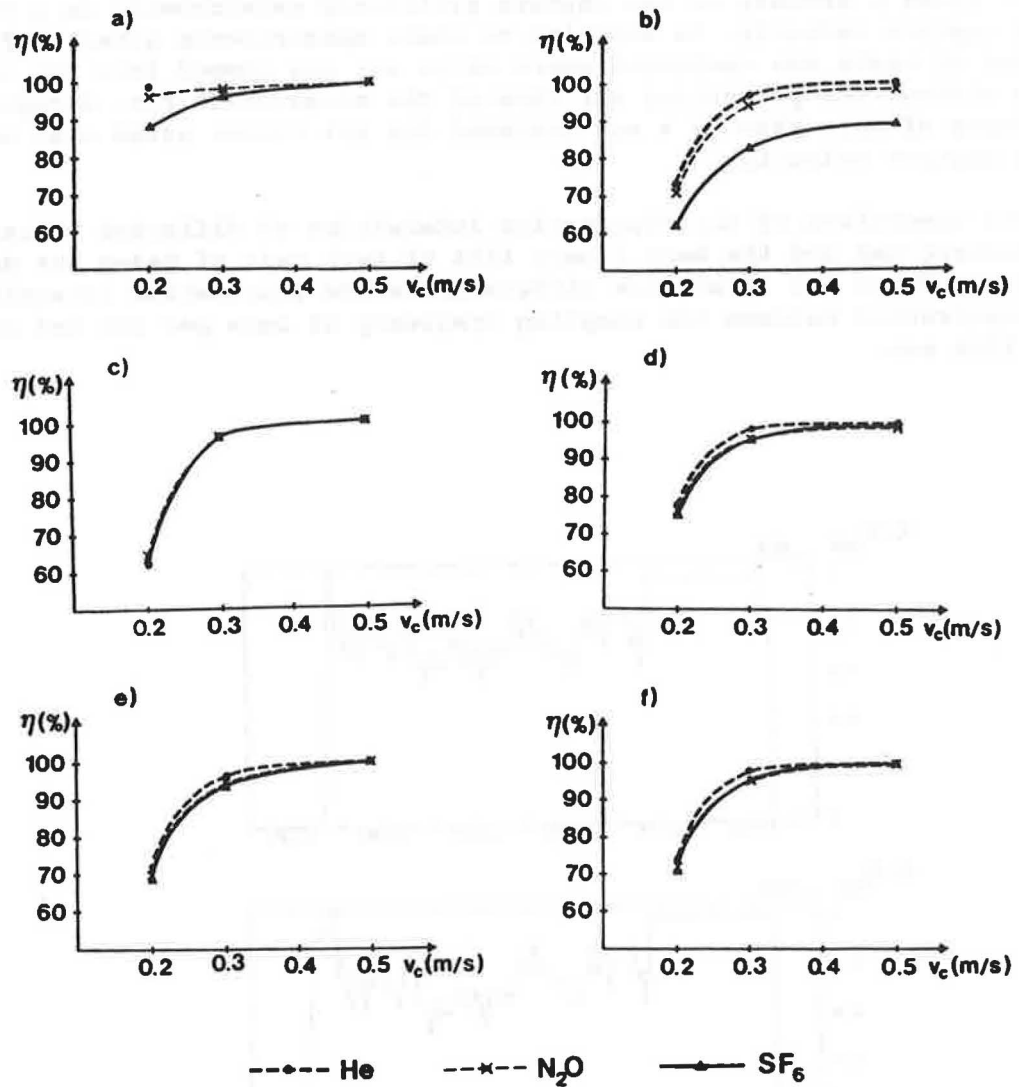every 15th sec.

Fig.6. Typical concentration curves for determining the capture effeciency.

a)

η(%)

100
90
80
70
60

0.2 0.3 0.4 0.5 v$_c$(m/s)

b)

η(%)

100
90
80
70
60

0.2 0.3 0.4 0.5 v$_c$(m/s)

c)

η(%)

100
90
80
70
60

0.2 0.3 0.4 0.5 v$_c$(m/s)

d)

η(%)

100
90
80
70
60

0.2 0.3 0.4 0.5 v$_c$(m/s)

e)

η(%)

100
90
80
70
60

0.2 0.3 0.4 0.5 v$_c$(m/s)

f)

η(%)

100
90
80
70
60

0.2 0.3 0.4 0.5 v$_c$(m/s)

