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Application of Tracer Gas Techniques to Ventilation and Indoor Air Quality Investigations

Key Words

Ventilation investigations
Odours
Indoor air quality
Ventilation efficiency
Tracer gases

Abstract

This paper reviews a selected number of tracer gas techniques which are suitable for use in ventilation studies and indoor air quality investigations in multi-storey office and residential buildings. Emphasis is placed on those techniques which have been successfully used by IRC researchers for such applications. Examples of using these techniques in field measurements are discussed.

Introduction

ASHRAE Standard 62-1989 'Ventilation for Acceptable Indoor Air Quality' [1] states that 'acceptable indoor air quality is achieved by providing ventilation air of specified quality and quantity to the space'. For most buildings, the quality and quantity of ventilation air can be determined by measuring the minimum ventilation rate, air distribution patterns, contaminant flow patterns, and re-entrainment of exhaust air. Tracer gas techniques using a single tracer gas are used for such measurements.

For buildings with complex floor plans, some areas may be overventilated and others inadequately ventilated, even though the total ventilation (outdoor air supply) rate is adequate. To ensure that every area (or room) receives the required amount of ventilation air, it may be necessary to measure the outdoor air supply rate to a particular room or zone of a building. Multiple tracer gas techniques may be used for such measurements.

Single Tracer Gas Techniques

Minimum Ventilation Rate

Ventilation air comes from two sources – outdoor air supplied directly by HVAC systems and air infiltration through cracks and unintentional openings in the building envelope [2, 3]. As air infiltration is weather dependent, the minimum ventilation rate occurs when the weather is warm, calm, and the outdoor air dampers are set at their minimum positions. A building's air change rate measured under these conditions is equal to its minimum ventilation rate.

As an example, tracer gas tests were conducted to measure the minimum ventilation rate of a fully air-conditioned 8-storey office/library building in which the first 4 floors contain offices and the remaining 4 house library stacks. The building has a central core area housing passenger elevators, stairwells, washrooms, service shafts, study carrels, and small sitting areas. Except for the 2nd and 3rd floors, the floor space is fairly open, with very few individual offices. The building has 9 air-conditioning systems identified as systems 1–9 (fig. 1).

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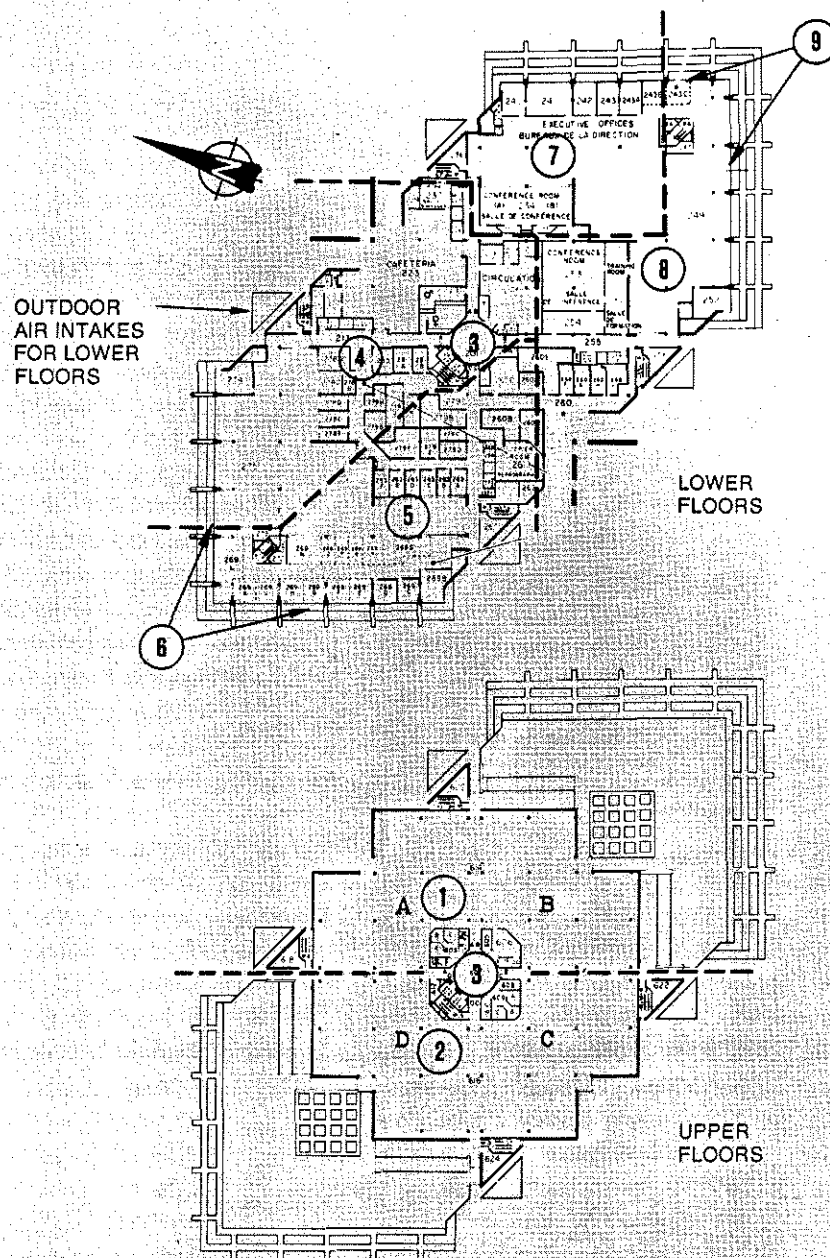


