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Developing Tracer Gas Technique to Determine Inter-zonal Air Exchange Rate

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Abstract

The use of local exhaust is considered to be the most effective way to control pollutant dispersion from intense sources, such as in kitchens, in toilets, as well as in copy machine rooms. The optimum air exhaust rate required to prevent pollutants from escaping into the major occupant areas very much depends on the natural air exchange rate(AER) between the hooded room and the major room space. This paper presents a mathematical model and a test procedure of using tracer gas technique to quantify the AER. In this study, the mathematical model analyzes the balance of a tracer gas in two adjacent zones, and establishes two correlations between the dimensionless increase/decay rates of the gas concentrations and the AER. The mathematical model reveals two alternative ways to determine the AER: a). Tracer gas concentrations in both rooms involved be monitored; b).Tracer gas concentration in one of the two spaces be monitored. The latter method was validated in a test for AER quantification between ceiling void and room in a test chamber. Finally the proper use of the two methods is discussed, and it is suggested that the techniques developed in this study can be used for estimating minimum exhaust rate requirement for ventilation system renovation in existing buildings.

List of Symbols

AER: Air exchange rate between two adjacent spaces defined as $3600 \times v/Vc$ (1/hr)
$C_{R,0}$: initial tracer gas concentration in the room space(mg/m^3)
$C_{C,0}$: initial tracer gas concentration in the hooded space(mg/m^3)
C_R : tracer gas concentration in the room space(mg/m^3)
C_C : tracer gas concentration in the hooded space(mg/m^3)
C_b : equilibrium concentration in the whole space(mg/m^3)
V_R: volume of the room space(m^3)
V_C: volume of the hooded space(m^3)
v: air exchange volume between two adjacent spaces(m^3/s)
t: time
t_0: initial time
τ: time

1. Introduction

It is well established that the most effective way to control indoor air pollutants is to directly extract the pollutants at the source location before they are dispersed into the occupancy zones[1, 2]. Range hoods are widely used for kitchen ventilation. Window or wall mounted low-pressure fans are used in toilet/bath rooms. Local exhausts have traditionally been widely used to control pollutants in industrial places, such as welding fumes. In modern commercial buildings, there is an increasing use of various electronic/electrical equipment. Some equipment such as printers and copy machines are known emission sources of some volatile organic compounds[3, 4]. Quite often in Hong Kong, copy machines are located in separate rooms in some open plan offices and libraries. Also, locating electrical appliance in a separate space will reduce noises in the occupied zones. However, there is a question of how to determine the optimum flow rate required for the local exhaust. Ideally, the exhaust should produce such a low pressure in the separate space so that no pollutants will escape into the major spaces concerned. In industrial or laboratory applications, the exhaust air flow rate is determined in such a way so that a minimum facial velocity at the openings of the controlled space are produced to prevent toxic gases from entering the working space. However, the required flow rate determined in such a way may be too high to be cost-effective for commercial and residential applications when there are large openings such as doors in between.

The pollutant may transport through the large openings by diffusion, convection, and pressure differences. In practice, wind pressure distribution around buildings should firstly be considered, and the suspected pollutant sources should be located in low pressure zones. Ultimately, the air-tightness of the building is important in alleviating the wind pressure influences. If this is out of control, the effect of mechanical exhaust will be minimized. Suppose that the wind pressure influence is negligible, it is the natural convection of the hot plumes produced by various indoor heat sources and their interactions with the mechanical air distribution system that determine the distribution of the pollutants. The mechanical ventilation is considered as the control measure to overcome the natural convection processes. Therefore, knowing the exchange due to the convection alone will be useful for the proper design of the local exhaust in this case. The research described in this paper is on the determination of the air exchange between two adjacent zones in buildings when the mechanical ventilation effects are not included. Then, how to determine the local exhaust rate based on this AER will be discussed in the result analysis section.

2. Methods.

The inter-zonal air exchange through a large opening caused by natural convection may be illustrated as in Figure 1. The plume produced by a heat source such as a copy machine will cause the entertainment of the surrounding air. In the confined space, there will be recirculation at the higher level of the plume. This plume in combination with temperature differences existing between the two zones may create air flows through the opening, with air leaving and entering the high temperature space through the upper area and lower area respectively. If the velocity profile through the openings can be determined, the AER can be calculated. However, as demonstrated in many studies, measurements of the detailed flow

velocities are extremely difficult and subject to large errors[5]. Therefore, the method proposed in this study involves the use of tracer gas techniques, which have traditionally been used for determination of air-infiltration rate through building envelopes. The proposed method here is the development of the technique for the determination of interzonal air-exchange rates.

