Ventilation Effectiveness of Ceiling-Supplied Displacement Ventilation System for Office Room (Part 1) Comparison of Temperature and Contaminant Concentration Distributions under Different Ventilation Systems using Full-Scale Experimental Chamber

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Abstract. It is recognized that the displacement ventilation is a superior ventilation system for the infection prevention. There is, however, a problem for displacement system that the space for diffusers and vertical duct is needed. If it is possible to install the supply diffuser on the ceiling, the flexibilities of the supply diffuser layout will be increased, which will make the displacement ventilation more easily used.The aim of this study is to develop a novel ceiling supply displacement system using a large supply diffuser with honeycomb to straighten the airflow and make the low velocity air supply. In this study, the effect of supply velocity on the distribution of concentration of the gaseous contaminant emitted from person simulators was examined by full-scale model experiment.CO2 was used as a tracer gas, and three types of ventilation system were tested using the full-scale model chamber. As a result, the novel ceiling diffuser brought the value of 0.3~0.4 of exhaust concentration, depending on the supply flow rate. It can be said that the ceiling-supplied ventilation system developed with a novel supply diffuser can accomplish quite higher ventilation effectiveness than mixing ventilation even if it is not a perfect displacement ventilation.

1 Introduction

Displacement ventilation is well known as an efficient ventilation with high ventilation system especially for the contaminant originated from human such as bio-effluent or infectious droplet nuclei. Nevertheless large supply diffuser on the floor is needed for normal displacement ventilation, which often makes it expensive and difficult to apply to usual office air conditioning system.

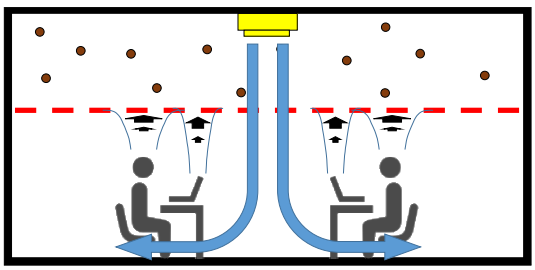

Fig. 1. Schematic outline of ceiling-suppled ventilation.

So the authors propose the novel displacement ventilation system, the ceiling-supplied displacement ventilation system for office room as shown in Fig.1. So far, the ceiling-supplied displacement ventilation have been used for commercial kitchen by Kondo et al.[1] and Kosonen[2] etc . But for general office room, there seems to be no examples before, except for displacement ventilation with chilled ceiling or diffuse ceiling ventilation system, e.g. Peterson et al.[3] or Su [4].

In the case of this system, it is foreseen that the entrainment of the contaminated air into the buoyant jet from ceiling carry the contaminant down to the occupancy zone. In order to avoid this kind of contamination, new supply diffuser with low speed and low turbulence supply airflow was developed.

In this study, the experiment using full-scaled chamber was conducted to test the vertical distribution of temperature and concentration of tracer gas (CO_2) simulating bio-effluent and infectious droplet nuclei. The effect the parameters, supply airflow rate and diffuser type (ceiling supply, near-floor supply and ceiling anemostat diffuser) were made clear, and the possibility of the ceiling-suppled displacement ventilation for office room will be discussed.

2 Experiment

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2.1 Experimental set-up

The experimental chamber is shown in Fig.2. The chamber is supplied with fresh air through the air duct and supply air diffuser. The temperature and airflow can be controlled by AHUs at an arbitrary temperature. As a supply air diffuser, three types of differs were prepared; (Case C) ceiling supply opening for displacement ventilation, (Case F) ceiling supply opening with vertical insulated duct for near-floor supply for displacement ventilation, (Case M) anemostat diffuser for mixing ventilation, as are shown in Fig.3. The ceiling supply diffuser was newly developed for the achievement of ceiling-supplied displacement ventilation as Fig.3(a), which includes honeycomb-shaped rectifying grid with the diameter of 13mm and the depth of 26mm for reducing the turbulence and the size of turbulent scale.

