Airflow Characteristics in Room with Hybrid Air-conditioning System of Task Air Supply and Natural Ventilation

Eunsu Lim[1], Kazunobu Sagara[1], Toshio Yamanaka[1], Hisashi Kotani[1], Masashi Yamagiwa[2], Susumu Horikawa[3], Tomoaki Ushio[3]

[1]Div. Architecture of Engineering, Osaka University, Osaka, Japan
[2]THE KANSAI ELECTRIC POWER CO., INC
[3]NIKKEN SEKKEI LTD.

lim_eunsu@arch.eng.osaka-u.ac.jp

SUMMARY

The mechanism of the structure of indoor air environment and thermal environment in the hybrid air-conditioned office room is investigated by the measurement with the pulse method of tracer gas and CFD analysis. The room is air-conditioned by under-floor air supply outlets for task zone and the ambient zone is naturally ventilated by the special ventilation openings located below the ceiling near the window. Local mean age of air, CRI3 (contribution ratio of indoor climate No.3) and SVE4 (scale for ventilation efficiency No.4) were calculated by means of tracer gas pulse method to investigate the distribution characteristics of fresh outdoor air in the room. In addition, CFD analysis was conducted for the measured room. The simulated values showed good agreement with the measured values, and the effect of the outside wind direction and outdoor temperature on the air streams in the office room were examined by CFD.

INTRODUCTION

The target building has hybrid air-conditioning system of task air supply and natural ventilation [1]. The building was designed so as to make an effective use of the prevailing wind from the west and that is located in Osaka, Japan. In middle season, the task zone around the occupants is air-conditioned by task outlet on the floor and the general ambient zone is air-conditioned by natural ventilation. Fig. 1 shows the floor plan of the office room. There are 20 natural ventilation openings in total on each floor; 6 in the east, 4 in the west, 2 in the south, and 8 in the north. They are all

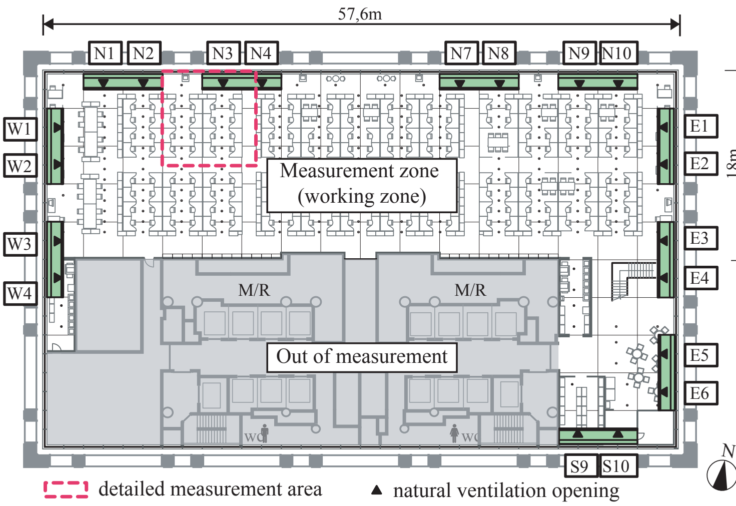

Fig. 1 Plan of office floor (30th floor)

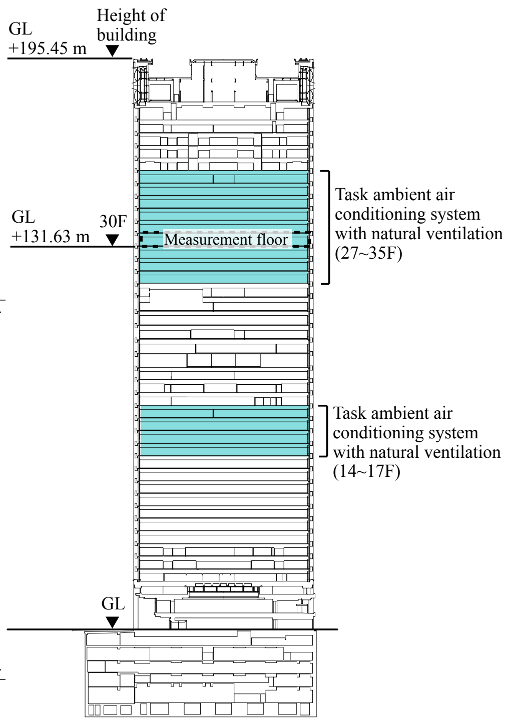

Fig. 2 Section of building

installed on the ceiling near the windows. There are 226 task outlets on the floor. One task floor outlet is provided for each person in principle. Fig. 2 shows the section of the entire building. Natural ventilation is introduced to 14 – 17th floors and 27 – 34th floors, and the object of measurement is the 30th floor (GL + 131M). In this paper, based on the results of measurement and CFD analysis, the influence of each supply opening on the airflow around the occupants will be investigated.

