Influence of Partition Curtain on Vertical Profile of Temperature and Contaminant Concentration in Sickroom with Displacement Ventilation

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Abstract

For patients, the sickroom is a place where they receive medical treatment and also a living space where they spend most of time in a day. Therefore, good indoor air quality and comfort should be kept in sickroom.
We propose to use the displacement ventilation as a means of obtaining high indoor air quality in sickrooms. The purpose of the study is to examine the validity of this system. This paper shows the experiment results and CFD analysis results to examine the effect of partition curtain in the displacement-ventilated room.

Keywords: Displacement ventilation, Sickroom, Curtain, CFD analysis, Prediction model

1. Introduction

The mechanism of displacement ventilation is referred in many textbooks or papers (e.g. REHVA, 2002, Skistad. H, Mundt. E, Nielsen. P, Hagstrom. K, Railio. J). The prediction model of vertical temperature profile is presented by Nielsen and Mundt. It is known that the contaminant interface is formed at the height where supply airflow rate is equal to the total airflow rate of the plumes from the heat sources such as persons. Therefore, contaminant concentration profile can be predicted briefly. The relationship between the ventilation heat loss and contaminant concentration in the lower zone was investigated previously (Yamanaka and Kotani et al. 2001). It is, however, necessary to predict the effect of cool wall on the pollution of the air in the lower zone for occupants. The approach to predict the vertical profile of temperature and contaminant concentration was examined by means of macro-model (Higashimoto and Yamanaka et al. 2003). As observed above, a lot of studies for displacement ventilation are researched, but displacement ventilation for sickroom has not been studied enough.

Most sickrooms in Japan have four beds, and there is a problem of the odor from patients or diapers. Therefore the authors have proposed to use the displacement ventilation for sickroom. This study is intended to examine the applicability of the displacement ventilation system for sickroom. In the previous study, the temperature and contaminant concentration profile in displacement-ventilated room were figured out. But, the actual sickroom has partition curtains to keep patient’s privacy and it is predicted that the curtain has great influence on the temperature and contaminant concentration profile. This paper shows the experiment results and CFD analysis results to examine the effect of partition curtain in the full-scaled sickroom with displacement ventilation. In addition, the experiment results were compared with the calculated results by zonal model presented by the authors before.

2. Experiment method

Experiments are performed in a full-scale displacement-ventilated room. The test room has 2.68m heights, 3.0m widths and 3.0m length, as shown in Fig.1. The floor, ceiling, and walls are insulated with 50mm thick polystyrene foam. The supply inlet is a half-cylinder displacement-type diffuser (kranz Q-ZH) located along the wall on the floor. The exhaust outlet is a 200 ϕ hole located in the corner on the ceiling. A mannequin with heating-cable is used as a human simulator. Heat generation rate of the mannequin is maintained at 40W as sensible heat load of sleeping human. The each end of a 100% polyester cloth with a thick of 0.5mm is fixed to the wall as a curtain.

Fresh air is supplied at 22 ^{o}C from the diffuser, and the surroundings of the test room are kept at 22 ^{o}C. CO_2 was emitted at the chest of heated mannequin as tracer gas. CO_2 flow rate is controlled at 0.5L/min by mass flow controller. Room air temperature, wall surface temperature and CO_2 concentration are measured at steady state.

Fig.2 shows measurement points of temperature and CO_2 concentration. Air temperature is measured at 9 points (P1~P9) in horizontal plane and at 22 points vertically, that is 198 points in total. Wall surface temperature (Wa~Wl) is measured at 6 points vertically (i.e. 72 points for all). CO_2 concentration (P1~P3, P6~P9) is measured at 12 points vertically (i.e. 84 points for all).

As parameters of the experiment, supply flow rate and bottom height of curtain were changed. Table 1 shows the experimental conditions. The results of the experiment performed at 2006 are quoted, and the conditions without curtain are added in the table.

3. Experiment results

Table 2 shows balance of heat flow. The experimental results are expressed by mean value in equal height of the measurement points (P1, P2, P7 and P8) inside of the curtain and the measurement points (P3, P6 and P9) outside of the curtain.

