VERTICAL DISTRIBUTION OF CONTAMINANT CONCENTRATION IN ROOMS WITH FLOOR-SUPPLY DISPLACEMENT VENTILATION

Toshio Yamanaka[1], Ryuji Satoh[2], Hisashi Kotani[3]

[1]Dept. of Architectural Eng., School of Eng., Osaka University, 2-1 Yamadaoka, Suita, Osaka, 565-0871 Japan, Tel : +81-6-6879-7644, Fax : +81-6-6879-7646, yamanaka@arch.eng.osaka-u.ac.jp, http://www.arch.eng.osaka-u.ac.jp/~labo4/index.html
[2]Dept. of Architecture, Faculty of Eng., Osaka Institute of Technology, 5-16-1 Oomiya, Asahi, Osaka, 535-8585 Japan, Tel : +81-6-6954-3350 Fax : +81-6-6957-2132, ryusatoh@archi.oit.ac.jp
[3]Dept. of Architectural Eng., School of Eng., Osaka University, 2-1 Yamadaoka, Suita, Osaka, 565-0871 Japan, Tel : +81-6-6879-7645, Fax : +81-6-6879-7646, kotani@arch.eng.osaka-u.ac.jp, http://www.arch.eng.osaka-u.ac.jp/~labo4/index.html

Summary
The experiment to know the vertical distribution of contaminant concentration emitted from human body was conducted by means of scaled room with floor supply ventilation system. From the result of the experiment, simple zonal models for displacement flow and semi-displacement flow were constructed. The comparison between measured concentration and the predicted concentration leads to the proof of the validity of these models for the practical design based on IAQ for occupants.

Introduction

The displacement ventilation system can enable the excellent ventilation effectiveness for the pollutant from occupants like carbon dioxide or bioeffluents especially. Usually specific diffusers are installed along the walls for this kind of ventilation. In offices, however, the area of the room is sometimes so large that wall is far from the occupants. In order to keep good air quality in the center of a large office, the best way is to supply fresh air through the floor. Fortunately, modern office rooms often have raised floors for wiring, and this under-floor space can be used as a supply air chamber. In Japan, this type of floor-supply air conditioning system is getting popular for office buildings. The floor-supply air-conditioning system is normally designed for the purpose of comfortable thermal environment of the occupants, but it is necessary to design this ventilation system from the point of view of IAQ. This floor supply air conditioning system can be referred to as "floor supply displacement ventilation" in this meaning. As the effectiveness of the floor supply displacement system has not been studied enough, the authors aimed to investigate the vertical distribution of contaminant concentration inside the room and make the calculation model to predict the concentration distribution. Although many kinds of diffusers are used for supply openings in the floor, simple circular openings are selected for the basic study.
In this paper, the result of the experiments with a scaled room and the simple zonal model of airflows inside the room are presented to show the validity of this model to predict the contaminant distributions inside the room ventilated by floor-supply ventilation system.

Experimental Setup

The scaled experimental room was used. Figure 1 shows the outline of experimental room. The scale of the model is 0.731, and the other physical variables are scaled so that Reynolds number *Re* and Archimedes number *Ar* are the same as the actual room. The scale factors are listed on Table 1.

Table 1 Scale factors of various variables

Geometry	0.731
Velocity	1.37
Volume airflow rate	0.731
Temperature difference	2.56
Heat transfer rate	1.87

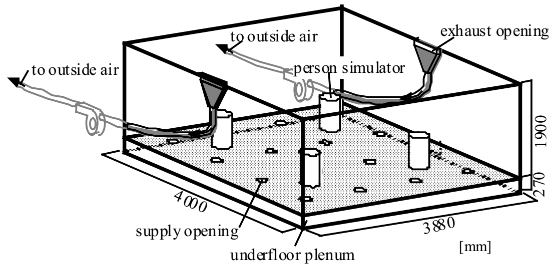


Figure 1 Outline of the experimental room.