DEFINITION AND MEASUREMENT OF VENTILATION INDICES

Definition

・Local mean age of air for the specific supply opening [2]

The local mean age of air is defined as the average time of air to travel from the supply opening to the measurement point *P* in the room. The mean age at point *P* is expressed by the following equation. This index is different from the normal index of local mean age of air.

$$\bar{\tau}_{ip} = \frac{\int_0^\infty t \cdot A_{ip}(t)dt}{\int_0^\infty A_{ip}(t)dt} \quad (1)$$

where :

$A_{ip}(t)$: the number of molecules arriving at the point *P* from the *i*-th supply opening after the elapsed time *t*

・Scale for Ventilation Efficiency No.4 (SVE4 [3])

$$SVE4(P,i) = C_i(P) / C_{i0} \quad (2)$$

where:

$SVE4\ (P,i)$: contribution ratio of the *i*-th supply opening at the point *P*

$C_i(P)$: concentration at the point *P* where tracer is generated at the *i*-th supply opening at generation rate *q* (m^3/s)

C_{i0} : concentration of the tracer at the *i*-th supply opening, $C_{i0}=q / Q_i$

q : tracer gas generation rate at the *i*-th supply opening (m^3/s)

Q_i : air flow rate at the *i*-th supply opening (m^3/s)

・Contribution Ratio of Indoor climate No.3 (CRI3 [4])

$$CRI3_i(P) = \Delta T_i(P) / \Delta T_{total}(P) \quad (3)$$

where:

$\Delta T_i(P)$: for heat sink $(W_i < 0, \Delta T_i(P) < 0)$, temperature drop at a point *P* with the *i*-th heat sink of W_i

$\Delta T_{total}(P)$: for heat sink $(W_i < 0)$, absolute value of temperature drop at a point *P* with all the heat sinks including virtual heat sinks in exhaust openings

Measurement of ventilation indices by tracer gas pulse method

・Local mean age of air for the specific supply opening

Usually, in order to measure the local mean age of air by pulse method, a bulk of tracer gas is injected into the air in the duct supplying. In the measurement of this research, however, the tracer gas was emitted in each supply opening. Local mean age of air for the specific supply opening is expressed by the following equation.

$$\bar{\tau}_{ip} = \frac{\int_0^\infty t \cdot C_{ip}(t)dt}{\int_0^\infty C_{ip}(t)dt} \tag{4}$$

where :

$C_{ip}(t)$: the concentration response of tracer gas at the point P at time t after the pulse of volume v (m^3) is generated at the i-th supply opening

v : tracer gas emission volume at the i-th supply opening (m^3)

・Scale for Ventilation Efficiency No.4 (SVE4)

$R_{ip}(t)$ is concentration response at the point P after the unit pulse input of tracer gas is generated at the i-th supply opening. $R_{ip}(t)$ is given by equation (5).

$$R_{ip}(t) = \frac{C_{ip}(t)}{v} \tag{5}$$

The $SVE4$ (P,i), which is contribution ratio of the i-th supply opening at the point P, is developed by the following.

$$SVE4(P,i) = \frac{C_i(P)}{C_{io}} \tag{6}$$

$$= \frac{\int_0^\infty q \cdot R_{ip}(t)dt}{q / Q_i} \tag{7}$$

$$= \int_0^\infty Q_i \cdot R_{ip}(t)dt \tag{8}$$

Substitution of the equation (5) in equation (8) leads to equation (9)

$$SVE4(P,i) = \int_0^\infty Q_i \cdot \frac{C_{ip}(t)}{v} dt \tag{9}$$

・Contribution Ratio of Indoor climate No.3 (CRI3)

CRI3 is intended to be calculated by the CFD analysis, but it can be calculated by the measurement with tracer gas pulse method. When the air supplied from the i-th supply opening is a factor of the temperature drop at point P in a room, supplied heat rate W_i at the i-th supply opening is given as

$$W_i = c\rho(\theta_i - \theta_e)Q_i \tag{10}$$

where :