Plume above
a heat source

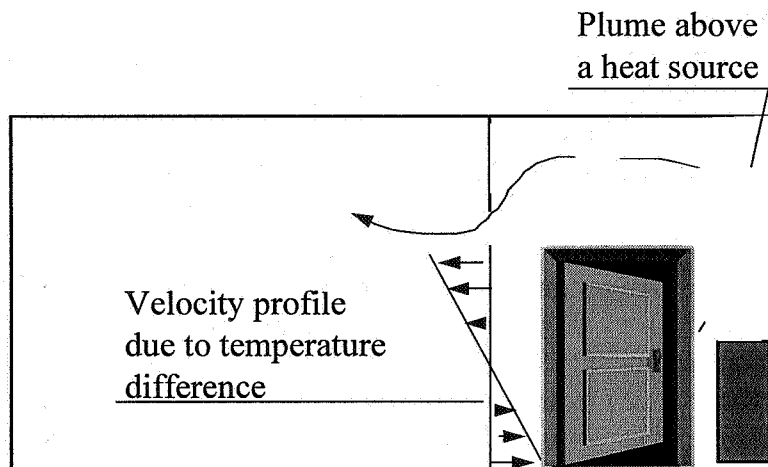Velocity profile
due to temperature
difference

Figure 1. Possible air exchanges between two adjacent zones driven by natural convection

The tracer gas technique involves releasing a gas into the building spaces concerned and monitoring the change of the gas concentration. If there is no adsorption/absorption for the gas, the gas concentration change is caused by air-change from outside or adjacent spaces. Based upon mass balance for the tracer gas, this air change rate can be calculated from the monitored concentration change. In the case of air-exchange between two adjacent zones, different formulation from that for infiltration studies will be required to calculate the air exchange rate. The essential difference is that, unlike the air-infiltration cases, as the concentration decays in one space, there will be an increase of concentration in the adjacent space. The detailed model which addresses this characteristics is described in the Appendix of this paper. The model provides two alternative methods to calculate the AER according the two dimensionless concentration decays monitored. Consequently, two monitoring methods are proposed, with one requiring monitoring the tracer gas-concentration in one space only, and the other requiring monitoring the tracer gas concentrations in both spaces. Either of the methods will enable us to calculate AER using Equation (A.10). As illustrated at the end of the Appendix, only when one room is much larger than the other, can the correlation for infiltration study be used to quantify the AER between two enclosed zones.

3. Test Case and Test Results

To verify the feasibility of the formula described in the Appendix, a test is performed in a test chamber, in which cooled-ceiling panels are installed. Gaps exist between the ceiling panels, so that air exchange will occur between the room and ceiling void(Figure 2). Such a design is to maximise the cooling capacity of the ceiling panels since the upper surface of panel will also heat by convection. However, this cooling capacity will very much depends on the amount of air that penetrate through the ceiling gaps. The cooled-ceiling panels also function as a partition

between two adjacent spaces. Therefore, the tracer gas technique described in the Appendix is valid for this case, although the practical indication of this air exchange is different from that between two adjacent zones. Therefore, test results performed in this test chamber will be presented here to demonstrate the proper use of the technique.
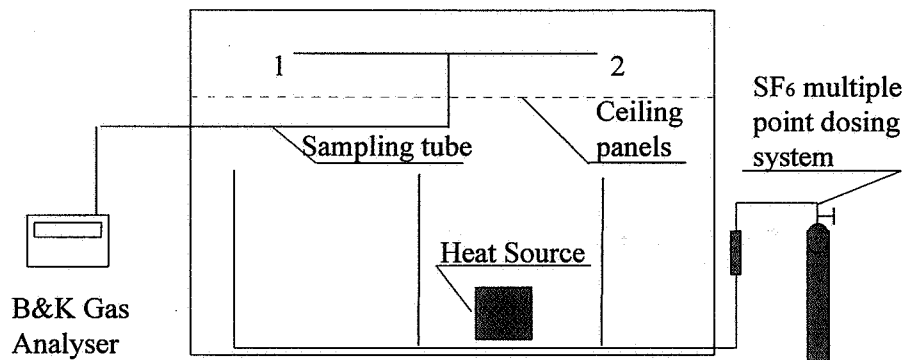