Fig. 1. Typical floor plans showing the HVAC systems.

To obtain the minimum ventilation rate, the measurements were conducted on calm days with the outdoor air temperatures near 20°C and the outdoor air dampers at their minimum-opening positions. A small amount of tracer gas, SF₆, was injected into every floor through the supply air ducts of systems 1, 2, 6 and 9. The total amount of tracer gas required was calculated from the equation:

$$m = V \cdot C_i$$

where m = amount of tracer gas, V = building volume, C_i = maximum concentration (depending upon analyzer sensitivity).

Based on a building volume of 80,000 m³ and a maximum concentration of 50 ppb, the total quantity of pure SF₆ required was:

$$\begin{aligned} m &= 80,000 \text{ m}^3 \cdot 1,000 \text{ l/m}^3 \cdot 50 \text{ parts SF}_6 / 10^9 \text{ parts air} \\ &= 8 \times 10^7 \text{ litres} \cdot 50 \times 10^{-9} \\ &= 4 \text{ litres pure SF}_6. \end{aligned}$$

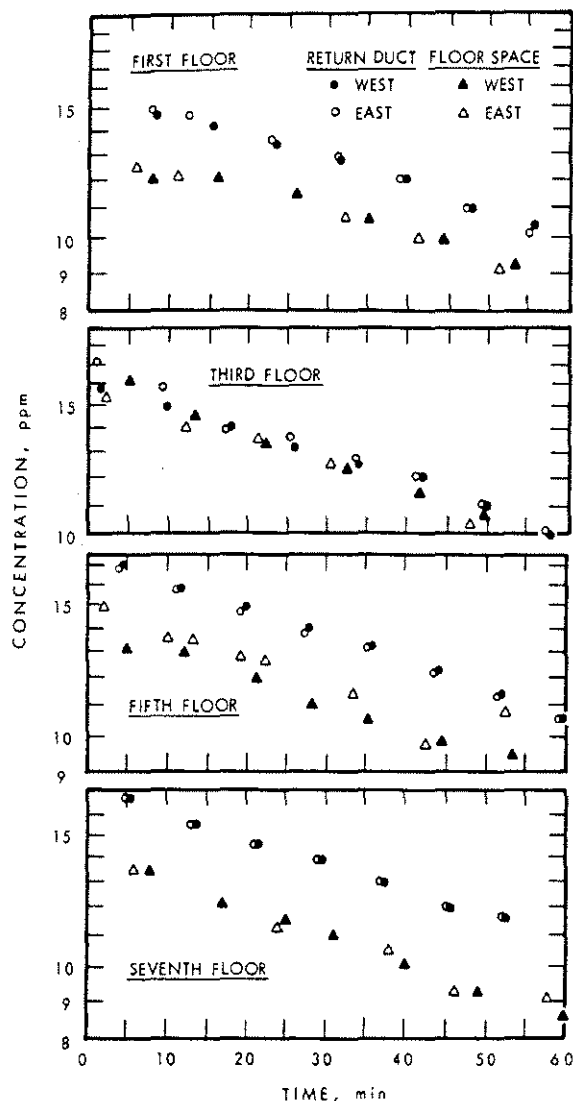


Fig. 2. Air change rate measurements, SF_6 concentrations versus time for various sampling locations.