θ_i : supply air temperature (°C)

θ_e : exhaust air temperature (°C)

Q_i : air flow rate at the i-th supply opening (m^3/s)

$c\rho$: volumetric specific heat (J/m^3°C)

Response of heat rate to the pulse input W_i can be written by equation (11).

$$c\rho\theta_{ip}(t) = W_i dt \cdot R_{ip}(t) = c\rho(\theta_i - \theta_e)Q_i dt \cdot R_{ip}(t) \tag{11}$$

where :

$\theta_{ip}(t)$: temperature change by the supplied air at the point P at time t after the pulse of heat $W_i \cdot dt$ is generated at the i-th supply opening

On steady supplied heat rate from the i-th supply opening i, the temperature change at point P is defined by the equation below.

$$\Delta\theta_{ip} = \int_0^\infty \theta_{ip}(t)dt = \int_0^\infty (\theta_i - \theta_e)Q_i \cdot R_{ip}(t)dt \tag{12}$$

CRI3 by the i-th supply opening at the point P is developed by the following.

$$CRI3_i(P) = \frac{\Delta T_i(P)}{\Delta T_{total}(P)} = \frac{\Delta\theta_{ip}}{\sum_j \Delta\theta_{jp}} \tag{13}$$

$$= \frac{\int_0^\infty (\theta_i - \theta_e)Q_i \cdot R_{ip}(t)}{\sum_j \int_0^\infty (\theta_i - \theta_e)Q_j \cdot R_{jp}(t)} \tag{14}$$

Substitution of the equation (5) in equation (14) leads to equation (15).

$$CRI3_i(P) = \frac{\int_0^\infty (\theta_i - \theta_e)Q_i \cdot \frac{C_{ip}(t)}{v}}{\sum_j \int_0^\infty (\theta_i - \theta_e)Q_j \cdot \frac{C_{jp}(t)}{v}} \tag{15}$$

METHOD AND RESULTS OF MEASUREMENT

Method of measurement

Local mean age of air, CRI3 (contribution ratio of indoor climate No.3) and SVE4 (scale for ventilation efficiency No.4) were calculated by means of tracer gas pulse method to investigate the distribution characteristics of fresh outdoor air in the room. SF6 was used as a tracer gas. In this report a new measurement method of the pulse method was presented. The measurement was conducted during the time when the natural ventilation was carried out steadily in the day time of October 30th, 2005. During the measurement the outdoor wind direction was from the west. A mannequin (60W) was placed instead of a occupant in the west side of the office. The tracer gas was emitted in the floor outlets T-1~10 and natural ventilation openings W1+2, W3+4. The emission points of the tracer gas are marked in the Fig. 3 and Fig. 4 measurement points of concentration are marked in the Fig. 4. The method of gas emission is shown in the Fig. 5. In the natural ventilation openings, exploding 4 balloons filled with SF6 of 1500ml at the

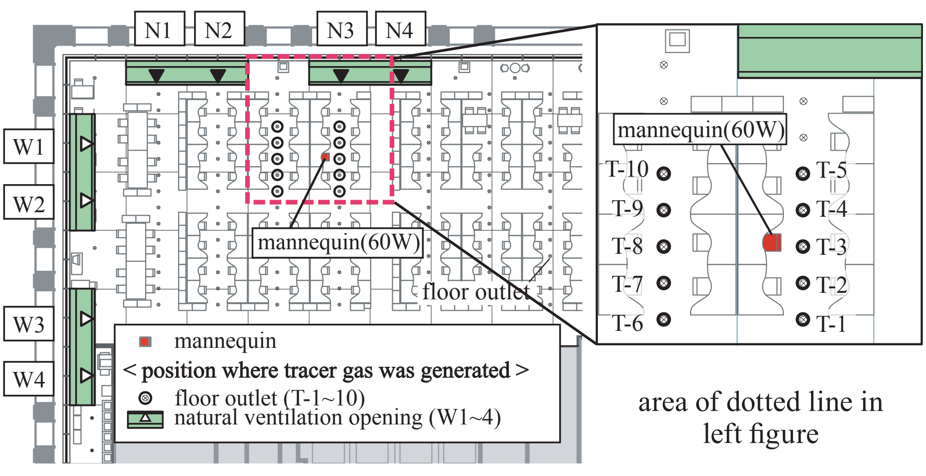

Fig. 3 Emission points of the tracer gas

same time produced the pulse. For the floor outlets, a balloon filled with SF6 of 800ml placed under the faceplate of floor outlet and exploded as shown in Fig. 5. Black lamps of 60W were instead of person, laptop PC and ceiling light was installed as an internal heat load.

