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Effect of Contaminant Source Location on Indoor Air Quality

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Abstract

This paper presents an experimental study for understanding the indoor air quality in a room. A model room, which had a ceiling-mounted supply and a sidewall-mounted exhaust, was used to examine the effect of air exchange rate (AER) and contaminant source location (CSL) as a function of the elapsed time. A tracer gas method, using carbon monoxide tracer, gas analyzers, and a data acquisition system, was applied to study the ventilation air distribution and the tracer removal efficiency, so-called pollutant removal efficiency, in the model room. The experiment was composed of two parts; firstly the AER was varied to examine its effect on the ventilation air distribution and the ventilation effectiveness and secondly both AER and CSL were considered to determine their effect on the pollutant removal efficiency. It was found that the ventilation effectiveness in the model was proportional to AER but not linearly. It was also found that changing the CSL can improve the pollutant removal efficiency. In some cases, the efficiency improvement by increasing AER was achieved by simply changing CSL.

Key words : Contaminant Source Location, Air Exchange Rate (AER), Removal Efficiency, Ventilation Effectiveness, Tracer Gas, Physical Model

1. INTRODUCTION

With development of human civilization the portion of human life spent indoor has been gradually increasing. Many reports show that people spend 80~90% of their time in indoor environments such as living, working, and transportation. It has been pointed out that the indoor air quality is frequently worse than that outdoor (Lolova *et al.*, 1997; Ando *et al.*, 1996; Baek *et al.*, 1995). These findings have made people recognize the importance of indoor air quality (IAQ), and many projects are on the way to improve and maintain the quality of indoor air (Jokl *et al.*, 1993; Parker *et al.*, 1992).

Indoor air pollution today includes various emissions which can be harmful to humans, animals, and properties. Furthermore, the recent rapid increases in industrial development and traffic make ambient air quality worse, which is another possible source of indoor air pollution (Bahnfleth *et al.*, 1987).

Mechanical ventilation has usually been adopted to control the indoor air quality, but minimizing the operational cost has frequently precedent maintaining good IAQ. Building management under this situation often leads to seal building tightly and to recirculate indoor air with relatively small amount of outdoor air, 20~40% (ASHRAE, 1989). This can contribute to sick building syndrome (SBS).

Whenever designing new buildings or improving existing ones, the strategy for IAQ control needs to be considered for health indoor environment and energy efficiency. The purpose of this study is to understand how air exchange rates (AERs) and contaminant source locations (CSLs) affect ventilation effectiveness and pollutant removal efficiency of the ventilation system in a room.

2. THEORY

Common strategies for controlling IAQ are removing pollutants at source, preventing dispersion of emitted pollutants, installing pollutant control devices, and reducing occupant's exposure to the pollutants. Fig. 1 shows that the ventilation is the largest factor related to IAQ problems. This result can be supported by the common use of ventilation for IAQ improvement. For instance, people in domestic dwellings use ventilation to remove smoke emitted inside or to control the temperature or humidity. In this case, ventilation is simply done by opening doors or windows. AER of 0.2 ~ 0.7 ACH is typical in most buildings by means of infiltration (Godish, 1989). Consequently, utilizing ventilation is an effective way to control IAQ, even though all other factors need to be under control too.

Ventilation for IAQ control is a mechanism to remove or dilute emitted pollutants by introducing fresh ambient air to the indoor environment. The quantity of ventilation is expressed as 'ACH', air changes per an hour, which indicates the amount of air being supplied to a room. But the local ventilation is normally different from the room ventilation due to the mixing of indoor air within the outdoor air coming.