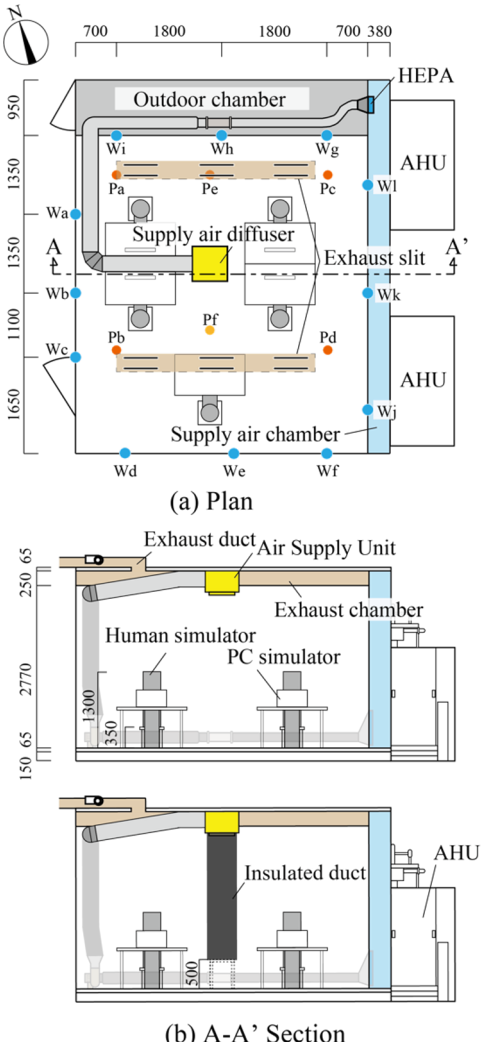
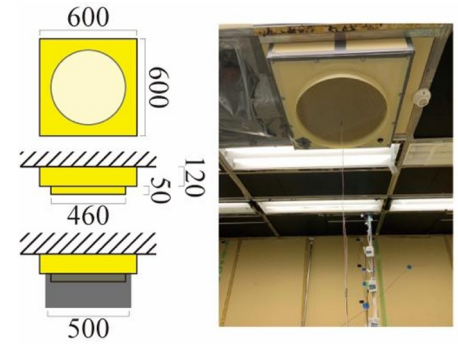


Fig. 2. Plan and Section of Experimental Chamber.



(a) Ceiling Supply Diffuser for Displacement Ventilation

(b) Ceiling Supply Diffuser with Vertical Duct for Near-Floor Air Supply (left)
(c) Anemostat diffuser for Mixing Ventilation (right)

Fig. 3. Three Kinds of Supply Openings for Each Supply Type.

2.2 Measurement method of temperature and CO_2 concentration

Air temperature and wall surface temperature were measured by T-type thermocouple and CO_2 concentration was measured by portable CO_2 analyzer (RTR-576, T&D Corporation) at many points inside the chamber. The vertical distribution of measurement points in the chamber were shown in Fig.4. As for the measurement of CO_2 concentration of supply and exhaust air, handheld CO_2 Meter (GM70, Vaisala) was used. The locations of the measurement of temperature are shown in Fig.2(a) (Pa~Pf for air temperature and CO_2 concentration, and Wa~Wl for wall surface temperature.) In addition, the vertical temperature distribution below the center of each supply opening

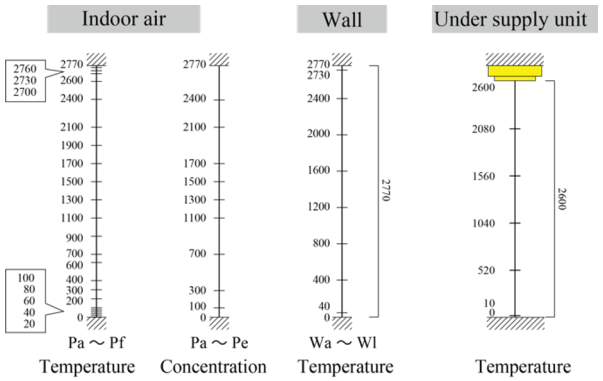


Fig. 4. Measurement Points of Temperature and CO_2 Concentration.

was measured including inside the vertical duct for near-floor air supply.

The averaging time for each measurement data was determined to be 30 seconds. After the attainment of steady state condition both thermally and from the viewpoint of CO_2 concentration, the data was used for averaging.

2.3 Experimental conditions

The experimental conditions were listed in Table 1. In total nine cases were tested in the period from January through June.

For each supply opening, three airflow rates of 400, 600 and 750 m^3/h were tested. As there are five person simulators, the airflow rate for one person is 80, 120 and 150 m^3/h respectively.

During the experiment, supply air temperature was controlled in order to minimize the heat transfer rate through the outer walls, so the supply temperature was changed according to the temperature around the chamber.