Results of measurement

・Influence of supply opening on the environment of occupant zone

The local mean age of air of the specific supply opening is defined as the average time of air to travel from the specific supply opening to the measurement point in the room. The calculated result of this index is shown in the Fig. 6. All every height, the value of the floor outlet T-3 and natural ventilation opening W 1+2 are small. This means that the air from those openings reaches rapidly measurement point. At the measurement point of FL+0.1m, the air from floor outlet T-1~5, which are near the mannequin, shows small value, but as the position gets higher, the air from T-6~10 on the opposite side gets smaller and thus the air from the floor outlet on the opposite side of the desks reaches upper zone earlier than the same of the desks. Fig. 7 shows the result of SVE4, which shows the ratio of the air volume from each supply opening to the total volume of air which reached measuring point.

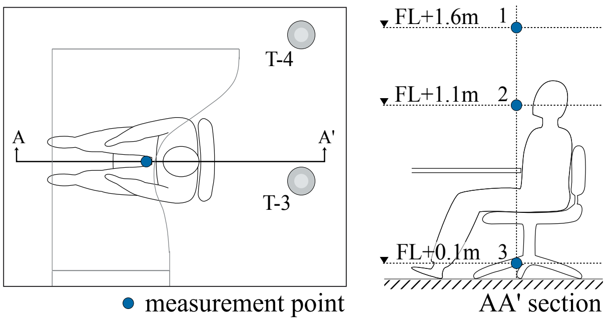

Fig. 4 Measurement points of tracer gas concentration

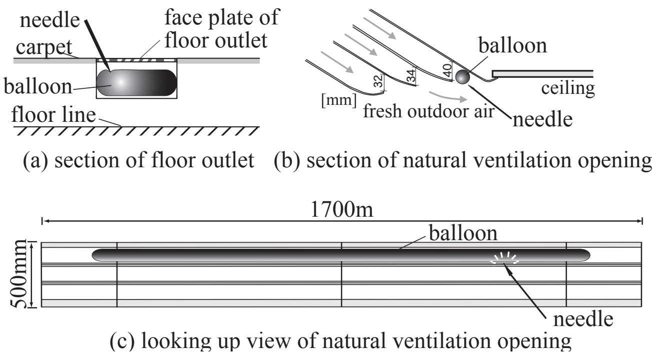

Fig. 5 Method of gas emission

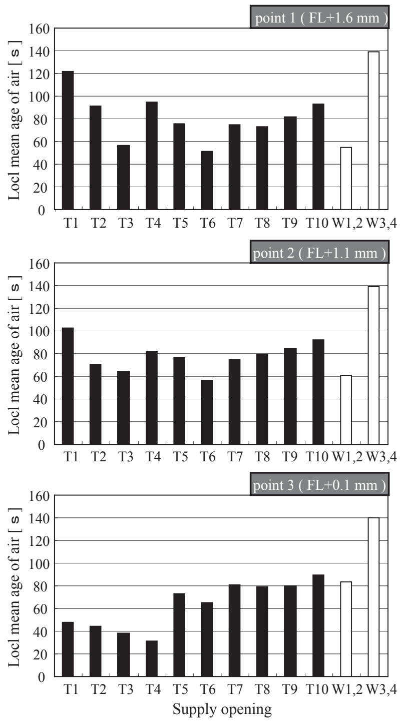

Fig. 6 Local mean age of air for the specific supply opening

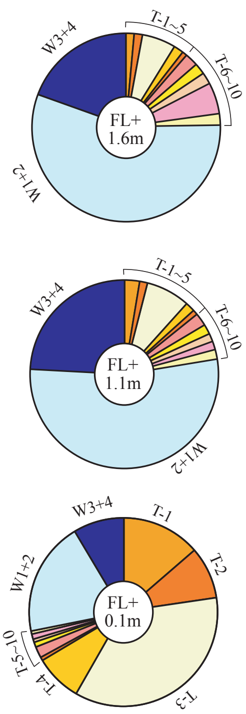

Fig. 7 SVE4 for the specific supply opening

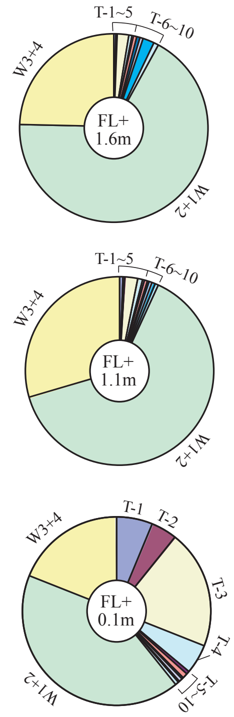

Fig. 8 CRI3 for the specific supply opening

Table 1 Supply and exhaust air temperature

Supply air temperature [degC]												Exhaust air temperature [degC]
T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	W1+2	W3+4	
21.3	21.2	21.1	20.1	20.1	21.3	21.2	21.1	20.9	20.9	16.8	16.6	22.6

At the higher measurement point, SVE4 of the natural ventilation opening becomes larger, which indicate that more volume of air reaches from the natural ventilation. At FL+0.1m, SVE4 of floor outlet is bigger than that of natural ventilation. Among all supply opening the SVE4 of T-3 is the largest and thus the influence of T-3 is dominant. At the measurement points 1 and 2 (FL+1.1m, 1.6m), the influence of air supply from the natural ventilation is dominant, and at the measurement point 3 (FL+0.1m), the floor outlet is dominant. Fig. 8 shows the result of CRI3 calculation, which indicate the influence of the supply opening on the indoor temperature