This experimental room has 16 supply openings on the floor, and the conditioned air is supplied in the chamber under the floor. Four person simulators were arranged on the floor, and the heat emission rate of each person simulator is 187 W, which correspond to 100W of actual person. The actual size of this simulator (Mundt, 1996) is a cylinder whose diameter is 0.4m with a height of 1.0m. The experimental conditions are listed on Table 2. Two kinds of ventilation rate correspond to two different presumed interface height in the case of displacement ventilation. The higher presumed interface height is 1.3 m and the lower presumed interface height is 0.80. Carbon dioxice was injected at the tops of person simulator as a tracer of bioeffluent of occupants. The emission rate of carbon dioxide is 45 L/h for one person simulator. After steady state was achieved, the profiles of temperature and CO_2 concentration were measured at many points inside the room, and in addition the vertical distribution of center velocity of a jet from one of the supply openings was measured.

Table 2 Experimental conditions.

title of condition	ventilation rate	throw*	diameter of supply opening
(ventilation rate)-(throw)	[m^3/h]	[m]	[mm]
S-S	(S) 210.4	(S) 0.40	131
S-M		(M) 0.85	72.7
S-L		(L) 1.49	45.6
L-S	(L) 315.6	(S) 0.73	122
L-M		(M) 1.41	67.3
L-L		(L) 1.70	56.3

*throw : distance from the supply opening to the height where the center velocity becomes 0.25 m/s

Results

The temperature difference between the supplied jet and the ambient air is 3.8 K in the case of lower ventilation rate (210.4 m^3/h) , 2.6 K in the case of higher ventilation rate (315.6 m^3/h). Figure 2 shows the profile of CO_2 concentration. The concentration is the mean value of five points inside the room and the value was normalized. This figure shows the short throw of the supply jet bring the displacement flow with almost fresh air in the lower zone near the floor (case S-S and L-S). The other conditions make the concentration in the lower zone polluted to some extent. This is considered to be caused by the turbulent flow induced by the long throw of the jet through supply openings. These profiles imply there is some down flow from the upper zone to the lower zone conveying contaminant across the contaminant interface. These types of ventilation have an advantage of rather uniform temperature gradient which can avoid thermal discomfort of occupants resulted from large temperature difference between head and foot.

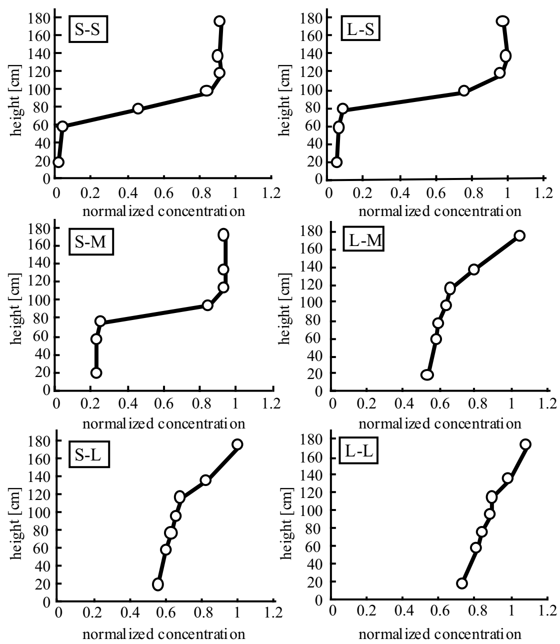


Figure 2 Vertical distribution of contaminant

Models

The vertical distributions of the contaminant were modeled except the case L-L as are shown in Figure 3. There are two kinds of flow model. One is “displacement ventilation” and the other is “semi-displacement ventilation”. “Displacement ventilation” is applied providing the maximum throw of the jet is shorter than the contaminant interface where total airflow rate in plumes is equal to ventilation rate. When the maximum throw is longer than the height of contaminant interface, the jet will destroys the interface and bring the pollution to lower zone.