3.1 Influence of Curtain on vertical profile of temperature and contaminant concentration

The horizontal axis of graph of temperature means the temperature difference from supply air temperature, and that of concentration means measured concentration minus supply air concentration which is normalized by the concentration difference between supply and exhaust.

Fig.3 and Fig.4 show the measured results of vertical profile of temperature and contaminant concentration respectively, under the condition of supply airflow rate of $100m^3/h$. Fig.3 shows thermal stratification is little formed outside of curtain (that is, the smaller zone without bed) when curtain is present. It is considered to be that the thermal plume from the mannequin is interrupted by the curtain. From Fig.4, it is seen that the concentration is high at a low position when curtain is presence. It is considered that the pollutant descends to the floor with downdraught along cool walls because conduction heat loss through perimeters is relatively large in this case. Then, there is a tendency that the concentration interface level falls inside curtain (the zone with a bed) and rises outside curtain (the zone without a bed) when the curtain is present. This is because that the supply air flowing into inside of curtain is decreased and that the outside space of curtain is filled with fresh air supply.

Fig.5 and Fig.6 show the measured results of vertical profile of temperature and contaminant concentration respectively, under the condition of supply airflow rate of $200m^3/h$. Fig.5 shows thermal stratification is little formed outside of curtain as is the case in supply air of $100m^3/h$. In Fig.6, it is seen that the concentration interface level falls inside curtain and rises outside curtain as is the case in supply air $100m^3/h$.

3.2 Influence of Bottom Height of Curtain

Fig.7 and Fig.8 show the measured results of vertical profile of temperature and contaminant concentration respectively when supply airflow rate is $200m^3/h$.

From Fig.7, it can be said that the difference of vertical temperature gradient is not so large in all cases. However, the temperature profile is slightly high when bottom height of curtain is 125mm.

Fig.8 shows concentration gradient inside of curtain is low when bottom height of curtain is 125mm. The supplied air flowing under curtain into inside of curtain is decreased and the supplied air flowing over curtain into inside of curtain is increased when the opening area under the curtain is small. Therefore, it is considered that the concentration interface is not formed clearly because of the mixture of fresh air and contaminated air when bottom height of curtain is 125mm. Then, there is a tendency that the measured values outside curtain approach the value of the case without curtain as bottom height of curtain rises. Therefore, it can be said that bottom height of curtain has large influence on the distribution of supply airflow rate into inside and outside of curtain.

4. CFD analysis

4.1 Analysis Method

CFD simulation is carried out in order to examine more detailed flow patterns in the room. The test room where experiments are performed is replicated as analyzed room. Fig.9 shows the analyzed room, and Fig.10 illustrates the mesh layout. The standard k-ε model is used as a turbulence model. Table 3 shows the analysis method. As for the boundary condition, the generalized log low is applied for the velocity, and the measured temperatures are provided for wall surface temperature. The heat emission rate of mannequin is 20W on the assumption that the convection heat accounts for 50% of total sensible heat load of sleeping human. Table 4 shows the boundary conditions of CFD analysis.

4.2 Results

Fig.11 and Fig.12 show temperature and velocity distribution obtained by CFD as for the condition of Q_s=200m^3/h and Y_{cb}=125mm.

In Fig.11(1), supply airflow and thermal plume from the heated mannequin are interrupted by the curtain. Therefore, the supply air flowing into the inside of curtain is decreased and the outside space of curtain is filled with fresh air.

In Fig.11(2), (3) and Fig.12, the cool supply air flowing over curtain into the inside of curtain is mixed with warm air inside curtain. This phenomenon explains the reason why the concentration interface is not formed clearly in the experiments in the previous chapter.

5. Validation of Zonal model

5.1 Outline of Zonal Model

In order to predict vertical profile of contaminant concentration inside curtain, the zonal model presented in the previous study is applied. This model is based on the balance of contaminant flow by convection and diffusion. Fig.13 shows the outline of the model. In this model, the room is divided into four zones vertically direction and “interface layer” (with layer(2) and (3)) including the contaminant interface is assumed. This layer has a width of W, and there is diffusive transfer of contaminant across the interface. Fundamental equations for this model are as follows.