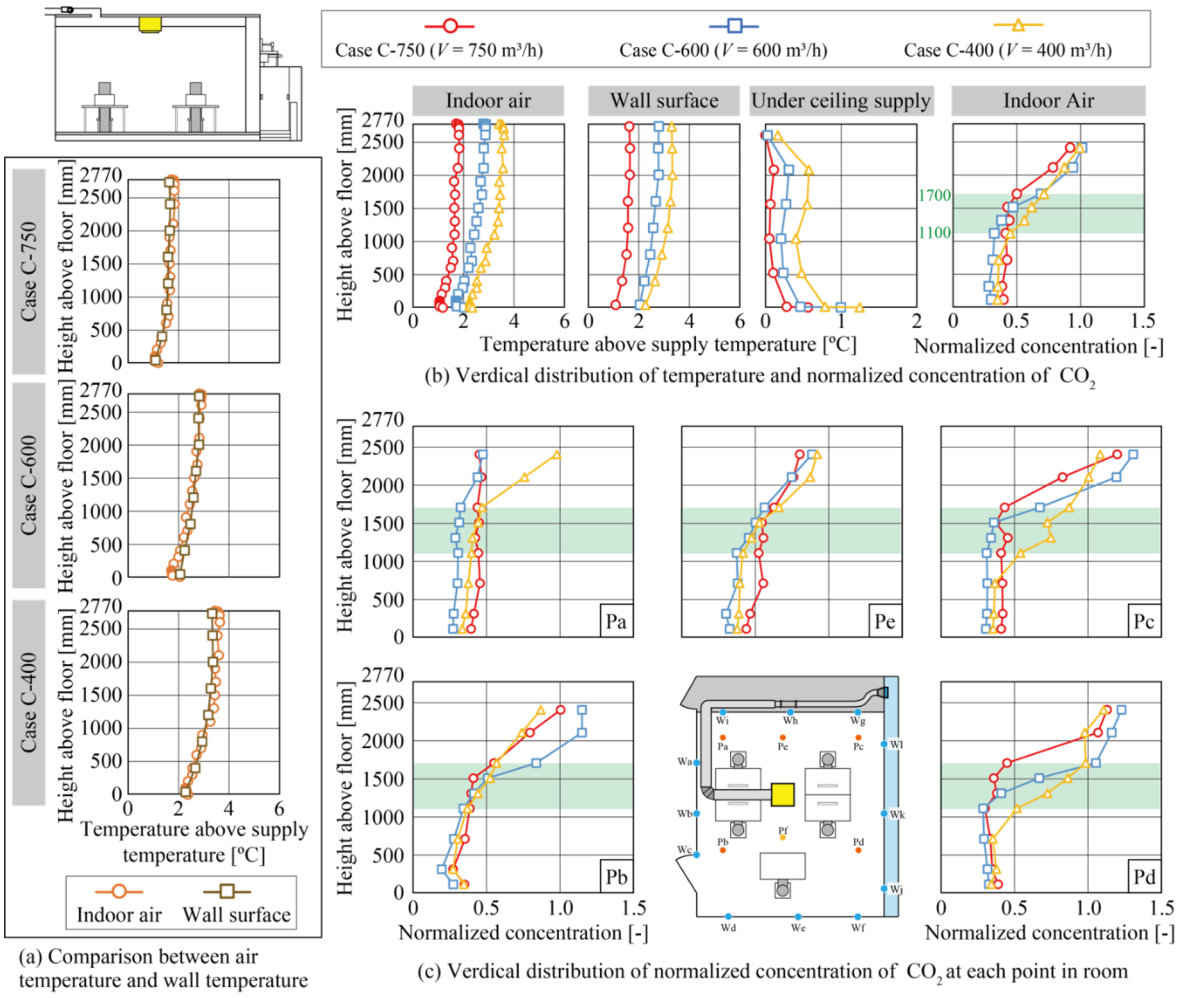
Table 1. Experimental Conditions.

	Supplyw	Airflo rat e V [m^3/h]	Experiment time
Case C-750	Ceiling supply	750	Summer (June)
Case C-600		600	
Case C-400		400	
Case F-750	Near-floor air supply	750	Winter (January)
Case F-600		600	
Case F-400		400	
Case M-750	Anemostat diffuser	750	Spring (May)
Case M-600		600	
Case M-400		400	

3 Result of experiment

3.1 Temperature and CO_2 concentration

In Fig.5 and Fig.6, the vertical distribution of air and wall surface temperature and CO_2 concentration in the chamber at each location.