decrement. Table1 shows the supply and exhaust air temperature Fig. 8 shows the similar results of SVE4 at each measurement point (Fig. 7). However CRI3 of the natural ventilation openings is larger than SVE4. That's because there is about 4 degree difference in temperature between the outdoor air and the supply air. This indicates that the natural ventilation openings has a great influence on the air temperature at the position of mannequin. From the above results, it is concluded that the air from the natural ventilation openings has a great influence on the airflow and thermal environment around the occupants.

Table 2 Outlines of CFD analysis

Code	FLUENT6.2.16
Turbulence model	Standard $k-\varepsilon$
Algorithm	Steady state(SIMPLE)
Analysed area	57.6×2.8×18(m) + 3×2.8×7.2(m)
Convectoion term scheme	QUICK
Wall boundary condition	Standard log-low, Adiabatic
Number of meshs	288×15×90 + 15×15×36

Table 3 Boundary conditions

Boundary conditions of flow rate

	Number	Each flow rate	Supply temperature
Flooroutlet	210	110m^3/h	23degC
Celling exhaust	294	78.6m^3/h	

Boundary conditions of internal heat load

Source	Number	Each heat load
Heat load by person	208	60W
Laptop PC	208	30W
Lighting at celling	294	32W 60% on setting position 40% on floor, desks and walls

Table 4 Analysis conditions

	Outdoor temperature	Outdoor wind direction	Outdoor wind velocity
Effect of outdoor temperature	15degC	West	5m/s
	20degC	West	
	25degC	West	
Effect of outdoor wind direction	17.5degC	West	5m/s
		Northwest	
		North	

METHOD RESULTS OF CFD ANALYSIS

Method of CFD analysis

In this section, the effect of the outside wind direction and outdoor temperature on the airflow and the thermal environment in the office room is examined by CFD. Table 2 shows the outlines of CFD analysis. The analysis model consists of the office and the workspace in the southwest, as is shown in Fig. 9. Fifteen natural ventilation openings of 120×10cm were installed under the ceiling. The flow rate of each natural ventilation opening was calculated from the measured wind pressure coefficients [5], under the outdoor velocity of 5m/s. The air was supplied into the indoor at an angle of 20 degree to the ceiling. The size of mesh is 20×20×20cm except the vicinity of the natural ventilation openings. Fig. 10 shows the detailed figure of the mesh system of CFD. A floor out-