The contaminant balance of the layer (2) can be expressed by

$$Q_{dr(y_u)}\left\{(C_u-C_d)(1-\frac{\eta}{2})+C_d\right\}-3600(D+D_t)\frac{\partial C}{\partial y}A_f=Q_{dr(y_u)}C_u$$

The contaminant balance of the layer (3) can be expressed by

$$Q_{ur(y_d)}\left\{(C_u-C_d)(\frac{1-\eta}{2})+C_d\right\}=-3600(D+D_t)\frac{\partial C}{\partial y}A_f+Q_{ur(y_d)}C_d$$

As the value of diffusion coefficient ($D+D_t$), 0.0005[m^2/s] is used, from the previous study.

The following equation can be derived from the balance of contaminant in layer(4).

$$\left(Q_s+\sum_{k=1}^{m}Q_{d_k(y_d)}\right)C_d=\left(\sum_{k=1}^{m}Q_{d_k(y_u)}\right)C_u+\left(\sum_{k=1}^{m}Q_{d_k(y_i)}-\sum_{k=1}^{m}Q_{d_k(y_u)}\right)\left\{(C_u-C_d)(1-\frac{\eta}{2})+C_d\right\}$$
$$+\left(\sum_{k=1}^{m}Q_{d_k(y_d)}-\sum_{k=1}^{m}Q_{d_k(y_i)}\right)\left\{(C_u-C_d)(\frac{1-\eta}{2})+C_d\right\}$$

The contaminant balance of the whole room can be expressed by

$$C_u=C_e=\frac{NM}{Q_s}$$

By solving these balance equations as a set of simultaneous equations of y_u, y_d, C_u and C_d, these variables can be obtained.

The lying patient on the bed is considered as a line heat source. In the previous study, the length of the line source is 0.5m and the source is located 0.8m below the human. The airflow rate of plume from the patient can be expressed by

$$Q_{P(y)} = 82.43y + 24.72$$

From the previous paper, the vertical airflow rate along a wall due to national convection can be calculated by cumulating the following increment of airflow rate.

$$\Delta Q_u(y) = \Delta Q_d(y) = 13.176 \left|\Delta T\right|^{\frac{2}{5}} y^{\frac{1}{5}} l \, \Delta y$$

In this paper, the model calculation is performed on the assumption that all the supply air flows into inside of curtain on that the two-third of supply air flows into inside of curtain based on the area ratio of both area divided by the curtain.

5.2 Calculation results

Fig.14 shows the comparisons of the calculation results of vertical profile of contaminant concentration with experimental one in the case that curtain is present. The experimental results are averaged values of the same height. In this figure, the calculation (1) is the result by $Q_{si}=Q_s$ and the calculation (2) is the result by $Q_{si}=2/3Q_s$.

Fig.14 (1) ~ (4) show that calculation (2) coincides with the experimental result when supply airflow rate is $100m^3/h$ or $200m^3/h$. However, fig.13 (5) shows the calculated result doesn't coincide with experimental one when supply airflow rate is $300m^3/h$.

5.3 Prediction by Means of Identified Supply Airflow Rate into Inside Curtain Area

In this section, vertical profile of contaminant concentration inside curtain is predicted by the supply flow rate identified from contaminant balance. The contaminant balance of the inside of curtain can be expressed by

$$Q_{si} = \frac{NM}{C_{ui}}$$

Therefore, supply air flowing under curtain into inside of curtain can be identified from the measured contaminant concentration above interface layer inside curtain.

Fig.15 shows the comparisons of the calculated results of vertical profile of contaminant concentration with experimental ones in the case that curtain is present. The identified supply flow rate and the ratio of that to actual supply flow rate are written in each figure. Fig.15 (1), (4) show calculated result coincides with the experimental result successfully in the case of Q_s=$100m^3/h$ and Y_{cb}=250mm or the case of Q_s=$200m^3/h$ and Y_{cb}=400mm. In other case, however, contaminant interface levels obtained by calculation are higher than experimental ones and both ones don't coincide. In general, the increase of supply flow rate raises contaminant interface height, so it is supposed that the identified supply flow rate is larger than the actual supply flow rate. This is because that the concentration isn’t measured at measurement points of P4 and P5 shown in Fig.2 and the high concentration over pollution source (that is mannequin) isn’t accounted for. When supply flow rate is small or bottom height of curtain is high, the horizontal profile of concentration above interface layer is considered to be uniform as little supply air is supposed to flow over curtain into inside of curtain. Therefore, supply flow rate is identified accurately and calculated results coincide with experimental ones even though the concentration over pollution source wasn’t measured.

