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Measurements of Ventilation Effectiveness in an Underfloor Air-Conditioned Space Using a Tracer Gas Technique

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Key Word : Ventilation effectiveness, Underfloor air-conditioning system, Tracer gas, Local mean age

Abstract

This paper investigates ventilation characteristics of an environmental chamber simulating an under-floor air conditioning system for isothermal and cooling supply air conditions. The tracer gas sulfur-hexafluoride (SF_6) was injected into a supply duct using step-up and step-down methods. Local mean and room mean ages were calculated from the concentrations measured at internal points and at the exhaust duct. The air change efficiency of the chamber has been found to be greater in cooling conditions than in isothermal conditions. Also the room air change efficiency is not significantly affected but slightly improved by the presence of a supply diffuser.

Nomenclature

C_p : Concentration of tracer gas at point P
C_S : Steady state concentration
$C(0)$: Initial concentration
ε_p : Local air change index
$\langle \varepsilon \rangle$: Air change efficiency
Q : Volumetric airflow rate
t : Time
τ_n : Nominal time constant
τ_p : Local mean age
$\langle \tau \rangle$: Room mean age
V : Volume of room

Subscripts

e : Point at exhaust
p : Internal point

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1. Introduction

Indoor air pollution is becoming a growing concern nowadays as various contaminants are generated indoors while buildings are becoming air-tight to reduce energy losses by infiltration. The demand for safe and comfortable indoor environments has increased as the standard of living has improved, and the residence time of occupants in buildings now increased. Clean indoor air is also needed to increase productivity at places such as a semi-conducto factory. Mechanical ventilation is often utilized to eliminate contaminants generated indoors and to provide fresh air to occupants. The performance of ventilation is determined not only by the total airflow rate but also by airflow distribution in a room. Depending on the locations of supply and exhaust grilles, fresh supply air may not be distributed to the space efficiently but short-circuits directly to the exhaust. Therefore, ventilation effectiveness should be considered to characterize the performance of ventilation. Ventilation effectiveness has been defined in various ways by many investigators. Sandberg(1,2) proposed the concept of age of air using a tracer gas, and Skaret et al.(3) proposed a two-zone model to explain ventilation effectiveness. A numerical method has been proposed by Han(4) to obtain local mean age distributions quantitatively from calculated turbulent airflow results.

This paper investigates ventilation effectiveness in an underfloor air-conditioned space using a tracer gas technique. An underfloor air-conditioning system (UFAC) has recently received great attention, since it can provide a flexible plane layout and good ventilation characteristics in cooling and heating operations. Air change efficiency is measured in an environmental chamber simulating an underfloor air-conditioning system under isothermal and cooling supply air conditions. The effect of a diffuser on room air change efficiency is also investigated.

2. Theoretical Analysis

2.1 Mean age

Ventilation effectiveness should be a measure which indicates the performance of a ventilation system; i.e. how well the contaminated indoor air is replaced by fresh supply air. Various definitions of ventilation effectiveness have been proposed. It is generally accepted, however, that the concept of age of air best characterizes the ventilation effectiveness. Local mean age of air is defined as the average time needed for the supply air to reach the location of interest. A location is "well-ventilated" if the local mean age is small. By averaging the local mean ages over the entire space, the room mean age which indicates the overall room ventilation effectiveness, can be obtained.

2.2 Injection methods

The local mean age is calculated from a concentration-time curve measured at a point using a tracer gas technique. The tracer gas

Table 1 Calculation of local mean age

Injection method	Local mean age
Step-up	$\tau_p = \int_0^\infty \left(1 - \frac{C_p(t)}{C_S}\right) dt$
Step-down	$\tau_p = \int_0^\infty \frac{C_p(t)}{C(0)}\, dt$

should be uniformly-mixed with supply air before being injected into a supply air duct. Some commonly used methods are pulsed, step-up, and step-down injections. In this study, a step-up method followed by a step-down method is used. Table 1 shows the quations to calculate the local mean age for two different injection methods.

The room mean age may be calculated by averaging local mean ages over the entire room space, which would require considerable amount of time and effort. It can also be calculated from the concentration-time curve at the exhaust according to the relations given in Table 2.