(a) Comparison between air temperature and wall temperature

(b) Verdical distribution of temperature and normalized concentration of CO_2

(c) Verdical distribution of normalized concentration of CO_2 at each point in room

Fig. 5. Comparison of Vertical Distribution of Temperature and CO_2 Concentration in the Case of Ceiling Supply Diffuser for Displacement Ventilation under Different Supply airflow Rate (Case C).

The measured CO_2 concentration was normalized by the following equation:

$$C_p^* = \frac{C_p - C_s}{C_e - C_s} \quad (1)$$

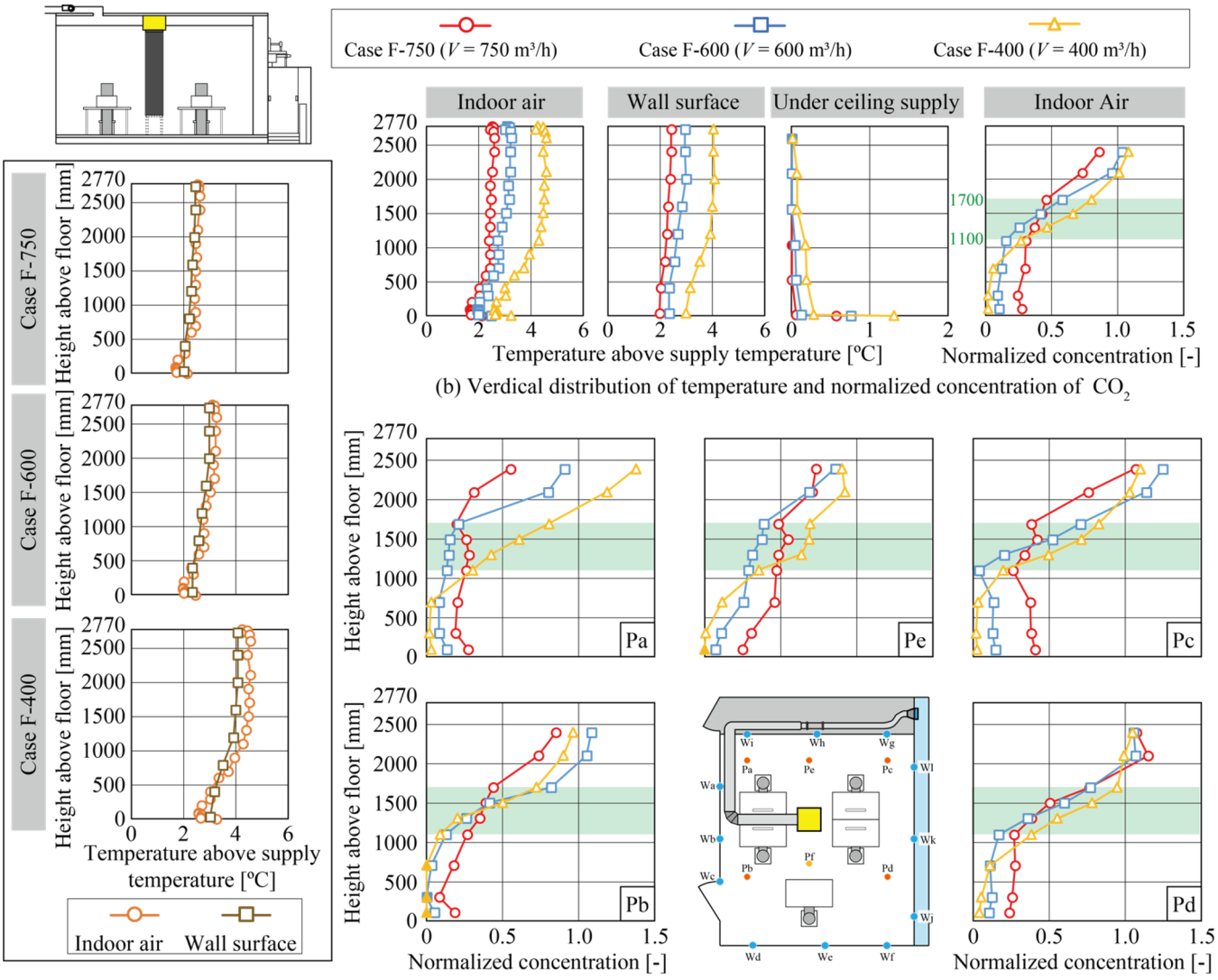
Here,
C_p^* : normalized CO_2 concentration measured at a certain point p in room
C_p : measured CO_2 concentration at a certain p in room
C_s : supply CO_2 concentration
C_e : exhaust CO_2 concentration

On the other hand, temperature is expressed by the difference between the measured temperature and supply air temperature (temperature above supply temperature).