After about 1 h (for mixing), samples were taken consecutively from each floor at the return ducts for another hour, using an automated sampling system. The samples were pumped continuously, one after another, to an electron capture gas chromatograph for analysis.

As adequate mixing of the tracer gas with the indoor air is important for such measurements, additional samples were collected manually at 10-min intervals from two locations on each floor to evaluate mixing. These samples were collected as follows. Just prior to the sampling time,

a 60-ml syringe was purged twice with air at the test location. At the designated time, 50 ml of air was collected in the syringe and injected into a 20-ml evacuated glass test tube with a rubber septum-stopper. This meant that the sample was stored under pressure, which was relied upon later to drive the sample into the gas chromatograph for analysis.

The air change rate was obtained by plotting the logarithm of the measured concentrations at each sampling location against time in hours. The data were then fitted to a straight line, and the slope of the line was the air change rate expressed in air changes per hour (ach). Figure 2 shows the measured SF_6 concentrations as a function of time for various sampling locations. It indicates that the air change rates from various sampling locations were similar. Concentrations in the occupied areas were also about the same, as were the concentrations in the return ducts. However, the concentration of the tracer gas was lower in the floor space than in the return ducts for most floors, suggesting that the concentrations in the floor space were higher near the return ducts than near the sampling locations. The average value of these air change rates was used as the mean air change rate (i.e., the minimum ventilation rate) of the building.

For buildings with adequate mixing, samples from the return ducts on each floor are drawn continuously through individual plastic tubes and mixed in a small manifold. A valve should be installed in each sampling tube to set and maintain identical flow rates from each location. The average air change rate can be determined directly from the samples drawn from the manifold.

Air Distribution

For assessing air distribution within the above building, a small amount of SF_6 was injected into the main supply duct of HVAC system 9 (or the main supply duct of another system) to create a point source. The amount of tracer gas injected was similar to that used for air change measurements. Immediately following injection, tracer gas sampling began and continued at 10-min intervals at the main return ducts on each floor, at eight locations on the 1st and 2nd floors, and at four locations on each of the 3rd–6th floors. Both the automated and manual sampling systems described above were used. The tracer gas concentrations of each sampling location were then plotted against time. Figure 3 shows a typical example of such a plot, in which the concentrations at all sampling locations reached a single level in approximately 80 min [2, 3]. This time can be used to assess the performance of the air distribution systems.

In the absence of a formal guideline or standard and experimental data from similar buildings, a less rigorous criterion was used to assess the air distribution of this building. As indicated in figure 3, tracer gas levels throughout the particular HVAC system zone were nearly equal within 30 min, which is less than the 60 min typically allowed for achieving adequate mixing when conducting air change rate measurements in buildings with the tracer gas decay method. This suggests that the air distribution system of this building performed as well as those in other buildings where tracer gas decay tests have been conducted.

Re-Entrainment of Exhaust Air

To determine whether exhaust air re-enters this building, a small amount of SF_6 was injected into an exhaust system, and samples were then taken at the outdoor air intake of each HVAC system using the syringe/test-tube technique. All exhaust systems of the building were checked, and the measured tracer gas concentrations were near 0, indicating that minimal re-entry of exhaust air had occurred [2, 3].

Air Change Efficiency and Ventilation Efficiency

Recently, air change efficiency and ventilation efficiency have been used to assess the performance of a ventilation system. The air change efficiency is a measure of how quickly the air in a space is replaced. European researchers [4, 5] define the air change efficiency as the ratio between the nominal time constant and the air exchange time for the room (the air exchange time for all the air in the room is equal to twice the room mean age of air). The ventilation efficiency is defined as the ratio between the steady-state concentration of contamination at the exhaust duct and the steady-state mean concentration of the room [4, 6]. Both air change efficiency and ventilation efficiency are surrounded by a confusing range of definitions: individual researchers have not always been consistent with terminology, and different authors have occasionally used different expressions to represent the same parameters [7]. Thus, further work is needed before these efficiency measures can be used in routine ventilation and indoor air quality investigations.