2.3 Air change efficiency

The nominal time constant of the room is defined as the time required to supply air to a space of volume V with a volumetric airflow rate Q, which is the inverse of air change rate per hour. In the case of complete mixing, the local mean age is uniform everywhere which is the same as the nominal time constant.

$$\tau_n = V / Q \tag{1}$$

The local air change index is defined as the ratio of nominal time constant to local mean age. Depending on the design and operation of the ventilation system, it may be less than unity but can be as great as infinity. Therefore, "index" is generally preferred instead of effectiveness or efficiency.

$$\varepsilon_p = \frac{\tau_n}{\tau_p} \tag{2}$$

The overall ventilation effectiveness of a space can be described by the air change efficiency, which is defined as the ratio of the

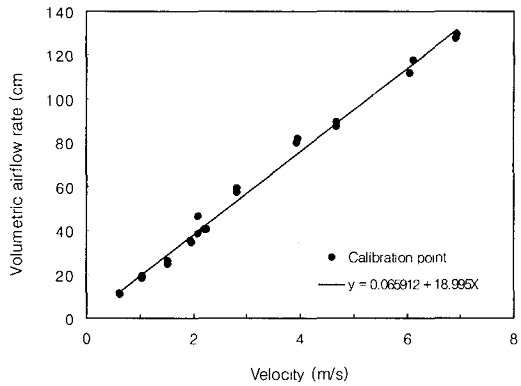

Fig.1 Calibration of volumetric airflow rate.

Table 2 Calculation of room mean age

Injection method	Room mean age
Step-up	$\langle \tau \rangle = \frac{Q}{V} \int_0^\infty t \left(1 - \frac{C_e(t)}{C_S}\right) dt$
Step-down	$\langle \tau \rangle = \frac{\int_0^\infty t \cdot C_e(t)\, dt}{\int_0^\infty C_e(t)\, dt}$

nominal time constant and the room mean age. This ratio is normally divided by 2, in order to have a plug flow or a displacement ventilation result in 100%, which theoretically gives the maximum efficiency. According to the definition, the air change efficiency is 50% in the case of complete mixing.

$$\langle \varepsilon \rangle = \frac{\tau_n}{2 \langle \tau \rangle} \tag{3}$$

3. Experiment

3.1 Experimental model

Experiments were conducted in an envir-

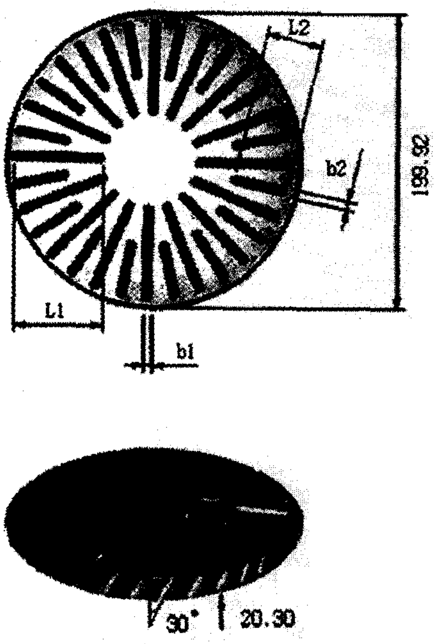

Fig.2 Diffuser used in the experiment.

onmental chamber located in Thermal/Flow Control Research Center of KIST. The chamber has dimensions of 2.5x2.5x1.89m, and has a circular opening of 0.21m in diameter at the center of the floor. There are four exhaust openings at four corners on the ceiling, whose diameters are 0.2m. The openings for supply and exhaust can be moved easily to any location on either the floor or the ceiling, and the chamber can be operated in different operating modes by adjusting its dampers.

The room air mixed with a tracer gas is not recirculated but exhausted completely so that 100% outdoor air is used to replace the exhaust air. The specification of the supply fan is 22 m3/min at 30 mmAq. The airflow rate is measured using 5 hot-wire anemometers located at the supply duct downstream of a flow straightener. The calibration curve is shown in Fig.1, which shows the relation between the overall airflow rate and the average velocity in the duct.

Table 3 Specification of SF6 gas detector

	Specification
Measurement range	0 ~ 3000 ppm
Output voltage	0 ~ 10 mV
Response time	30 sec
Sampling rate	150 cc/min

Table 4 Specification of diffuser

	b1	L1	b2	L2
Dimensions	7.3mm	64.38mm	7.12mm	37.68mm

3.2 Experimental apparatus

Sulfur-hexafluoride has been selected as a tracer gas, which is inert, non-toxic, and normally absent in the atmosphere. A SF6 gas detector is a coulometric analysis type, using a membrane galvanic cell which generates an electric current by electro-chemical reactions proportional to the partial pressure of SF6. Electrolyte solution should be replaced every 6 months. The gas detector specifications are listed in Table 3.