6. Conclusions

−When the curtain is present, the contaminant interface height rises inside curtain and falls outside curtain.

−When bottom height of curtain is small, the contaminant interface inside of curtain is not formed clearly.

−The CFD analysis shows that supply air flows over curtain into inside of curtain in the case of Q_s=200m^3/h and Y_{cb}=125mm.

−The calculated results by means of zonal model coincided successfully with experiment results if supply flow rate is small or bottom height of curtain is high enough.

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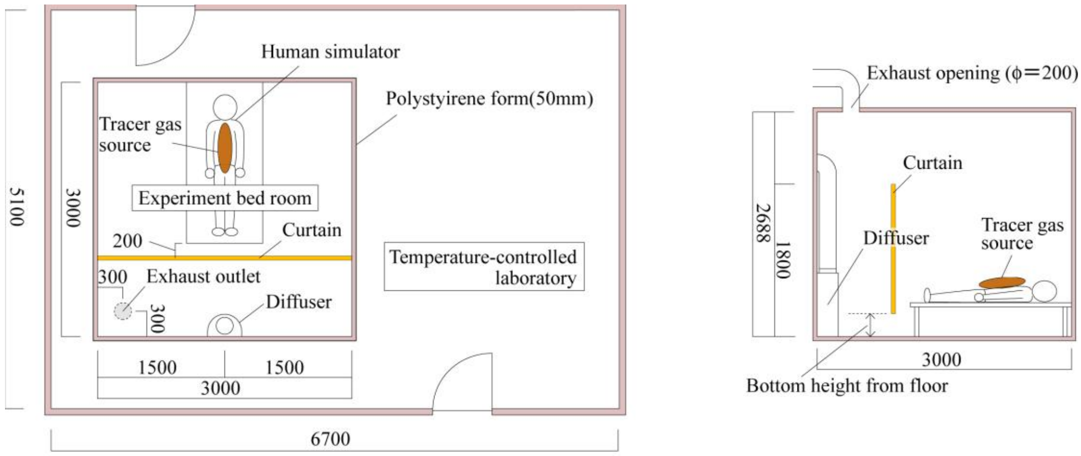


Fig.1 Experiment bed room

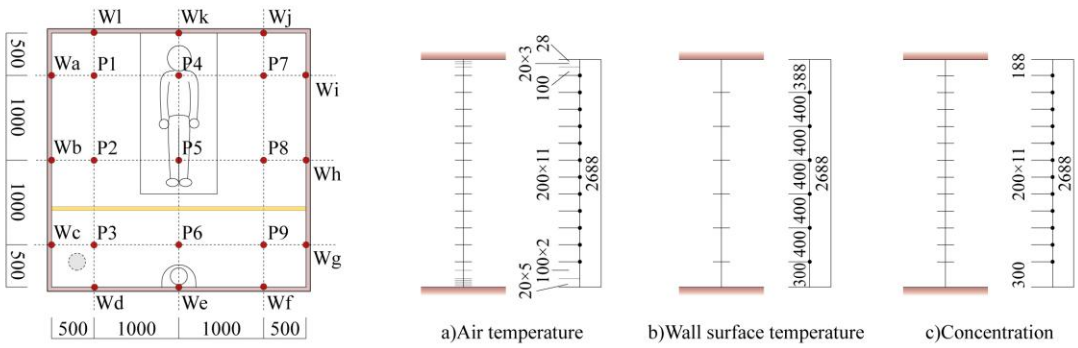


Fig.2 Measurement Points

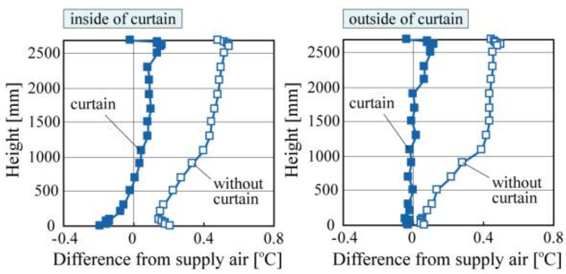


Fig.3 Vertical temperature distribution
(Q_s=100m^3/h)