Contaminant Flow Patterns

Odours are a common problem in high-rise apartments. As an example, tracer gas decay tests were conducted to determine how a contaminant dispersed from the ground floor garbage room to other areas within a 5-storey apartment building [8]. This building has a base-

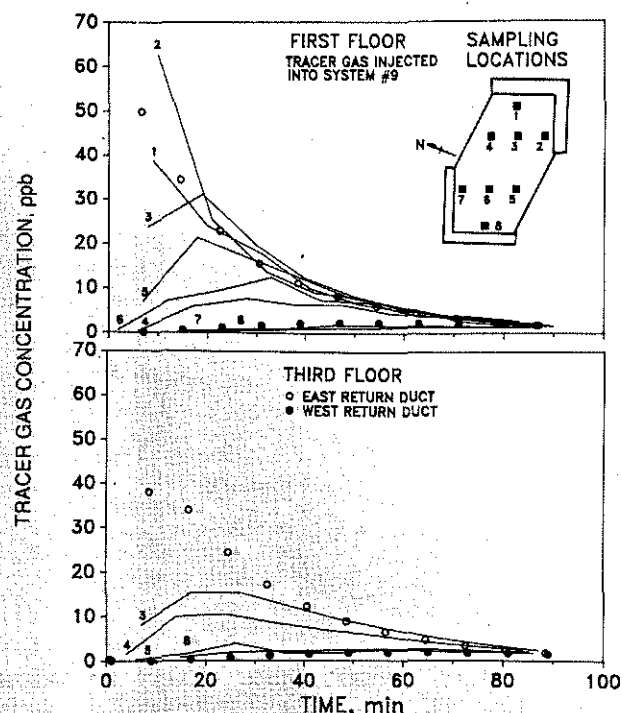


Fig. 3. Air distribution patterns with the tracer gas injected into supply air ducts of system No. 9.

ment, a ground floor and 4 typical storeys. Each typical storey has 12 apartment units; 6 on each side of a central corridor (fig. 4). The elevator shaft and enclosed garbage chute are located at the centre of the building. There are two stairways, one in each end of the building. The building has a central heating and ventilating system which supplies air to the corridor of each storey through two supply air registers. There are no return air grilles in the corridor. In each apartment unit, two exhaust fans, which discharge room air from the kitchen and bathroom, serve to draw the ventilation air into the apartment unit through the corridor.

To determine the odour migration patterns, a small amount of tracer gas SF_6 was injected into the garbage room. Immediately after the injection, the tracer gas concentrations at each storey were measured at 10-min intervals. The sampling locations were the centre of the corridor, the south stairwell, and 2 apartment units at each side of the corridor (indicated by solid dots in fig. 4). The measured tracer gas concentrations at each sampling location were plotted against time to indicate the magnitude and rate at which it dispersed to other locations.

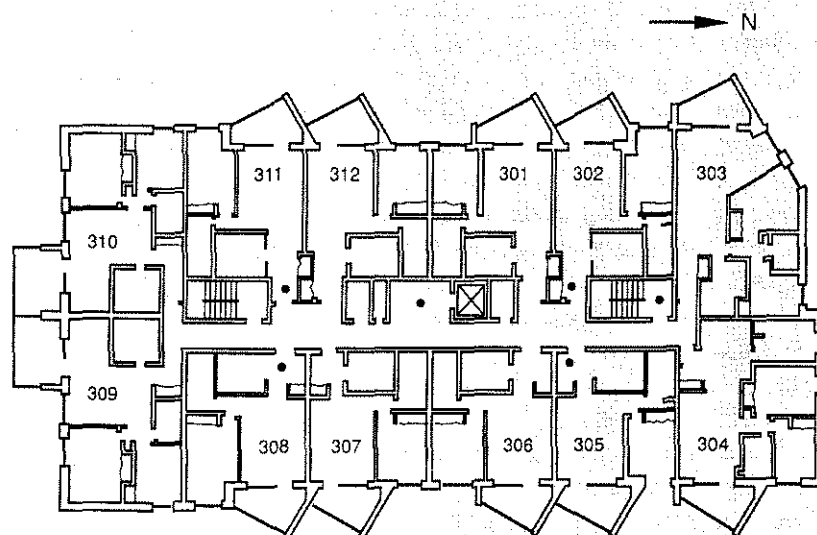


Fig. 4. Floor plan of typical floor showing tracer gas sampling locations.