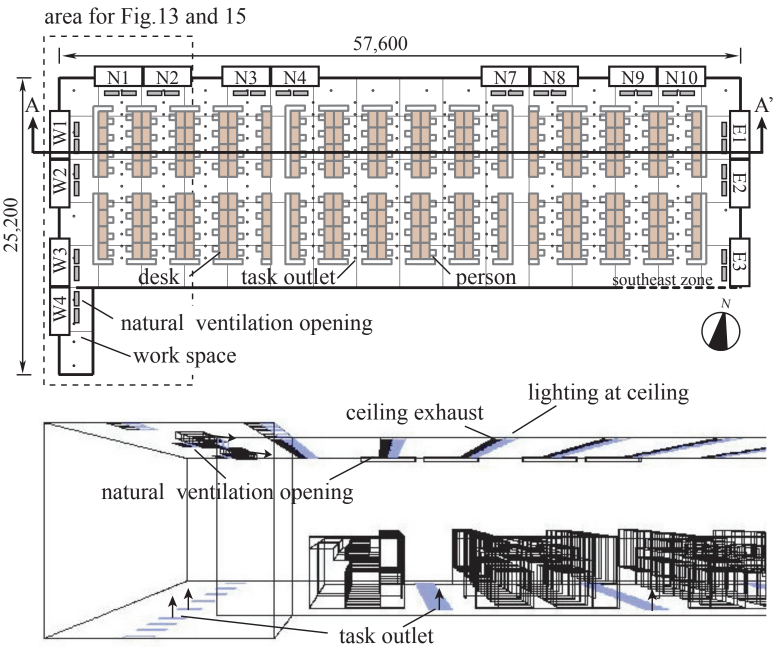

Fig. 9 Analysis area

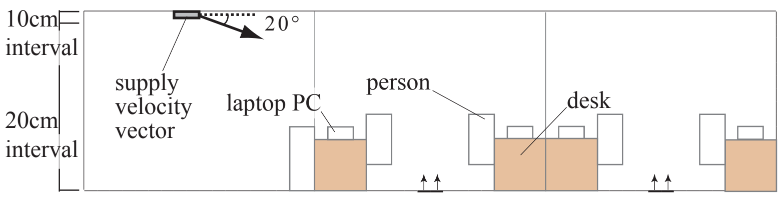

Fig. 10 Mesh layout

let was assumed to be a 400×400mm horizontal plan and the air direction was vertical. Table 3 shows the boundary conditions of CFD. Lighting equipment and exhaust openings were installed on the ceiling. The total flow rate of exhaust air is equal to the total amount of air from the floor outlet. The outdoor condition for CFD analysis is shown in Table 4. In order to compare the results with the measurement, the outdoor temperature was set at 17.5 degree and the wind direction was set at the west.

Results of CFD analysis

The temperature distribution at the height of FL+950mm is shown in Fig 11. The outdoor air flows into the office room through the west-side openings and the indoor air flows out through the north part. Therefore, the average temperature in the east-side zone becomes higher than that in the west-side zone. This shows a similar tendency as the measurement result. However, the temperature of the CFD result is higher than that of the measurement result by about 2 degrees. This might be because the thermal storage in the floor, walls, furniture and equipment is not considered in CFD besides errors of boundary condition. Fig. 12 shows the velocity distribution at FL+1100mm. It is considered that the outdoor air flows along the ceiling surface in the room due to the coanda effect. At the point about 20m away from the west wall, the wind velocity was about 0.2~0.5m/s, and on the east side the velocity was less than 0.2m/s. At FL+1100mm, the air flows through the passage.

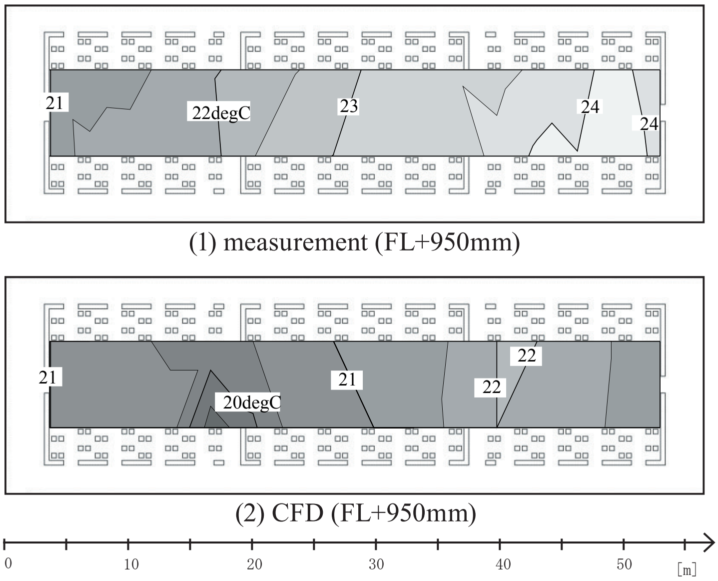

Fig. 11 Temperature distribution
(at the height of FL+950mm)