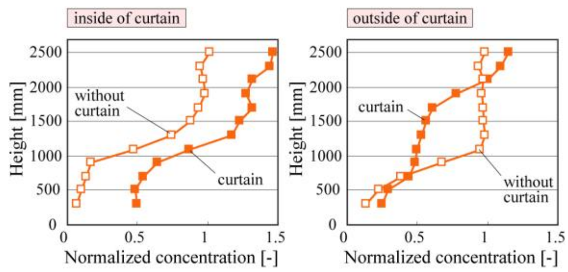


Fig.4 Vertical concentration distribution
(Q_s=100m^3/h)

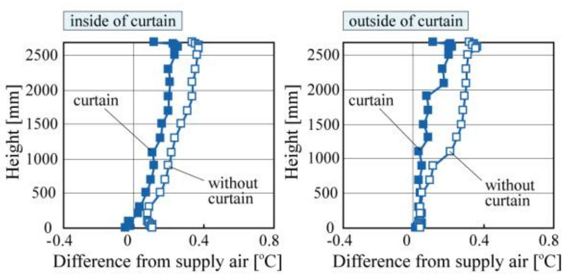


Fig.5 Vertical temperature distribution
(Q_s=200m^3/h)

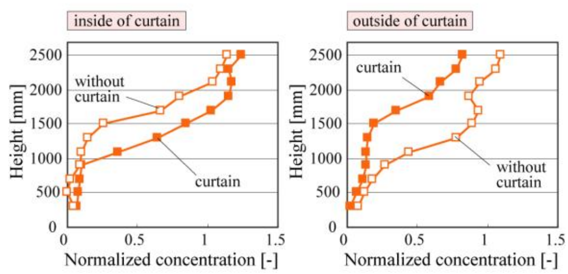


Fig.6 Vertical concentration distribution
(Q_s=200m^3/h)

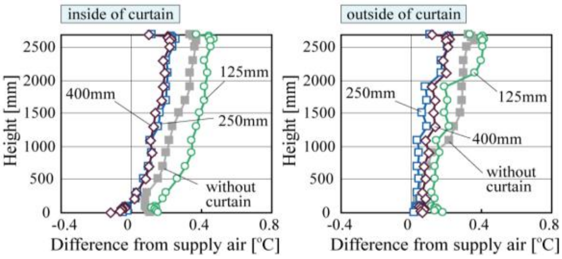


Fig.7 Vertical temperature distribution (Q_s=200m^3/h)

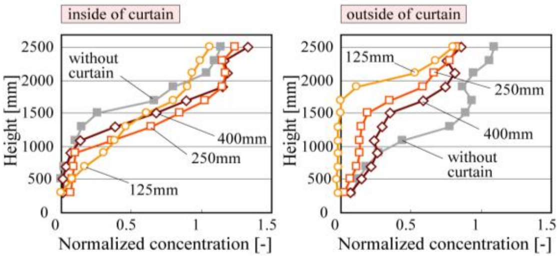


Fig.8 Vertical concentration distribution (Q_s=200m^3/h)

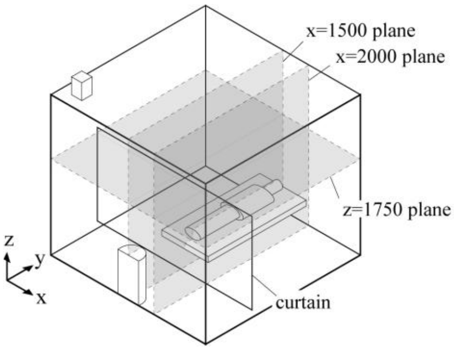


Fig.9 Analyzed room (Q_s=200m^3/h, Y_{cb}=125mm)