Figures 5 and 6 show the contaminant dispersed from the ground floor garbage room to other areas within the building [8] when the building's heating and ventilating system was operating normally. The wind was blowing from the south at 17 km/h, and the outdoor air temperature was 11°C during the test. The results indicate that immediately after injection, the tracer gas concentrations in the corridor of every floor increased rapidly. The concentrations in individual apartment units also increased, but at a slower rate. This suggests that the heating and ventilating system was inadequate to overcome the stack action. As a result, the contaminant (tracer gas) dispersed into the corridor on every floor through the garbage chute, stairwell and elevator shafts. The contaminant then migrated into individual apartment units from the corridors. Due to the influence of the southerly wind, more contaminant entered the apartment units on the northeast side than on the southwest side. The tracer gas concentrations at most sampling locations reached their peak about 40 min after injection. The results suggest that any contaminant generated in the garbage room will migrate into individual apartment units via the garbage chute and the corridors. The extent and rate of this migration will depend on wind speed and direction, stack action and the use of exhaust fans in the apartment units.

Multiple Tracer Gas Techniques

Standards such as the CAN/CSA-F326-M91 'Residential Mechanical Ventilation Systems' [9] specify a minimum ventilation rate for each room of a house. To meet

the requirement, it is necessary to measure the outdoor air supply rate for each room or zone of a house. The multiple tracer gas technique is often used for such measurements. It involves the injection of a different tracer gas into each of several interconnected spaces and the measurement of the tracer gas concentrations as a function of time. Based on the measured tracer gas concentrations, the interzonal airflows can then be calculated from the mass conservation equations for each tracer gas and the mass flow balance equations for the air [10, 11].

The application of the method is not straightforward [12]. To illustrate some of the problems, consider the simplest case, e.g., two interconnected rooms (rooms 1 and 2) where the airflows between the two rooms are controlled and measured (fig. 7). If a tracer gas, *g*, is injected into room 1 and another tracer gas, *s*, is released in room 2, the rates of change in tracer gas concentrations in the two rooms can be described by the following equations, assuming that the tracer gas concentrations outside the rooms are negligible:

$$\begin{aligned} \text{Room 1,} \\ V_1 (dC_{g1}/dt) &= -(F_{10} + F_{12}) \cdot C_{g1} + F_{21} \cdot C_{g2} + Q_g & (1) \\ V_1 (dC_{s1}/dt) &= -(F_{10} + F_{12}) \cdot C_{s1} + F_{21} \cdot C_{s2} & (2) \end{aligned}$$

$$\begin{aligned} \text{Room 2,} \\ V_2 (dC_{g2}/dt) &= -(F_{20} + F_{21}) \cdot C_{g2} + F_{12} \cdot C_{g1} & (3) \\ V_2 (dC_{s2}/dt) &= -(F_{20} + F_{21}) \cdot C_{s2} + F_{12} \cdot C_{s1} + Q_s & (4) \end{aligned}$$

The mass flow balance equations for the two rooms are:

$$\begin{aligned} \text{Room 1,} \\ F_{01} + F_{21} - (F_{10} + F_{12}) &= 0; & (5) \end{aligned}$$

Fig. 5. Contaminant dispersion patterns for the 2nd floor with the ground floor garbage room as the source location; winter conditions.

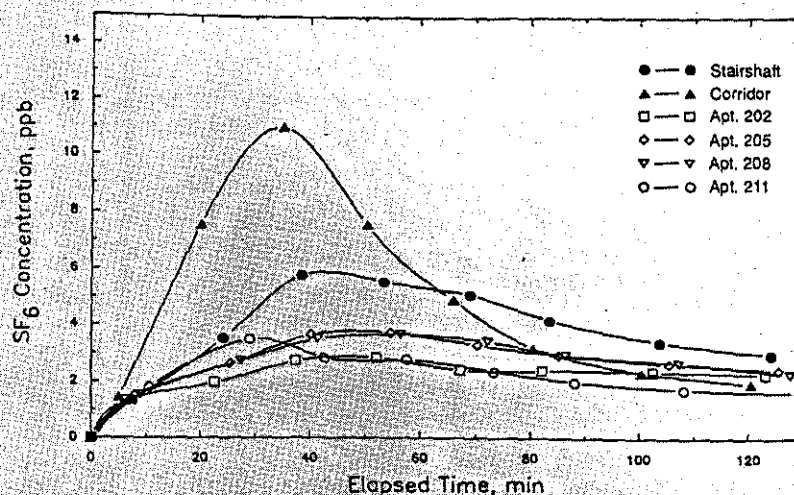
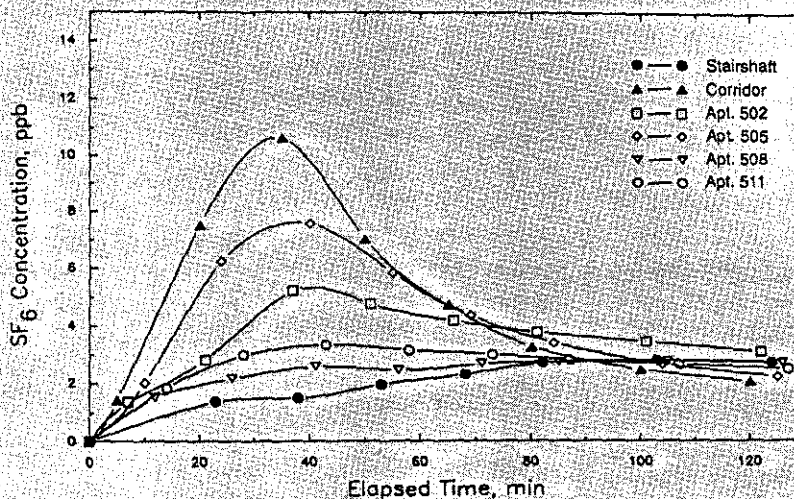