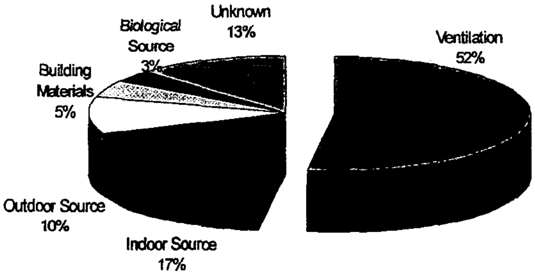

Fig. 1. Factors contributing to IAQ problem. National Institute for Occupational Safety and Health (NIOSH), USA conducted the research for 446 buildings.

In terms of emitted pollutant removal, ventilation can be classified into two types; general ventilation, so-called mixing ventilation, and local ventilation. The former dilutes emitted pollutants into indoor air and then removes them to outside with the supplied air by ventilation system. This method is not effective with pollutants heavier than the normal air. The latter removes emitted pollutants at source, and is used when the pollutants have high toxicity or when general ventilation is not very effective. In this study, a mixing ventilation system has been examined.

The ventilation effectiveness in a model room can be computed by considering the mass balance in a control volume as in Fig. 2 and it gives Equation (1) below (Burges *et al.*, 1989; Godish *et al.*, 1989; Lee, 1994). The supply and exhaust air of a ventilation system contain pollutants.

$$Q_{out}\, C_{out}\, dt + Sdt - Q_{in}\, C_{in} = VdC_{in}$$

In Equation (1), the first term on the left-hand side is the amount of pollutant being supplied with ventilation air into the control volume, the second term is the amount of pollutant being generated inside, the third term is the amount of pollutant being exhausted with air out of the control volume, and the term on the right side is the amount of pollutant being accumulated inside the control volume. To apply Equation (1) to the room, the conditions based on the physical model were modified as described in Lee's previous work (Kim *et*

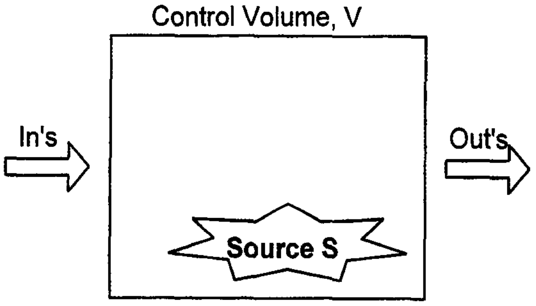

Fig. 2. Pollutant mass balance of control volume in a room.

al, 1993; Lee, 1994).

Because of low pressure difference in the system, Equation (1) can be rewritten by assuming balanced ventilation air flow, ($Q_{in}=Q_{out}=Q$)

$$(S-Q(C_{in}-C_{out}))dt = VdC_{in} \tag{2}$$

Equation (2) then yields Equation (3) and (4):

$$\int\frac{dt}{V}=\int\frac{dC_{in}}{S-Q(C_{in}-C_{out})} \tag{3}$$

$$S-Q(C_{in}-C_{out}) = (S-Q(C(0)-C_{out}))\exp\left(-\frac{Qt}{V}\right) \tag{4}$$

where C(0) is the tracer gas concentration in the control volume at begin of a test, t=0.

Considering a room without contaminant source inside (S=0), Equation (4) can be simplified to Equation (5). This equation shows the possibility to calculate the local ventilation rate at a certain point in a model room by making time serial measurements of tracer gas concentration.

$$Qlocal = -\frac{V}{t}\ln\frac{C_{in}-C_{out}}{C(0)-C_{out}} \tag{5}$$

Equation (4) can be rewritten for the inside concentration, C_{in}, in terms of source emission rate, S, under steady condition, as follows:

$$C_{in}=\frac{S}{Q}\left(1-\exp\left(-\frac{Qt}{V}\right)\right)+C_{out} \tag{6}$$

Adding a term to Equation (6) gives the inside concentration for unsteady source emission below:

$$C_{in}=\frac{S}{Q}\left(1-\exp\left(\frac{Qt}{V}\right)\right)+C_{out}+S_s\exp\left(-\frac{Qt}{V}\right) \tag{7}$$

where C_s is the concentration gas concentration showing the concentration at a certain time when the source emission rate is changed.