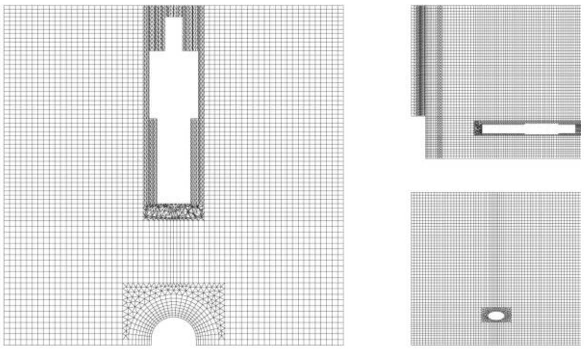


Fig.10 Mesh layout

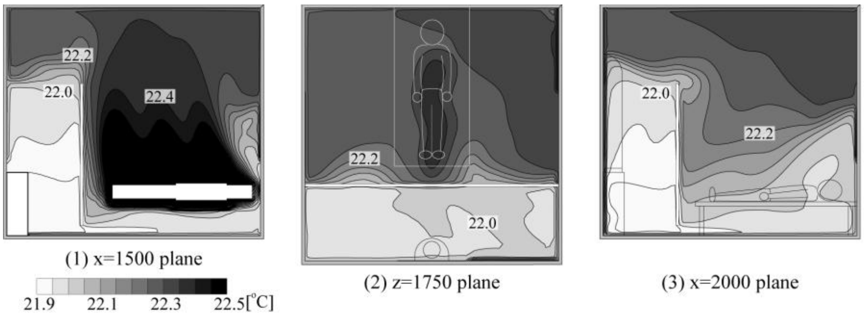


Fig.11 Temperature distribution

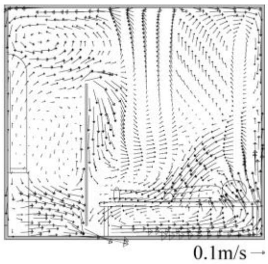


Fig.12 Velocity distribution (x=2000 plane)

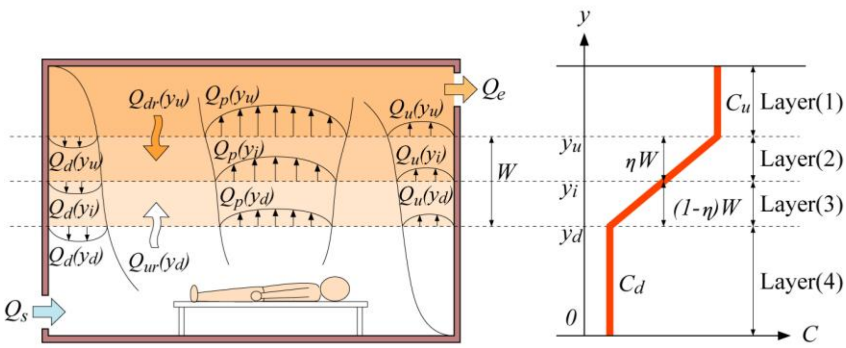
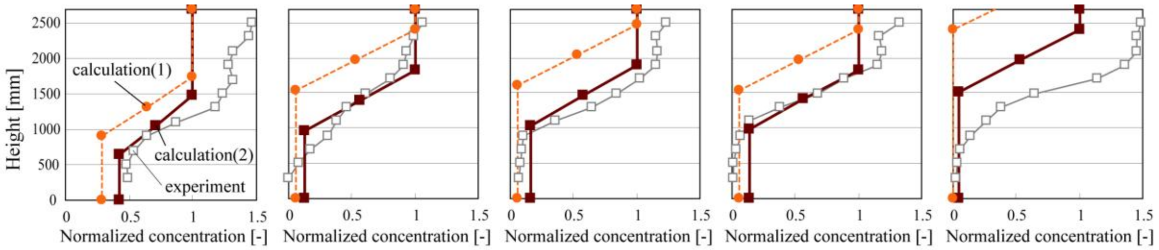
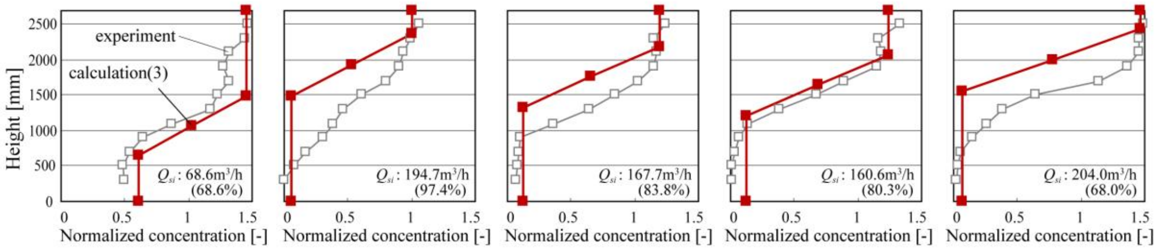