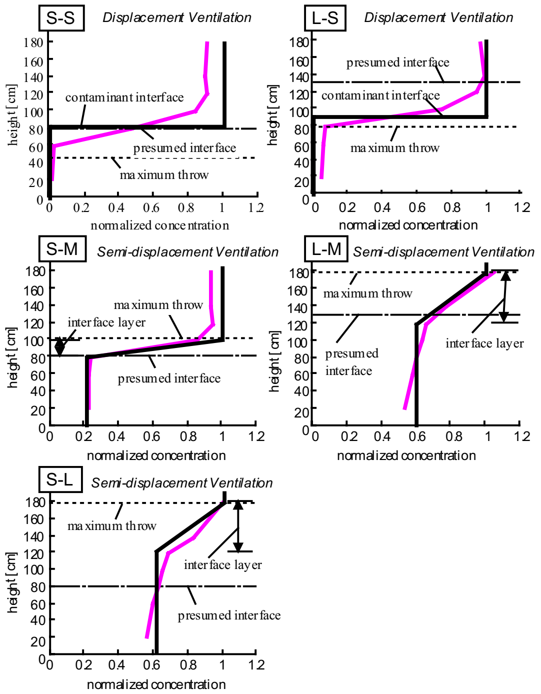


Figure 3 Models of contaminant distribution

The profiles of velocity on the central axis of jets are shown on Figure 4. It can be said that the maximum throw (where velocity gets to zero) can be calculated by the equation of non-isothermal jet (Koestel, 1954). The maximum throw of non-isothermal jet can be calculated by the following formula.

$$X_{mt} = D_o \left(\frac{K}{1.9 A_r} \right)^{\frac{1}{2}}$$

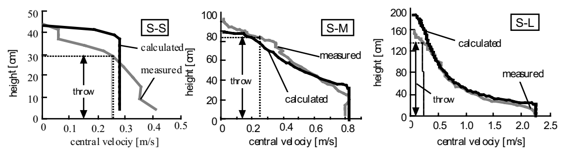


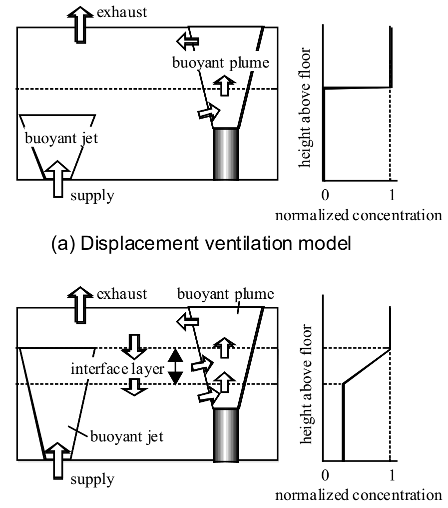
Figure 4 Profile of central velocity of jet

Figure 5 shows the zonal models based on the concentration models in Figure 3. Displacement ventilation model is the simple model presented before (Nielsen, 1993). Semi-displacement model is original one. In this model, the top of interface layer is located at the same height as maximum throw, and the concentration of the airflow from the interface layer to buoyant plumes is assumed to be the average value of the upper zone concentration and the lower zone concentration. The down flow rate is defined as the surplus flow rate of the plume flow at the top of interface layer :

$$V_e = V_p(X_{mt} - H) - V_S$$

The normalized concentration in the lower zone can be calculated by the following equation.

$$C_L = \frac{2V_e - nV_p(X_{mt} - H) + nV_p(X_{mt} - W - H)}{nV_p(X_{mt} - H) + nV_p(X_{mt} - W - H)}$$



(a) Displacement ventilation model

(b) Semi-displacement ventilation model

Figure 5 Two models for calculation

The plume flow rate of a person simulator can be predicted by the following equation which is the regression line in Figure 6.

$$V_p(h) = 166.2\,h + 47.36$$

The plume flow rate in Figure 6 means calculated values by means of the presented model, not measured values.