3. EXPERIMENT

The physical model was constructed at the Air Pollution Laboratory, University of Seoul, Korea. Fig. 3 shows the small-scale model, 1 m W × 1 m L × 0.5 m H, which represents a simple room with a ceiling-mounted supply and a sidewall-mounted exhaust. To get well distributed ventilation air, a circular type of diffuser was installed to the supply opening and used for all tests.

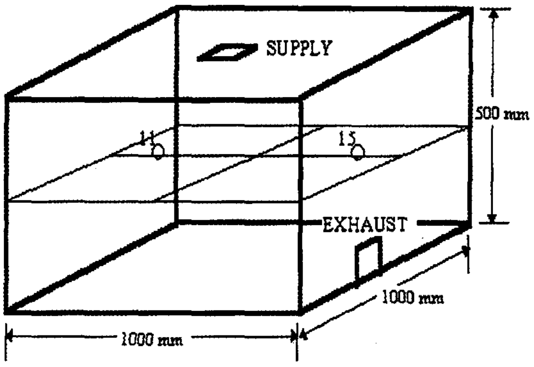

Fig. 3 Physical model room and the CSLs tested.

Carbon Monoxide (CO) was used as a tracer. It was the pollutant of main interest during a previous project because of worker's smoking inside the local operator's room in power plants. It has similar molecular weight (MW=28) to that of the standard air. The risk from CO was eliminated by extracting the exhaust air from the laboratory.

The ventilation system was continuously run in push-and-pull mode with 30% of recirculation, which is commonly used (ASHRAE, 1989), to keep stable air flow pattern in the model. Three air diaphragm pumps were set to supply, exhaust, and recirculate the ventilation air with three flow meters to control the flow rates. The AER was controlled for 2, 4, and 6 ACH which are in the range in practice.

Three CO analyzers (Mcsam series, Kimoto, Japan), applied non-dispersive infrared method (NDIR), were used to monitor the tracer gas concentration during the tests. The signal from the gas analyzers was acquired through an analog-to-digital (A/D) board (Model PCL-718, Advantech, USA) as a function of time. The raw data was analyzed by taking 1-minute-moving average to remove the random noise from the analyzers and the data acquisition system.

Ventilation effectiveness, using tracer decay method, was measured first to find the ventilation air distribution in the model room. To apply Equation (5), the components, V, C_{out}, C(0), were measured first and C_{in} was then monitored as a function of the elapsed time. In this study, the ventilation effectiveness is defined as the ratio of the local AER, which is measured and calculated from the tracer decay method, to the room AER, which is controlled by the ventilation system, and is given as:

$$\mathit{Ventilation\ Effectiveness} = \frac{\mathit{local\ AER}}{\mathit{Room\ AER}} \times 100[\%] \qquad (8)$$

To study the effect of AER and CSL on pollutant removal efficiency within the occupied zone, 25 measuring points were equally spaced in a horizontal plane at mid-height in Fig. 3. Eight points out of those 25 points were selected as CSLs in a half plane because the room had symmetrical geometry along the center line. Two of them were selected to show the CSL effect on the pollutant removal efficiency. One, Pt. 11 in Fig. 3, is in backward of the main air flow from the supply opening and towards the exhaust opening. The other, Pt. 15 in Fig. 3, is in forward of the main air flow which is closer to the exhaust opening. Further analysis including other CSLs will be presented in later publications.

Then the pollutant generation was simulated by emitting tracer gas through a spherical diffuser to conduct the experiment for studying the effect of AER and CSL on the pollutant removal efficiency. All tests were conducted under transient isothermal conditions. Trials to determine the molecular diffusion and the dispersion of the supply air were conducted and the pollutant removal efficiency was measured and expressed by Equation (9) below:

$$\mathit{Pollutant\ Removal\ Efficiency} = \left(1 - \frac{\mathit{Measured\ Conc.}}{\mathit{Calculated\ Conc.}}\right) \times 100[\%] \qquad (9)$$

where 'Measured Conc.' is the result from tracer pulse measurement, and 'Calculated Conc.' is the computed concentration for full mixing in the room.