Fig. 6. Contaminant dispersion patterns for the 5th floor with the ground floor garbage room as the source location; winter conditions.



Room 2,

$$F_{O2} + F_{12} - (F_{2O} + F_{21}) = 0; \quad (6)$$

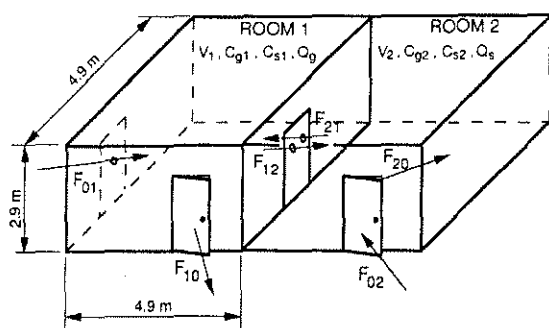
where V = room volume, C = tracer gas concentration, t = time, F = airflow rate, and Q = tracer gas release rate.

The subscripts O, 1 and 2 denote the outside, room 1 and room 2, respectively, and g and s refer to the tracer gases used. Thus, F_{1O} indicates that the airflow is from room 1 to the outside.

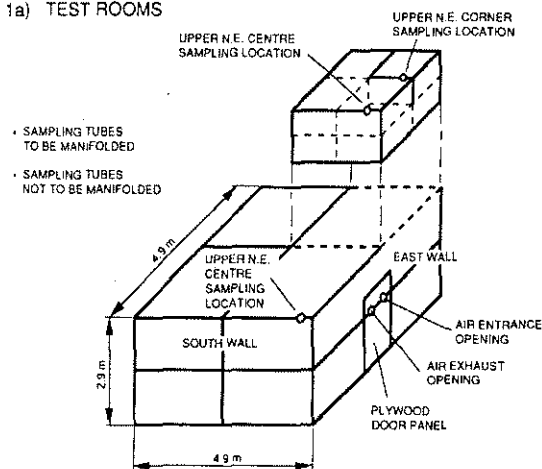
If a minimum of two tracer gases, g and s, are injected into rooms 1 and 2, respectively, and their concentrations are monitored, the six unknowns F_{1O} , F_{12} , F_{O1} , F_{2O} , F_{O2} and F_{21} can be evaluated from equations 1-6. In this

example, three tracer gases were injected. SF_6 and N_2O were introduced into rooms 1 and 2, respectively, using the decay technique, while CH_4 was injected into room 1 using the constant injection mode. As CH_4 and SF_6 were introduced into room 1 using different injection modes, it was possible to examine the effect of injection techniques on the calculated airflow rates.

Figure 8 shows a typical set of concentration profiles measured in the two rooms. Each set consists of six profiles, one for each tracer gas in each room. From such profiles, the concentrations of CH_4 and N_2O (representing a constant injection - decay test condition) corresponding to a sampling time 6 min after the injection of the tracer



1a) TEST ROOMS



1b) SAMPLING LOCATIONS

Fig. 7. Test rooms and sampling locations.