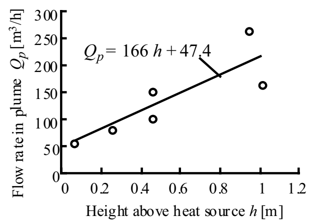


Figure 6 Volume flow rate in thermal plume

There is a problem to estimate the width of interface layer. Figure 7 shows the relationship between the down flow rate and the width of interface layer. From this figure, the regression line can be determined as,

$$W = 0.000956\, V_e\ .$$

If it is assumed that W can be determined only by the down flow velocity, the following equation can be written.

$$W = 53.4\ U_e$$

If it is converted to the actual room size,

$$W = 28.5\ U_e$$

can be obtained.

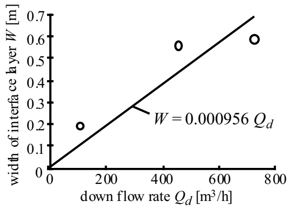


Figure 7 Relationship between down flow rate and width of contaminant interface layer

Discussion

The measured distributions of contaminant concentration and calculated ones are compared in Figure 8. In the case of L-L, the predicted maximum throw is longer than the ceiling height so that the there is no applying any models (except for perfect mixing model). From this figure, it can be concluded that the calculated concentrations are almost equal to the measured values. The presented models are applicable to the prediction of vertical distribution of contaminant concentration in the room with displacement or semi-displacement ventilation achieved by floor supply ventilation system.

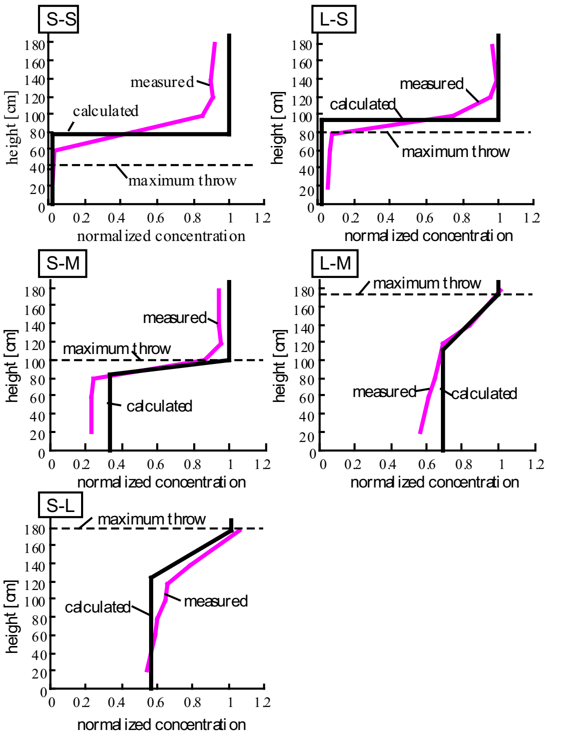


Figure 8 Comparison between experimental concentration and calculated concentration.

Conclusion

The semi-displacement ventilation flow is made when the maximum throw of the supply jet is longer than the contaminant interface of displacement ventilation, and the simple zonal models can be valid to predict the concentration distribution practically. The applicability to the general conditions with different room sizes or many kinds of diffusers should be examined before the establishment of practical design method for floor-supply ventilation system.

Acknowledgement

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Nomenclature

W : width of interface layer [m]
V_S : Ventilation rate [m³/h]
V_e : down flow rate [m³/h]
U_e : down flow velocity [m/s]
$V_p\ (h)$: airflow rate in the thermal plume above a person simulator at the height h from the top of the simulator [m³/h]
X_{mt} : height of maximum throw (top of interface layer) [m]
h : height above top of person simulator [m]
n : number of person simulators
H : height of person simulator [m]
D_0 : diameter of supply opening
K : throw constant (=5.0)
A_r : Archimedes number ($Ar=Gr/Re^2$)
G_r : Grashof number
R_e : Reynolds number
C_L : concentration of bioeffluent contaminant (tracer gas) in lower zone (occupants zone)

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