Experiments were conducted with and without a diffuser. A diffuser used in the present study has been specially designed for underfloor air-conditioning systems, which generates circular vortex so that sufficient mixing can take place. The diffuser specifications are listed in Table 4. When a diffuser is not installed, a circular empty opening is used as the supply inlet.

The injection rate of SF6 is adjusted by a globe valve, and it is measured using a rotameter. Various rotameters are installed to cover a wide range of gas flow rates depending on the room air volume and the airflow rate. A solenoid valve is used to control injection timing. In order to minimize the discharge momentum of a tracer gas, a porous sphere of 40 mm in diameter is connected at the end the of injection tube. Overall schematic of the experimental setup is shown in Fig.3.

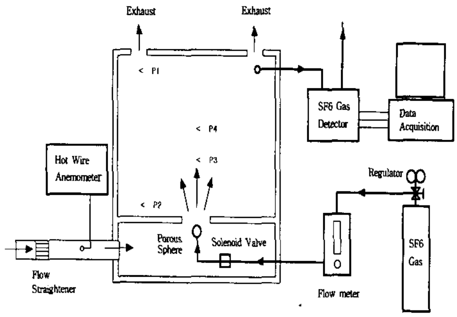

Fig.3 Experimental setup for ventilation effectiveness measurements.

3.3 Experimental procedure

The tracer gas is injected at time zero near a supply opening. The solenoid valve is turned on until the concentration in the room reaches a steady state (step-up), and it is turned off afterwards (step-down). The injection rate is fixed at the value of 100 cc/min, and the supply airflow rate is set at 24 cmh. Therefore, the mean concentration of tracer gas in the supply air stream is 250 ppm. Since the internal volume of the chamber is 11.8 m3, the nominal time constant is equivalent to be 1772 sec.

The tracer gas concentration is measured at 4 locations in the chamber, P1(100mm below the exhaust), P2(1790mm below the exhaust and 100mm above the floor), P3(300mm above the supply), and P4(950mm above supply). Table 5 summarizes the measurement locations and the experimental conditions.

The voltage outputs from the gas detector and thermocouples are recorded every 5 seconds for 3 hours for a step-up operation and another 3 hours for a step-down operation.

Table 5 Experimental conditions

Parameters		Experimental conditions
Room dimension (LxWxH) Volume of the room		2.5m x 2.5m x 1.89m 11.8 m^3
Airflow rate SF6 gas injection rate Nominal time constant		24 cmh 100 cc/min 1772 sec
Measurement points	P1	0.1m below exhaust
	P2	1.79m below exhaust (0.1m above floor)
	P3	0.3m above supply
	P4	0.95m above supply

Table 6 Local mean ages and local air change indices by step-up injection (isothermal)

Measurement Point	Step-up method	
	Local mean age	Local air change index
P1	2221 sec	0.80
P2	1235 sec	1.43
P3	1710 sec	1.04
P4	2146 sec	0.83

Table 7 Local mean ages and local air change indices by step-down injection. (isothermal)

Measurement Point	Step-down method	
	Local mean age	Local air change index
P1	2010 sec	0.88
P2	1490 sec	1.19
P3	1330 sec	1.33
P4	1781 sec	1.00

4. Results and Discussion

4.1 Isothermal condition

Concentration variations measured at four different internal points are plotted in Fig.4 after a step-up injection from a supply opening for an isothermal condition. Initially, the concentrations increase quite rapidly and finally approach to a steady state value. There are slow increases in the concentrations at P1 and P4, which are located far from the supply opening. The local mean ages at the points are calculated by obtaining the areas above the concentration curves. It is difficult to evaluate asymptotic concentration values exactly, therefore, errors occur during integration. The local mean ages calculated at those points are shown in Table 6 along with the local air change indices. The local mean ages are smaller at points near the floor compared to the points near the ceiling or exhaust as can be expected.