From Fig.5(a), it can be seen that the air temperature inside room is almost equal to the inside wall surface temperature at any airflow rate in the case of ceiling supply diffuser (Case C), and the temperature gradient of air is the larger as the airflow rate is the smaller. Four figures in Fig.5(b) show the vertical distribution averaged by many locations of the same height in room. From Fig.5(b) and (c), there is not such a large difference in CO_2 concentration at occupancy zone caused by supply airflow rate, but the height of contaminant interface is the lower if the airflow rate is the smaller.

The important thing is that the normalized concentration of CO_2 (0 means supply concentration and 1 means exhaust concentration) is around 0.3~0.4 in the occupancy zone in the case of ceiling supply decreased to the same ratio of 0.3~0.4. This is not the case of ideal value of displacement ventilation, but means that the ceiling supply diffuser has quite a high ventilation efficiency.

Fig.6 show the case of the ceiling supply diffuser with vertical insulated duct for near-floor air supply. It is clear that near-floor air supply brings lower concentration at the occupancy zone than ceiling supply ventilation system. Additionally, the smaller airflow rate enables the occupancy zone concentration almost zero, especially 400 m^3/h. The large ventilation rate will make a strong airflow along the floor that will go up straight at the inside wall stirring contaminated air at the higher



(a) Comparison between air temperature and wall temperature

(b) Verdical distribution of temperature and normalized concentration of CO_2

(c) Verdical distribution of normalized concentration of CO_2 at each point in room

Fig. 6. Comparison of Vertical Distribution of Temperature and CO_2 Concentration in the Case of Near Floor Air Supply for Displacement Ventilation under Different Supply airflow Rate (Case F).

zone, which might bring the contamination at lower zone.

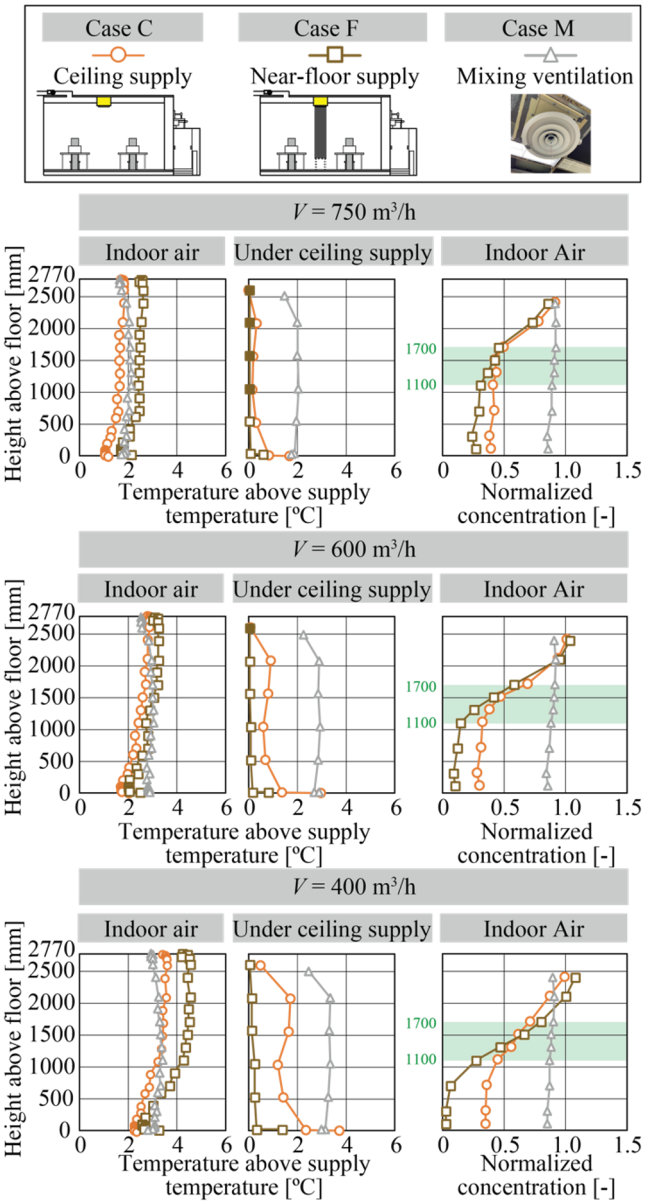


Fig. 7. Comparison of Ceiling Supply Opening Type in Vertical Distribution of Temperature and CO_2 Concentration under Different Supply airflow Rate (averaged data of many measurement points with the same height in room).