Figure 2. Test of the tracer gas technique in a room with ceiling-panels

In the test, the tracer gas used is sulphur hex-fluoride(SF_6), which is recommended based on its density, toxicity, reactivity, and easiness of being detectable. To realise a good initial well-mixed condition of the tracer gas in the room below, two approaches that enhance the mixing process are combined. Ten dosing points are located uniformly in the room to charge a sufficient amount of tracer gas into the room in a matter of several seconds. Simultaneously, an air fan located in the room was switched on for a few seconds to intensify the mixing. However, the fan will have interference on the natural convection. Therefore, it is essential that the fan, on one hand, is powerful enough to make the air fully mixed in a matter of several seconds while, and on the other hand, does not disturb or cause much air exchange through the ceiling gaps within this mixing process. Different fan mixing speeds were tested. It was found, by monitoring the concentrations at different locations in the room, that low fan speed worked very well, probably because the tracer gas is already purged into the room at diversified positions. Since the air enters the cavity from the room through the gaps scattered all over the ceiling, the average concentration might be close to the nominal instantaneous 'fully mixed concentration', even if the concentration in the room is not 100% uniform. Therefore, very short time fan mixing at low speed was used at the beginning of the measurements.

The monitored SF_6 concentration of the mixed samples from four locations in the cavity is shown in Figure 3. Due to the preliminary test, some background concentration exists in the room: the initial concentration $C_{C,0}$ in the cavity is about 17 mg/m^3. Since the tracer gas is dosed into the room space, the concentration in the cavity is increasing. It takes about 10 minutes to approach the equilibrium state. Observing from the curve, the equilibrium concentration is about 225 mg/m^3.

Some measurement errors are taken into consideration in the later data processing. In the later stage of the concentration increasing, the measured C_c will be very close to the final equilibrium concentration C_b. Consequently, any error in the measured value of C_c at this stage will create

large errors in the calculation of the logarithmic value of the dimensionless concentration $\ln(C_b - C_{C,o})/(C_b - C_C)$. Therefore, in the plotting of logarithm of the dimensionless concentration against time, only the measurements in the early stages- the first seven minutes - are used for regression analysis. The plotting shows a good straight line(Figure 4). The slope of the line k is $1/120$ s^{-1}. Then according to Equation (A.10), the air exchange rate v/V_C will be $k/(1+V_C/V_R) = 25$ *1/hour*. This amount is considerably high, and its effect certainly should not be overlooked.
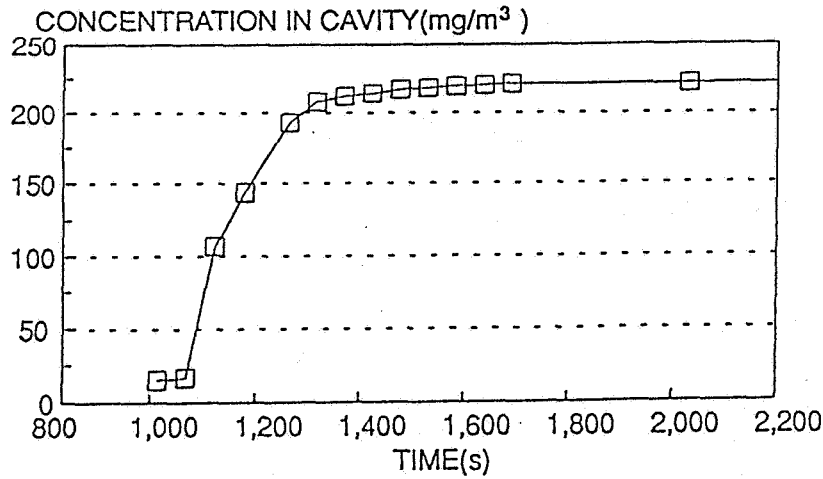
CONCENTRATION IN CAVITY(mg/m^3)

Figure 3. Monitored concentration increase of SF6 in the cavity
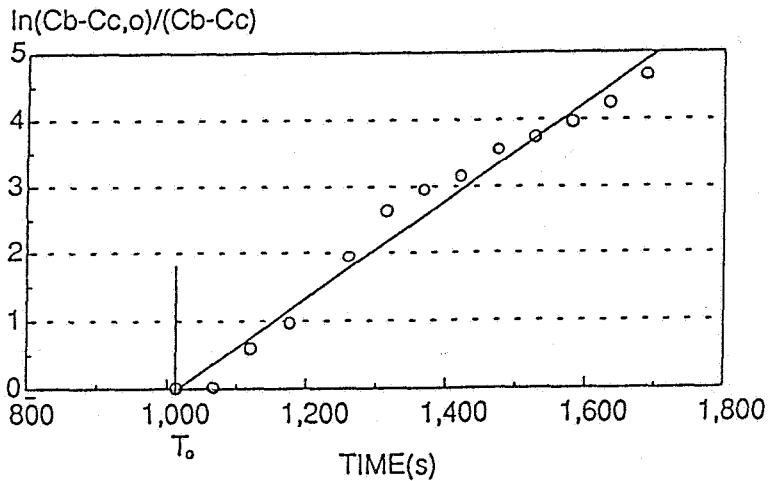
ln(Cb-Cc,o)/(Cb-Cc)