Concentration response after a step-down injection is shown in Fig.5. Table 7 shows the local mean ages and local air change indices for a step-down process. Table 7 indicates the same trend as shown in Table 6. However, the step-down method gives smaller values of local mean ages than the step-up method except at P2. In a step-down process the error associated with the asymptotic concentration does not

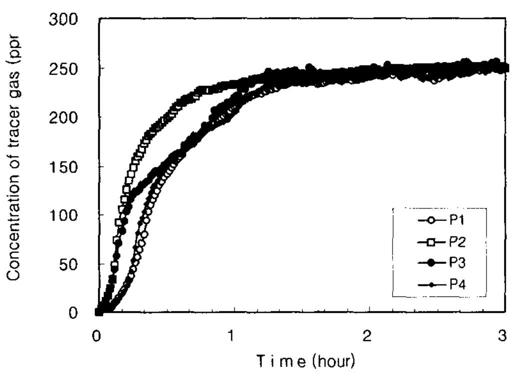

Fig.4 Concentrations by step-up injection. (isothermal)

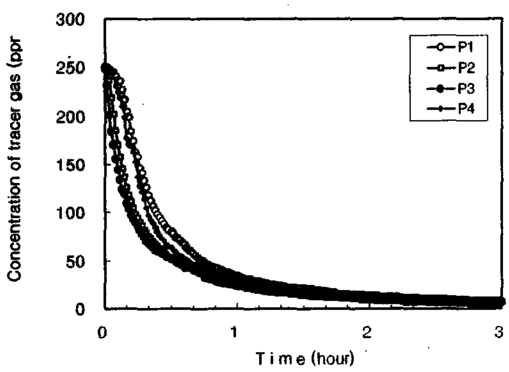

Fig.5 Concentrations by step-down injection. (isothermal)

Table 8 Local decay rates (isothermal)

Measurement point	Local decay rate (ACH)
P1	0.680
P2	0.633
P3	0.683
P4	0.706
Complete mixing	2.033

Table 9 Local mean ages and local air change indices by step-up injection (cooling)

Measurement Point	Step-up method	
	Local mean age	Local air change index
P1	2368 sec	0.75
P2	1049 sec	1.69
P4	2381 sec	0.74

exist. At P2, the local mean age by a step-up method is smaller than the value obtained by a step-down method. This can be explained by the fact that an injected tracer gas of high concentration moves along the floor to reach the point P2 before being mixed with room air in step-up operations. There is no mixing problems in step-down operations. It can be concluded that a step-down method is better, because it is easier to evaluate an asymptotic concentration and there is no mixing problem due to the density difference. Results of both methods agree to within 20%, however.

Figure 6 shows the decay curves in a semi-log graph superimposed with a constant decay rate for a complete mixing case. The decay rates are changing initially and become constant regardless of location. Local decay rates are obtained by fitting the graphs with exponential curves during the final hour. The values are shown in Table 8. As was concluded in Reference [4], the decay rate is not a good measure of indicating local ventilation effectiveness since the difference between points cannot be distinguished.

4.2 Cooling condition

Concentration variations after a step-up injection are shown in Fig.7 for a cooling condition.

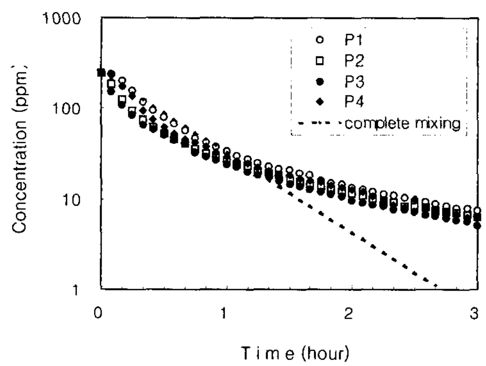

Fig.6 Transient concentration decays at various measurement points.

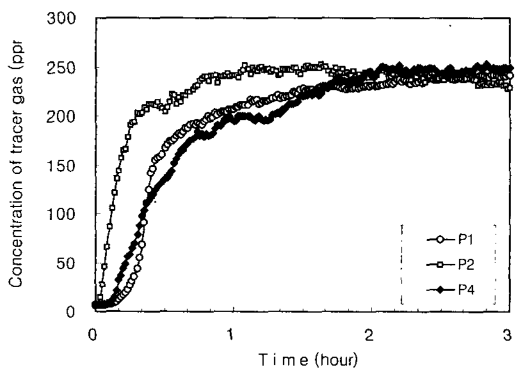

Fig.7 Concentrations by step-up injection. (cooling)

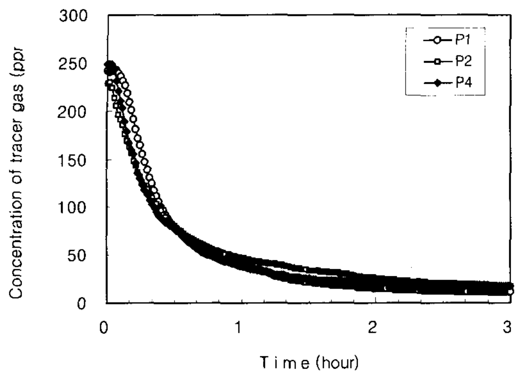

Fig.8 Concentrations by step-down injection. (cooling)