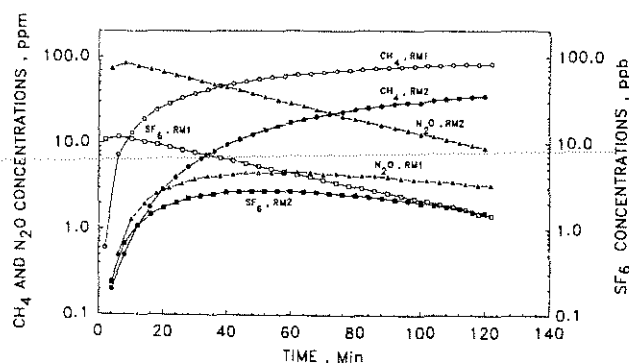


Fig. 8. Typical tracer gas concentration profiles.

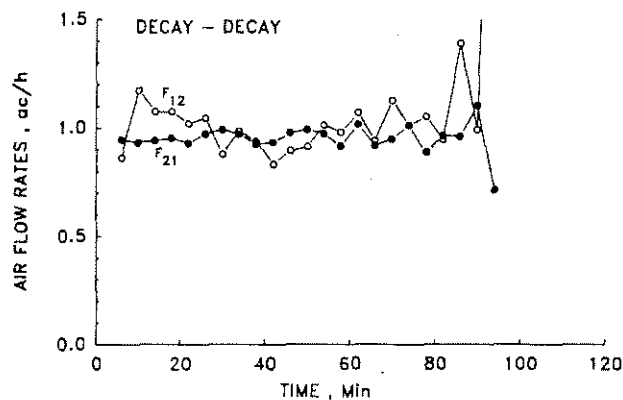
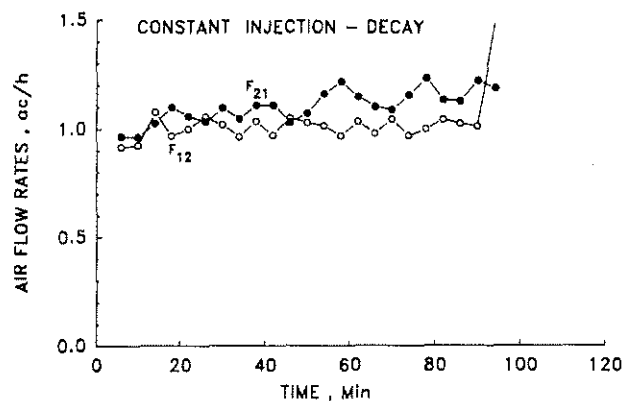


Fig. 9. Calculated interzonal airflow rates; set airflow rates $F_{12} = F_{21} = 1$ ach.

gases were selected and used to calculate F_{12} and F_{21} from Eq. 1-6. This calculation was repeated using sets of concentration values measured at 4-min intervals for about 2 h. Also, similar calculations were performed using the SF_6 and N_2O concentrations (representing a decay - decay test condition).

Figure 9 shows an example of the calculated interzonal airflow rates as a function of time [12]. The results indicate that:

(1) for the same test, the calculated airflow rates based on different sets of concentration measurements (measured at different times) were not always the same; (2) the calculated airflow rates, based on the concentrations measured between approximately 30 and 70 min after injection, agreed with the measurement within 20% of the measured rates; and (3) no clear evidence was found to

suggest that the technique used to inject tracer gases (e.g., decay or constant injection) has a significant or systematic effect on the calculated results.

These findings suggest that concentrations selected from only a certain portion of the measured profiles can give a good estimate of interzonal airflows. To determine the appropriate set of concentrations for calculating interzonal airflows, the following method has been proposed.

Because equations 1 and 4 are similar, as are equations 2 and 3, the solutions for the tracer gas concentration profiles (for tracer gas g) using equations 1 and 3 will be similar to those for tracer gas using equations 2 and 4. The basis for determining the appropriate tracer gas concentrations for use in interzonal airflow calculations can be derived by examining a typical pair of tracer gas concentration profiles for a single tracer gas released in one of the two rooms. Such profiles can be obtained analytically from equations 1 and 3 or 2 and 4.

By dropping the subscript g , equations 1 and 3 become:

$$V_1 (dC_1/dt) = -(F_{10} + F_{12}) \cdot C_1 + F_{21} \cdot C_2 + Q \quad (7)$$

$$V_2 (dC_2/dt) = -(F_{20} + F_{21}) \cdot C_2 + F_{12} \cdot C_1 \quad (8)$$

Substituting for C_2 from equation 7 into equation 8, and letting $N_1 = (F_{12} + F_{10})/V_1$ and $N_2 = (F_{21} + F_{20})/V_2$, we have,

$$d^2C_1/dt^2 = -(N_1 + N_2) \cdot (dC_1/dt) - [N_1 \cdot N_2 - F_{12} \cdot F_{21}/(V_1 \cdot V_2)] \cdot C_1 + N_2 \cdot Q/V_1 \quad (9)$$