Figure 4. Logarithmic plotting of the measured dimensionless concentration in the cavity

4. Conclusions and Remarks:

1. Tracer gas test procedures have been proposed to determine the air-exchange rate between two adjacent rooms. The method can be used to determine the air-exchange rate caused by buoyancy-driven flows.

2. Attention should be paid to air-flow control to the spaces tested. Basically, all external air-change routes should be cut-off while the test is being conducted.

3. Two alternative test procedures are proposed, with the single monitor method tested in an enclosed room. The single monitor method only requires one tracer gas detector to fulfill the measurement. As demonstrated in the test, when the v/V_C is around 25 1/hour, the equilibrium concentration required can be easily approximated from the first ten-minutes data. Therefore, the value of v/V_R should be estimated beforehand. If this value is two low, the second method described in the Appendix should be used since the time required to achieve equilibrium might be too long.

4. In using the methods, only the data obtained in the initial increase or decay stage should be used for calculating the slope k to avoid numerical errors that will be introduced in the dimensionless concentration calculation.

5. While the test method does provide an air exchange rate, the remaining question is how to design the exhaust air rate according to this air exchange rate. This exchange should be considered as the minimum exhaust air rate required. Below this rate, there are always pollutants escaping into the major room. However, providing a flow rate above this value does not guarantee that no pollutant escape will occur. This is because air exchange may still occur across the a large opening such as a door due to the buoyancy effect. Therefore, the relative location of the pollutant source and exhaust grill to the opening should be carefully considered. Actually, this is the other complicated aspect of the same issue that deserves special investigations. Bearing this in mind, the technique will be useful in estimating the minimum exhaust rate required when ventilation system upgrading is done for existing buildings.

APPENDIX

The idea of using tracer gas technique to measure air change rate is not new. However, for the measurements of air exchange through two adjacent room spaces, some specific mathematical formulation and test procedures will be required. The present contents are the derivation of these formulas.

Consider a room with two air spaces - the cavity above the ceiling and the room below the ceiling, or consider two adjacent rooms in a building, the living room and the kitchen. In this context, the two spaces will be called room spaces and hooded spaces respectively. Assume that natural convection will cause convective air exchanges between the two spaces. To investigate this buoyancy effect, no external air should be supplied. Imagine that a certain amount of tracer gas is purged uniformly into one of the two room spaces and quickly mixed in the room in a very short time interval(Figure A.1 a). Then we have an initial concentration of $C_{R,0}$ in the room and a $C_{C,0}$ in the cavity. After the tracer gas is switched off, the concentration in the room will decay while the concentration in the cavity will increase, as indicated in Figure A.1 c, or

vice versa. Ultimately, the concentration will reach the equilibrium state, with a uniform concentration C_b through out the room(Figure A.1 b). This decay or increase process can be described by the following mathematical method. Consider the cavity and the room as two well-mixed chambers. Then we have balance equation of the tracer gas in the room volume:

$$v\,(C_R - C_C) = -V_R\,\frac{d\,C_R}{d\tau} \qquad (A.1)$$

where, v is the air exchange volume between the two spaces, V_R is the volume of the room space. C_R and C_C are the tracer gas concentrations in the room space and the hooded space respectively. Similarly we have the balance equation of the tracer gas in the cavity space:

$$v\,(C_R - C_C) = V_C\,\frac{d\,C_C}{d\tau} \qquad (A.2)$$

where, V_C is the volume of the hooded space.

We also have the mass conservation of the tracer gas in the whole space:

$$V_C\,C_C + V_R\,C_R = (V_C + V_R)\,C_b \qquad (A.3)$$

where, C_b is the final equilibrium concentration in the whole space.