- - ● - - He   - - ✕ - - N$_2$O   ——▲—— SF$_6$

	Diffuser	Jet (2.5 m/s)	Air pumping	Miniature mixing fan	Cross draft (0.7 m/s)
a	x				
b	x				x
c	x		x		x
d		x	x		x
e		x			x
f	x			x	x

Fig. 7. The capture efficiency, η, vs. the capture velocity, v$_c$, of the local exhaust hood with different modifications of the injection device.
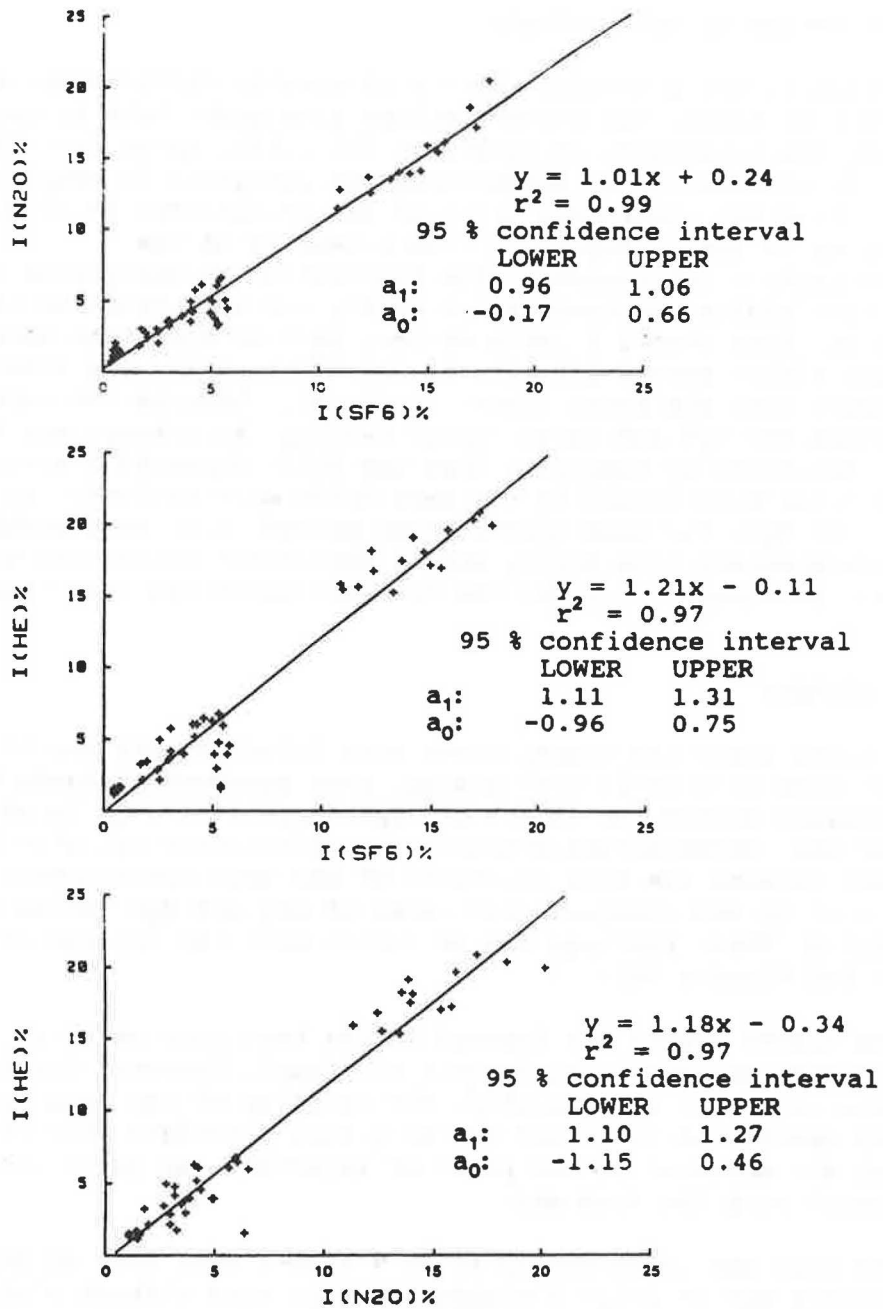
Fig. 8. The fluctuation intensity, I, during the measurement of the capture efficiency of the exhaust hood.