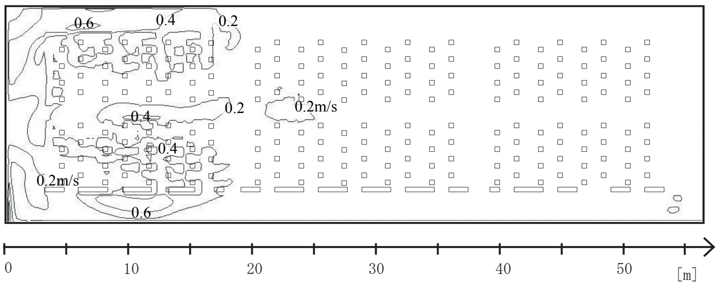

Fig. 12 Velocity distribution
(at the height of FL+1100mm)

Effect of the outdoor temperature on the indoor airflow pattern

Fig. 13 shows the temperature distribution on the west side of AA' section when the outdoor wind direction is west and the outdoor temperature is 15°C, 20°C and 25°C. Temperature gradient at the upper part of the room becomes uniform distribution as the outdoor temperature goes up. This implies that when the outdoor temperature is higher the air from the natural ventilation openings does not drop down near the openings, and it drops at the area farther away than. The SVE4 distribution at the height of FL+1100mm at AA' section is shown in Fig.14. In the figure, the ratio of each supply opening represents the degree which supply opening control the environment in the office. For all cases the SVE4 of natural ventilation openings is higher in the west-side

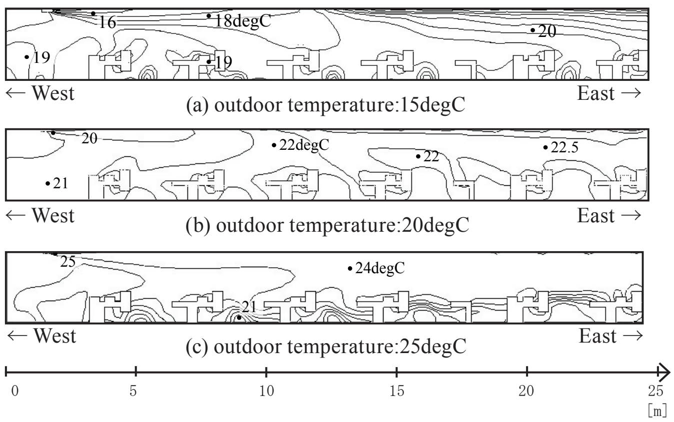

Fig. 13 Effect of outdoor temperature
on temperature distribution in AA' section

zone, while ratio of the floor outlet is higher in the east-side zone. In the east area where the outdoor air from the natural ventilation has a little effect, the indoor airflow was influenced by the floor outlet. The SVE4 value of the floor outlet becomes large as the outdoor temperature goes up. That of the natural ventilation in the east at the outdoor temperature of 25°C is almost zero. This is because the inflow air flows along the ceiling and flows out through the natural ventilation openings in the north side.

Effect of Outside Wind Direction on the Indoor Airflow Pattern

Fig. 15 shows the temperature distribution in the west side zone of AA' section for the wind direction of west, northwest and north at the outdoor temperature of 17.5°C. The inflow openings are W1~4 and E3 for west wind, W1~4, N1~4, N7 and N8 for northwest wind, N1~4 and N7~10 for north wind. In this figure, the temperature range around the natural ventilation openings is about 18~20°C, and the temperature around the occupants is about 21~22°C. There are large temperature changes near the ceiling surface due to the influence of the wind direction. Fig. 16 shows the SVE4 distribution at the height of FL+1100mm at AA' section. For all the wind directions, the SVE4 of natural ventilation opening takes a large value around the natural ventilation openings. SVE4 of the natural ventilation openings shows higher value for northwest wind than west or north wind. This implies that the effect of inflow of the outdoor air is large in the case of northwest wind because the depth of the room is shorter.