From Equation (A.3), we have

$$C_R = (1 + \frac{V_C}{V_R})\,C_b - \frac{V_C}{V_R}\,C_C \qquad (A.4)$$

Substitute C_R in Eq.(A.2) with Eq.(A.4), we get

$$v\,(1 + \frac{V_C}{V_R})\,(C_b - C_C) = V_C\,\frac{d\,C_C}{d\tau} \qquad (A.5)$$

Let

$$C_{b\text{-}C} = C_b - C_C, \qquad (A.6)$$

Since C_b is a constant, Equation (A.5) can be changed into

$$-\frac{d\,C_{b\text{-}C}}{C_{b\text{-}C}} = \frac{v}{V_C}\,(1 + \frac{V_C}{V_R})\,d\tau \qquad (A.7)$$

Integration of Equation (A.7) yields

$$\ln\frac{C_{b\text{-}C,\,0}}{C_{b\text{-}C}} = \frac{v}{V_C}\,(1 + \frac{V_C}{V_R})\,(t - t_0) \qquad (A.8)$$

where,

$$C_{b-C,0} = C_b - C_C(t_0) \tag{A.9}$$

That is to say, the logarithm of the dimensionless concentration is directly proportional to the time. Therefore, if the concentration increase in the cavity is measured, and results are plotted according to Equation(A.8), then the air exchange volume v is related to the slope k of the curve(Figure A.1 d) according to the equation

$$v = k \frac{V_C}{1 + V_C / V_R} \tag{A.10}$$

It should be noted that the concentration in the room space, C_R, does not appear in Equation (A.6), (A.8) and (A.9). This means that the concentration in the room is actually not required in monitoring the concentration increase/decay process. What is required is the equilibrium concentration C_b, which is theoretically the ultimate concentration after a infinitely long period. In practice, this value should be reasonably approximated by observing the concentration increase/decay curve of C_R after a reasonable period.

An alternative set of formulations can be derived. From Equation(A.3), we can derive such a correlation:

$$C_R - C_C = (1 + V_C/V_R)(C_b - C_C) \tag{A.11}$$

Substitute this into Equation (A.8), we have

$$\ln \frac{C_{R,0} - C_{C,o}}{C_R - C_C} = \frac{v}{V_C} \left(1 + \frac{V_C}{V_R}\right)(t - t_0) \tag{A.12}$$

On the left hand side of this equation, only when the concentration changes in both rooms are measured, can the dimensionless concentration be calculated. Consequently, air exchange volume v can be calculated according to Equation (A.10). This means that at least two tracer gas monitors will be required. On the other hand, the equilibrium concentration will not be required. This method may be advantageous when the AER is small and the time required to achieve the equilibrium is long.

When $V_R \gg V_C$, and if the tracer gas is initially released only into the hooded space, we will have $C_{R,0} = C_R = 0$. Then both Equation (A.9) and Equation (A.12) will become

$$\ln \frac{C_{C,o}}{C_C} = \frac{v}{V_C} (t - t_0)$$

which is actually the conventional equation used in the decay method to quantify air change rate in infiltration studies.
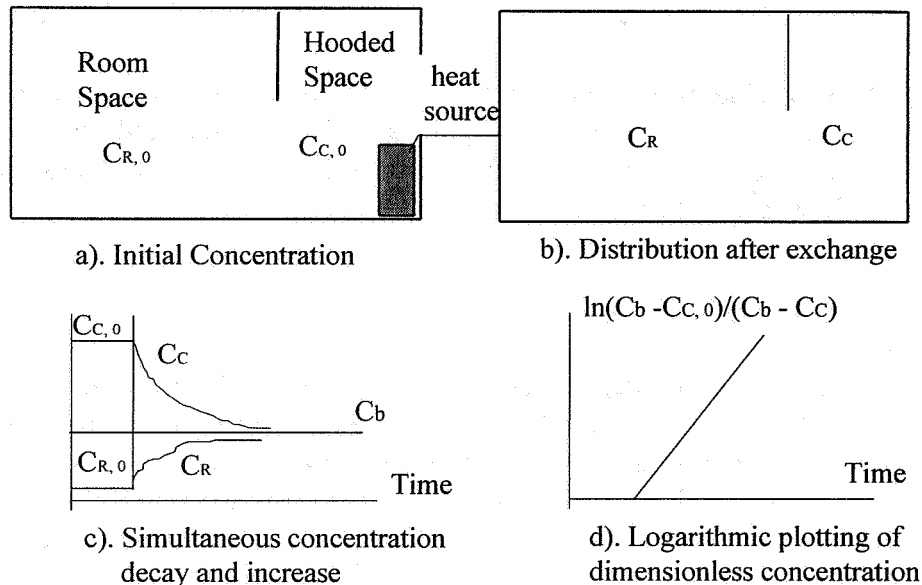

a). Initial Concentration

b). Distribution after exchange

c). Simultaneous concentration
decay and increase

d). Logarithmic plotting of
dimensionless concentration

Figure A.1 Illustration of the tracer gas concentration increase and decay in two adjacent spaces

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