Fig.13 Outline of the zonal model



(1) Q_s=100m³/h, Y_{cb}=250mm (2) Q_s=200m³/h, Y_{cb}=125mm (3) Q_s=200m³/h, Y_{cb}=250mm (4) Q_s=200m³/h, Y_{cb}=400mm (5) Q_s=300m³/h, Y_{cb}=250mm

Fig.14 Vertical concentration distribution in area inside curtain



(1) Q_s=100m³/h, Y_{cb}=250mm (2) Q_s=200m³/h, Y_{cb}=125mm (3) Q_s=200m³/h, Y_{cb}=250mm (4) Q_s=200m³/h, Y_{cb}=400mm (5) Q_s=300m³/h, Y_{cb}=250mm

Fig.15 Vertical concentration distribution in area inside curtain

Table 1 Experimental conditions

		without curtain	curtain (bottom height from floor)		
			125mm	250mm	400mm
Supply airflow rate	100m³/h	○		○	
	200m³/h	○	○	○	○
	300m³/h			○	

Table 2 Heat balance

Supply airflow rate	100m³/h	200m³/h			300m³/h
bottom height from floor	250mm	125mm	250mm	400mm	250mm
Heat Value of Human Simulater [W]	40	40	40	40	40
Ventilation Heat Loss [W]	-3.64	-20.29	-11.40	-15.63	-20.69
Conduction Heat Loss [W]	-24.95	-5.34	-13.55	-7.17	-0.01
Total Heat Balance [W]	11.41	14.36	15.05	17.20	19.31

Table 3 Analysis method

CFD code	Fluent6.3
Turbulence model	Standard k- ε model
Density	Incompressible ideal gas
Calculation algorithm	Steady state (SIMPLE)
Discretization scheme	QUICK
Number of mesh	64×73×57

Table 4 Boundary conditions

Wall	Generalized log law
inlet	0.1179m/s, 21.88℃
	$k = 3(UI)^2/2$ (I=3%)
	$\varepsilon = C_\mu^{3/4} k^{3/2}/L$ (L=0.005m)
outlet	Pressure 0 [Pa]
Heat generation from human	14.5W/m² (total 20W)

【Symbol】

A_f : Floor area [m²]
C_e : Contaminant concentration of the exhaust air [-]
C_u : Contaminant concentration above the interface layer [-]
C_d : Contaminant concentration below the interface layer [-]
C_{ui} : Contaminant concentration above the interface layer inside of curtain [-]
D : Diffusion coefficient by molecular [m²/s]
D_t : Diffusion coefficient by turbulence [m²/s]
l : Horizontal width of the wall [m]
M : Contaminant emission rate per heat source [m³/h]
N : The number of the human [-]
Q_s : Supply airflow rate [m³/h]
Q_e : Exhaust airflow rate [m³/h]
Q_{si} : Supply airflow rate flowing into inside of curtain [m³/h]
$Q_p(y)$: Air flow rate of the plume of the person at height of y [m³/h]
$Q_u(y)$: Upward airflow rate of the wall at height of y [m³/h]
$Q_d(y)$: Downward airflow rate of the wall at height of y [m³/h]
$Q_{ur}(y)$: Upward airflow rate at height of y [m³/h]
$Q_{dr}(y)$: Downward airflow rate at height of y [m³/h]
ΔT : Temperature difference between wall and room temperature [°C]
W : Vertical width of interface layer [m]
y : Height above floor [m]
Δy : Vertical width of small wall part [m]
y_u : Height of the upper edge of interface layer above the floor [m]
y_i : Height of contaminant interface [m]
y_d : Height of the lower edge of interface layer above the floor [m]
Y_{cb} : Bottom height of curtain [m]
η : Height ratio of the interface in interface layer [-]
$\partial C/\partial y$: Vertical gradient of concentration within the interface layer [/m]