Discussion

Errors in concentration measurements

In addition to the potential effects of density differences, errors in the measurement of tracer gas concentrations also contribute to uncertainties in determining the parameters in equations (1)...(3). Apart from the zero-drift, the uncertainty in determining the integrals in equations (1) and (2) resulting from the instrument error of the IR-analyzer is ± 3 %. The instrument error is due to departure from linearity of the voltage-concentration relationship, the fluctuation in analytical signal, as well as the sensitivity and temperature drift. The zero-drift of the SF_6-analyzer was less than 0.5 ppm/h whereas that of N_2O might amount to 1.5 ppm/h. The higher zero-drift rate of the N_2O-analyzer was likely due to the interference with the water vapour in the air, because the infrared absorption bands for N_2O and water vapour overlap. An attempt was made to correct the zero-drift by supposing that the drift depended linearly upon time. The uncertainties caused by the zero-drift were estimated to be ± 3 % for SF_6 and ± 5 % for N_2O. The mass spectrograph proved to be very stable in short term measurements like these, and no zero-drift correction was needed. The estimated instrument error for the He measurement was less than ± 3 %.

General ventilation

In the cases where the tracer gases were injected into the inlet air or into the test room with artificial mixing, good agreement between different gases was attained within the limits of experimental errors. In addition to the errors in the concentration measurement, differences can also be caused by the difference between the time constants of the mass spectrometer and the IR analyzer as well as non-constant flow rates of SF_6 and N_2O during the injection period. These findings are in accord with the reports of Grimsrud (4) Shaw (5) and Olander (6).

When the tracer source was located in the test room at point 1 without artificial mixing, no notable difference was found. However, the data of the repeated tests scattered considerably. The equality of the mean ratios was statistically tested and justified by the t-test procedure. The results indicate that air movement at the point of injection was great enough to mix the tracer gases with the room air.

The mean exit age of He was 13 to 26 % higher than that of SF_6, when the tracer source was at point 2 within the test room without mixing fans. This bias is greater than the experimental error. No significant difference between the SF_6 and N_2O data was observed. The difference between the two gases with extreme density and diffusion characteristics was likely due to the stagnant region at the point of tracer release. The extra air pumping into the injection device didn't enhance mixing enough.

Capture efficiency

The results in Fig 7a and b show that SF_6, the heaviest tracer gas used, gave 10 to 15 % lower values for the capture efficiency than the other

gases, when the basic construction of the injection device was used. At cross draft velocities of 0.1 to 0.2 m/s, naturally found in the test space, the difference of about 10 % between SF_6 and the other gases was observed only at the lowest capture velocity of 0.2 m/s. When the cross draft velocity was 0.7 m/s, the bias between SF_6 and the other gases existed also at the higher capture velocities. However, this difference disappeared by accelerating tracer gas mixing by pumping extra air into the tracer source or by modifying the injection device, (increase of the emission velocity up to 2,5 m/s) or by using the miniature mixing fan in the cylinder.

The results in Fig. 8 indicate that the fluctuation intensity of He was slightly higher than that of SF_6 and N_2O. This means that He, as a light gas, has a tendency to mix more readily with air than the heavier gases. Another explanation for higher fluctuation is that the mass spectrometer had a shorter reponse time than that of the IR analyzer.

Conclusions

The results of this study show that differences between various tracer gases may occur if the tracer gas is incompletely mixed with air. However, the differences observed were only slightly greater than the experimental errors found in the laboratory measurements. In contrast to the well controlled laboratory conditions, tracer gas measurements in industrial work rooms are generally performed under circumstances, in which experimental errors might be notably greater than those in this study. Other factors, therefore, play more important role than differences in density. In field measurements, however, particular care has to be laid on the effective mixing between the pure tracer gas and the extra dilution air flow to avoid stratification. Another alternative is to use highly diluted tracer gas mixtures. When considering the results of this study, one should bear in mind that air contaminants with different densities and diffusion properties are emitted from various industrial sources. There are light contaminants such as ammonia (r.d. 0.7) whereas many organic solvents, widely used in industry, are heavier than air (r.d. from 3.0 to 5.0).

Acknowledgements

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SUMMARY

Sulphur hexafluoride, nitrous oxide and helium were compared to determine the mean age of air in a test room and the capture efficiency of a local exhaust hood. The mixtures of tracer gases were fed into the inlet air and two sites in the test room with and without mixing of room air. We determined the capture efficiency by releasing the tracer gases through the cylindrical injection device in front of the exhaust hood at different capture velocities and under various cross draft conditions.The results of the measurements in the test room showed good agreement between the different tracer gases exept in the stagnant zone. The first capture efficiency measurements indicated that SF6, the heavest gas, gave smaller values obviously due to incomplete mixing of tracer gases. However, the difference disappeared by accelerating tracer gas mixing by pumping extra air or by modifying the injection device.