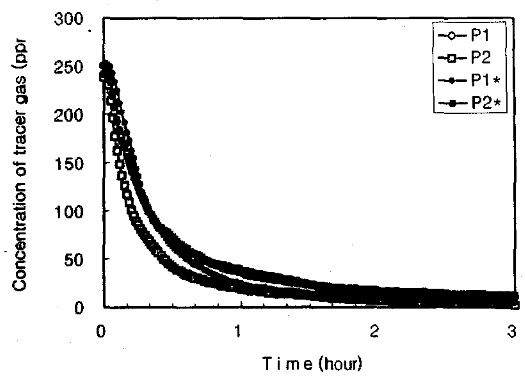

Fig.9 Concentrations with a diffuser installed. (* : *cooling operation*)

Mean temperature difference between supply air and indoor air is approximately 1.8 ℃. Local mean ages and local air change indices are shown in Table 9.

As shown for the isothermal condition, local mean ages are small near the floor and large near the exhaust. The value at P2 is exceptionally small compared to other points for the step-up operation. The concentration decays during a step-down operation are shown in Fig.8. The calculated local mean ages and air change indices are shown in Table 10.

Results by step-up and step-down methods agree to within 12% except at P2. Again, the tracer gas is not well mixed with the room air but reaches the measuring point near the floor earlier than expected. The results by a step-down method are considered to be more reliable since there are fewer problems associated with mixing. Therefore, experiments with a diffuser installed were conducted according to a step-down method only.

4.3 Diffuser

Experiments were repeated with a diffuser installed at the supply for isothermal and cooling conditions. Concentration variations are shown in Fig.9. Table 11 compares the results with and without a diffuser. Local air change index is improved from 0.88 to 0.93 at P1 and from 1.19 to 1.38 at P2 by installing a diffser for an isothermal condition. For a cooling condition, the local air change index increases from 0.81 to 1.05 at P1 and from 0.72 to 0.89 at P2. With a diffuser installed, room air seems to be well mixed with the supply air.

4.4 Room mean age

Room mean ages are obtained from concentration variations at the exhaust according to Equation (3). Table 12 summarizes the overall air change efficiency for various conditions. Air change efficiency under the cooling condition is greater than that for the isothermal condition, regardless of the presence of the diffuser. The lower part of the chamber is filled with cool supply air, and warm air is pushed upwards to the exhaust. The effect of the diffuser on the overall air change efficiency is not significant, however.

5. Conclusions

Table 10 Local mean ages and local air change indices by step-down injection (cooling)

Measurement point	Step-down method	
	Local mean age	Local air change index
P1	2186 sec	0.81
P2	2477 sec	0.72
P4	2109 sec	0.84

Table 11 Local mean ages and local air change indices

Measurement Points		LMA (εp)	
		Without diffuser	With diffuser
Isothermal	P1	2010 sec (0.88)	1897 sec (0.93)
	P2	1490 sec (1.19)	1282 sec (1.38)
Cooling	P1	2186 sec (0.81)	1682 sec (1.05)
	P2	2477 sec (0.72)	1996 sec (0.89)

Table 12 Room mean ages and air change efficiencies

Experiment mode		Room mean age	Air change efficiency
Without diffuser	Isothermal	2525 sec	0.35
	Cooling	2143 sec	0.41
With diffuser	Isothermal	2639 sec	0.34
	Cooling	2051 sec	0.43

Experiments were performed to measure ventilation effectiveness in an underfloor air-conditioning space using a tracer gas. Local mean ages and room mean ages were obtained from the measured concentration variations. The following conclusions were drawn from the air change efficiency data obtained under isothermal and cooling conditions with and without diffusers.

(1) Results obtained by a step-up method and by a step-down method differ by 20%. A step-down method provides consistent results compared to a step-up method, and it does not exhibit a mixing problem due to density difference between the tracer gas and air.

(2) With a diffuser installed, the local air change indices increase at several points, but the overall air change efficiency of the room does not change significantly.

(3) Air change efficiency under cooling supply air conditions is larger by 25% approximately than that under isothermal supply air conditions. The underfloor air-conditioning system provides better ventilation characteristics especially for cooling operations.

Further research is needed to investigate the effects of diffuser type and cooling conditions on ventilation effectiveness, and to improve the technique of measuring ventilation effectiveness using a tracer gas.

Acknowledgments

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