4. RESULTS AND DISCUSSION

To evaluate the spatial distribution of ventilation effectiveness at the measuring plane of the model, the room ventilation effectiveness was measured by using tracer decay method. Fig. 4 shows the relation between the AER and the ventilation effectiveness. The values 71\%, 75\%, and 81\% represent the averaged ventilation effectiveness corresponding to the AER of 2, 4, and 6 ACH, respectively. The vertical line at the center of each bar shows the distribution of measured effectiveness, which reveals that each AER creates different air flow structure. However the averaged ventilation effectiveness is proportional to the AER, though not linearly. This result implies that an improvement to ventilation effectiveness can be expected with increasing AER, which requires additional resources and cost.

The pollutant generation for the tracer pulse method was simulated under different AER and CSL condition and the measured tracer gas concentrations were plotted in Fig. 5. Each line shows the test result under

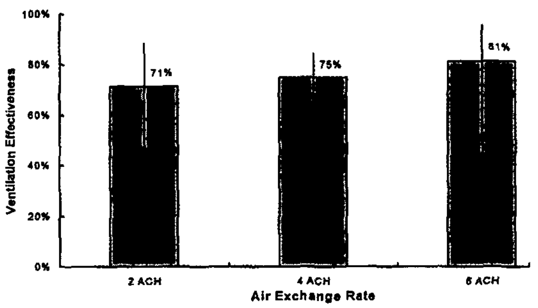

Fig. 4. Ventilation effectiveness in the model room with different AERs, done by tracer decay measurement at the mid-high plane.

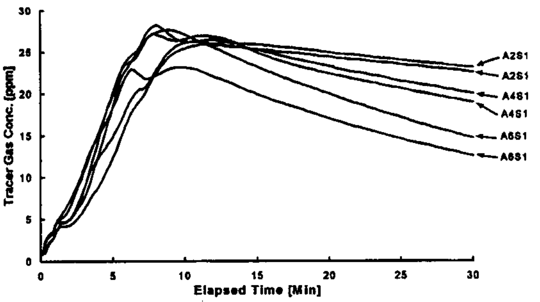

Fig. 5. Mean time serial measurement of tracer gas ceoncentration in the model room. 'A' in the plot means AER and 'S' means CSL in the room. Each line represents the condition as in the order of legend at the end of line.

different AER and CSL condition as in the order of legend at the end of each line. It shows the effect of CSL on the pollutant removal efficiency at a given AER, which is lower tracer gas concentration. It also shows that the difference in tracer gas concentration with different CSL is getting bigger with the AER. This can be read in Fig. 4, which is the effect of high AER. Hence, the trend in Fig. 5 will be different at other CSLs. In other words, the pollutant removal efficiency can be varied by changing the CSL in the indoor space. Comparing the two points in this case shows that the closer the source is to the exhaust the better the pollutant removal efficiency, which is reasonable.

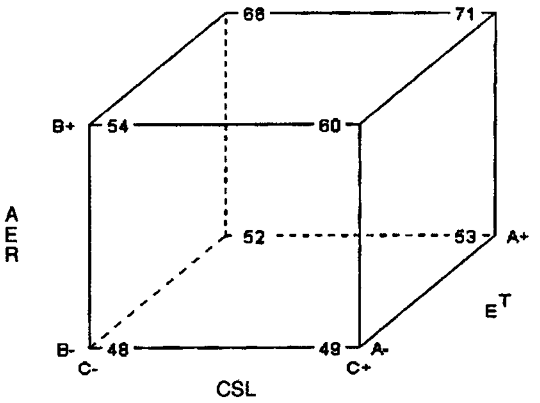

Fig. 6. Cube plot of pollutant removal efficiencies with the factors; AER, CSL, and Elapsed Time. B- means 2 ACH, B+ 6 ACH, C- backward position (Pt. 11 in Fig. 3), C+ forward position (Pt. 15 in Fig. 3) compared to the main air stream in the model room, A- 5 min, and A+ 10 min.