The solution to C_1 can be obtained by the method of Laplace transformation [12]. Thus,

$$C_1(t) = X_1 \cdot \exp(-at) + Y_1 \cdot \exp(-bt) + Z_1 \quad (10)$$

where

$C_1(t)$ = tracer gas concentration in room 1 at time t ;

$$X_1 = [(b - N_1) \cdot C_1(0) + F_{21} \cdot C_2(0)/V_1]/(b - a);$$

$$Y_1 = [(N_1 - a) \cdot C_1(0) - F_{21} \cdot C_2(0)/V_1]/(b - a);$$

$$Z_1 = [Q \cdot G_1 \cdot b/(b - a)] \cdot [1 - \exp(-at)] - [Q \cdot G_1 \cdot a/(b - a)] \cdot [1 - \exp(-bt)] + [Q/[V_1 \cdot (b - a)]] \cdot [\exp(-at) - \exp(-bt)];$$

$$A = N_1 + N_2;$$

$$B = N_1 \cdot N_2 - F_{12} \cdot F_{21}/(V_1 \cdot V_2);$$

$$a = [A - (A^2 - 4B)^{0.5}]/2;$$

$$b = [A + (A^2 - 4B)^{0.5}]/2; \text{ and}$$

$$G_1 = (F_{21} + F_{20})/[(F_{12} + F_{10}) \cdot (F_{21} + F_{20}) - F_{21} \cdot F_{12}].$$

Similarly, $C_2(t)$ can be expressed by the equation,

$$C_2(t) = X_2 \cdot \exp(-at) + Y_2 \cdot \exp(-bt) + Z_2, \quad (11)$$

where

$C_2(t)$ = tracer gas concentration in room 2 at time t ;

$$X_2 = [(b - N_2) \cdot C_2(0) + F_{12} \cdot C_1(0)/V_2]/(b - a);$$

$$Y_2 = [(N_2 - a) \cdot C_2(0) - F_{12} \cdot C_1(0)/V_2]/(b - a);$$

$$Z_2 = [Q \cdot G_2 \cdot b/(b - a)] \cdot [1 - \exp(-at)] - [Q \cdot G_2 \cdot a/(b - a)] \cdot [1 - \exp(-bt)]; \text{ and}$$

$$G_2 = F_{12}/[(F_{12} + F_{10}) \cdot (F_{21} + F_{20}) - F_{21} \cdot F_{12}].$$

If a single tracer gas (SF_6) is released in room 1 using the decay mode, then $Q = 0$; $Z_1 = 0$, $Z_2 = 0$ and equations 10 and 11 become,

$$C_1(t) = X_1 \cdot \exp(-at) + Y_1 \cdot \exp(-bt) \quad (12)$$

$$C_2(t) = X_2 \cdot \exp(-at) + Y_2 \cdot \exp(-bt), \text{ respectively.} \quad (13)$$

Equations 12 and 13 define the tracer gas concentration profiles for a typical case of two interconnected zones. If all the airflows for such a case are known, the tracer gas concentration profiles can be calculated explicitly from these equations.

The approach proposed here, therefore, is to estimate the airflow rates from equations 1–6 using a set of concentrations measured at some arbitrary time approximately 30 min after injection. These airflows are then used to estimate the concentrations for a later time from equations 12 and 13 [13]. These estimated concentrations are then compared with the corresponding measured concentrations, and, if the agreement is not satisfactory, the procedure is repeated with a set of concentrations measured at a later time. This comparison is made for concentrations at two different times, five sampling intervals apart, to ensure that the agreement between the calculated and measured concentration profiles is not accidental (e.g., the two profiles cross each other at one time but do not agree in general). The final calculated airflow rates are achieved when satisfactory agreement between the measured and calculated concentrations is reached at the two points. The procedures have been successfully used to solve for interzonal airflows for cases of two and three interconnected rooms [12, 13].

Summary

This paper gives brief reviews of various tracer gas techniques which can be used in ventilation studies and indoor air quality investigations. Included are single tracer gas techniques for assessing the performance of HVAC systems of office buildings and measuring the contaminant migration patterns within high-rise apartment buildings, and multiple tracer gas techniques for measuring interzonal airflows. All the methods discussed have been applied successfully in both residential and office buildings.

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