3.2 Overall comparison between three types of air supply systems

In Fig.7, vertical distributions of air temperature in room, air temperature below ceiling supply diffuser and CO_2 concentration are shown at different airflow rate to compare the results of three supply diffuser types. As for temperature gradient of indoor air, the case of near-floor supply shows the largest gradient and the next is ceiling supply, while the case of anemostat differ shows the finest gradient. It can be said that even if the ceiling supply was used, it is possible to form indoor temperature stratification necessary for displacement ventilation. It is understandable that a lower airflow rate would reasonably increase the temperature stratification in any supply types. Regarding the temperature distribution below the center of ceiling supply diffuser, the temperature in the vertical duct is almost the same as supply air temperature and the case of mixing ventilation brings the higher and uniform temperature distribution.

4 Discussion

In Fig.5, there can be seen an asymmetry of the vertical distributions of normalized CO_2 concentration between Pa and Pc. This asymmetry seems to be brought by two factors, one of which is the effect of supply duct on the ceiling shown in Fig.2(a) and the other is the effect of supply air chamber on the left side of AHU in Fig.2. It can be possible that there is some horizontal airflow bringing CO_2 gas from the left side to the right side of the room, that is, from Pa to Pc, at higher zone in the room. However, this horizontal airflow was not confirmed by observation yet.

In Fig.5, the complex effect of airflow rate can be seen. At most location in room, the normalized concentration of CO_2 in the case of 600 m^3/h shows the lowest concentration in the occupancy zone. At the colored middle height, however, the case of 750 m^3/h shows the lowest values. This tendency seems to be caused by the mixed result of two effects of supply airflow rate. That is, the high supply airflow rate entrains contaminant (CO_2) in the upper zone and bring the contaminant to lower zone, but at the same time high airflow rate push up the contaminant interface height. It can be presumed that there is an optimum solution for the supply airflow rate in the case of ceiling supply displacement ventilation. This is the most interesting but most difficult design problem.

As the theoretical temperature in the room under perfect mixing without any heat loss through room envelopes are 2.5, 3.1, 4.6 ºC at 750, 600, 400 m^3/h respectively, there seems to be some amount of heat loss through the envelopes. This heat loss implies the existence of downdraft along the walls. In the case of ceiling supply diffuser, a slight temperature rise after supply can be seen in Fig.7 at the airflow rate of 400 and 600m^3/h, though not as high as in the mixing ventilation case.

In terms of contaminant distribution in Fig.7, the near-floor supply can achieve typical distribution of contaminant concentration, that is zero at the lower zone and the highest at higher zone in the room at 400 m^3/h. However, at large airflow rate as 750 m^3/h, the concentration becomes a little high as 0.25, which was considered to be brought by the impinging supply jet with high momentum going upward along the wall and make some circulating airflow in the room. In the case of mixing ventilation with anemostat diffuser, contaminant concentration is vertically uniform and equal to be the exhaust concentration. The slight discrepancy of the concentration of the concentration near ceiling seems to be caused by some error of measurement.

As for the case of ceiling supply diffuser developed for this study, it can be said that semi-displacement ventilation is formed in room. The normalized concentration is around 0.3 at the height of mouth of human simulator (1100mm+FL). This means ventilation requirement can be decreased to 1/3 for this room with this ceiling supply diffuser.

5 Conclusion

As a conclusion, it is turned out that using the developed ceiling supply diffuser with low turbulence intensity and short turbulent scale the semi-displacement ventilation with high ventilation efficiency of more than 3 of contaminant removal effectiveness at the height of the mouth of sitting persons under the airflow rate ranging from 400 to 750 m^3/h for five persons.

The ventilation performance of the ceiling supply displacement ventilation is determined by the entrained air into the downward jet from a ceiling supply differ. This entrainment air ratio will be affected by the supply air velocity, supply air turbulent energy and scale of turbulence etc. The velocity distribution will be also important. The authors intend to examine various parameters at supply air characteristics which affect the ventilation performance by CFD etc.

In the following (Part.2), result of a parametric study on the indoor environment examined by CFD analysis will be presented.

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