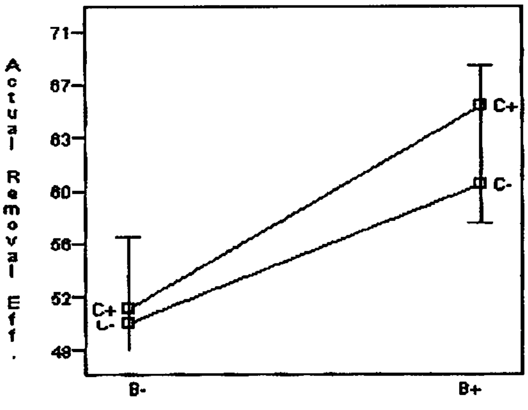

Fig. 7. Interaction between AER and CSL where B- for 2 ACH, B+ for 6 ACH, C- for Pt. 11, and C+ for Pt. 15.

Design Ease, Stat-ease, Inc., USA, was used to carry out 2-level-full-factorial analysis for the three variables at the two center points of the AER and the elapsed time in Fig. 5. The difference in pollutant removal efficiencies with different test conditions are shown in the cube plot, Fig. 6. The axes indicate AER (y), CSL (x), and Elapsed Time (z), respectively. The B- in y-axis represents 2 ACH, the B+ represents 6 ACH, the C- in x-axis represents backward position (Pt. 11 in Fig. 3), the C+ represents forward position (Pt. 15 in Fig. 3) compared to the main air stream in the model room, the A- in z-axis represents 5-min elapsed time, and the A+ represents 10-min. The result for 4 ACH ventilation was inserted as a center point in this analysis. The improvement of pollutant removal efficiency in the model can be seen in the axes of AER, CSL, and Elapsed Time. Two factors, AER and CSL, were selected for further analysis because the Elapsed Time on z-axis is not controllable. Fig. 7

shows the pollutant removal efficiency which considers these two factors. It shows that the pollutant removal efficiency is improved by increasing AER, B- to B+, or by changing CSL, C- to C+, which means that the selection of an optimal CSL in indoor space can be another alternative to improve IAQ rather than modifying the ventilation system. It also implies that the required improvement in pollutant removal efficiency can be reached by combining both factors. In some cases, the improvement by increasing the AER was achieved by simply changing the CSL. Mundt (1994) also experiemented and showed the effect of CSL on ventilation effectiveness in displacement ventilation.

5. CONCLUSION

The effect of two IAQ factors, air exchange rate (AER) and contaminant source location (CSL), were examined through experimentation in a model room which had a ceiling-mounted supply and a sidewall-mounted exhaust. The tracer gas techniques, tracer decay and tracer pulse method using carbon monoxide tracer, gas analyzers, and a data acquisition system, were used to determine the ventilation effectiveness and the pollutant removal efficiency in the model room. It was found that the ventilation effectiveness in the model is proportional to the AER but not linearly. And changing contaminant source location helps to improve the pollutant removal efficiency, which implies that the required improvement in pollutant removal efficiency can be reached by combining both AER and CSL. In some cases the pollutant removal efficiency improvement was achieved by simply changing CSL rather than increasing AER.

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Nomenclature

$C(0)$	Initial tracer gas concentration
C_{in}	Tracer gas concentration in a room
C_{out}	Tracer gas concentration in supply air
Q_{in}	Exhaust air rate
Q_{out}	Supply air rate
S	Pollutant emission rate in a room
V	Volume of a room

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