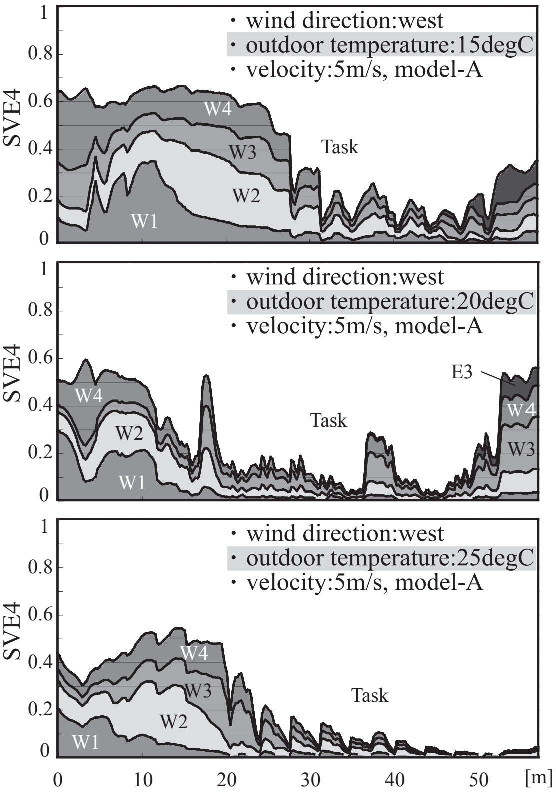

Fig. 14 Effect of outdoor temperature on SVE4 distribution in AA' section

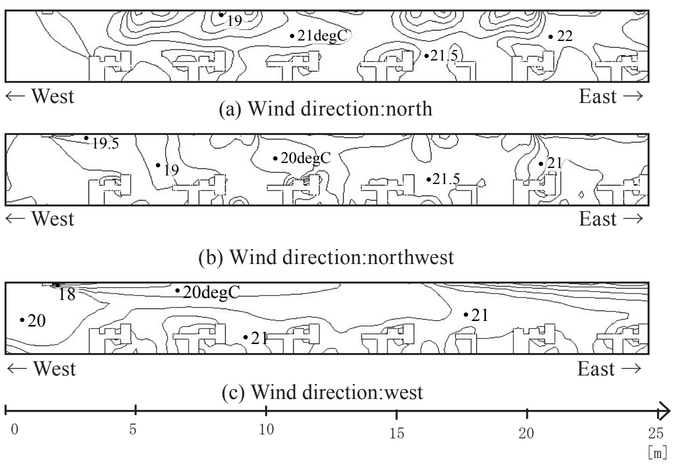

Fig. 15 Effect of wind direction on temperature distribution in AA' section

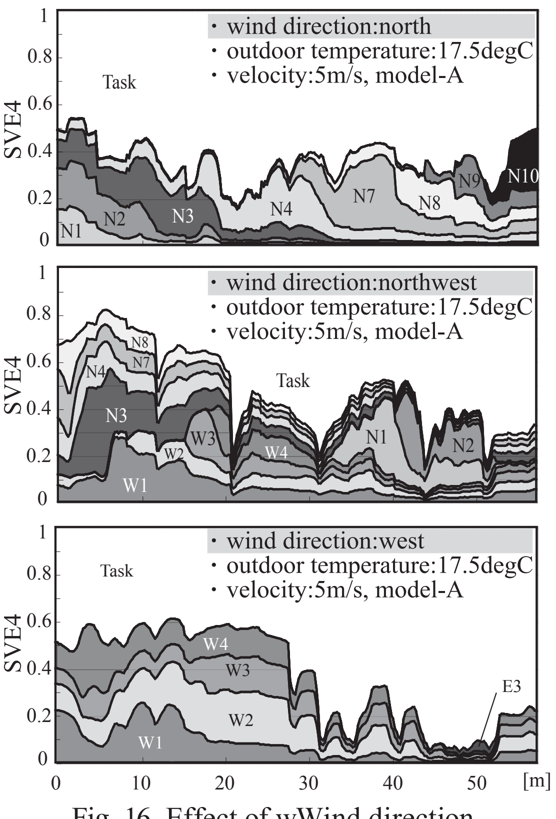

Fig. 16 Effect of wWind direction on SVE4 distribution in AA' section

CONCLUSION

This paper showed the results of measurement and CFD analysis for the indoor airflow patterns and thermal environments of an office room when indoor is air conditioned by the natural ventilation and floor outlets. The measurement results suggest that the airflow of natural ventilation have a great influence on the airflow pattern and the thermal environment around the occupants. The influence of the outdoor wind direction and temperature on the indoor airflow pattern and the thermal environment was examined based on CFD analysis. As the result, when the outdoor temperature is higher the air from the natural ventilation openings does not drop near the openings, and it drops at the point farther away than when the temperature is lower. The SVE4 value of the floor outlet becomes large as the outdoor temperature goes up. For all the wind directions, the SVE4 of each natural ventilation opening takes the large value around the natural ventilation openings at the area of near the west-side wall.

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