INFLUENCE OF MOVING OBJECTS ON VENTILATION PLAN FOR SMOKING ROOM

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ABSTRACT

Ventilation plan for smoking room must deal with pollutants since they affect the air quality of adjacent rooms. Although ventilation plan typically maintains a negative room pressure to remedy this problem, the transport of indoor air pollutants between rooms is affected by moving objects, such as human movement and door opening. The purposes of this study were to evaluate the effects of moving objects on the rate of transport of indoor air pollutants and to propose a method of controlling contamination for smoking room.
First, we measure the inter-zonal air exchange rate by uniformly dispersing sulfur hexafluoride (SF_6) as a tracer gas with swinging of the door between an air-contaminated room and corridor. We also measure the direction and velocity of air flow to ascertain variations in air flow around the door due to door opening and closing. Results of these measurements were compared to results of Computational Fluid Dynamics (CFD) analysis with overset mesh technics to verify that CFD analysis was consistent with actual findings. Then, we evaluated the inter-zonal air exchange rate by influence of moving objects with isothermal/non-isothermal conditions. In addition, we evaluate the several ventilation planning to decrease pollutants leakage from the smoking room, such as installation of sliding door or air curtain system.
The measured absolute rate of inter-zonal air exchange as a result of opening and closing the door once differed little from the result of CFD analysis, so the results roughly coincided. Although the air curtain operation was ineffective to decrease the inter-zonal air exchange rate when the temperature differential between two adjacent spaces is little, the air curtain operation was predictably effective when the temperature differential between two adjacent spaces is large. Moreover, use of a sliding door in smoking room with exhaust ventilation system limited the inter-zonal air exchange rate more than use of a swinging door. However, the inter-zonal air exchange rate increased when human movement was combined with use of a sliding door.

KEYWORDS

Ventilation, Air exchange rate, Moving object, Smoking room, Computational fluid dynamics

1 INTRODUCTION

Ventilation plans for rooms with contaminated air, such as laboratories, smoking rooms, and bathrooms, must deal with pollutants since they affect the air quality of adjacent rooms. A ventilation plan typically maintains a negative room pressure to remedy this problem. However, the transport of indoor air pollutants between rooms is affected by moving objects, such as human movement and door opening, despite planned ventilation. Although there have been many studies evaluating the performance of such rooms with negative room pressure [N. Rice et al. (2001)], there have been relatively fewer studies assessing how door opening motions and human passage through the door [Adams NJ et al. (2011), Petri Kalliomäki et al. (2013), Julian W. Tang et al. (2013)], and the effect of air curtain system [J.C. Goncalves et al. (2012), D. Frank et al. (2015)]. The purposes of this study were to evaluate the effects of moving objects on the rate of transport of indoor air pollutants and to propose a method of controlling contamination in an indoor environment.

2 METHODOLOGY

2.1 Measurement and verification of CFD analysis

The space studied is shown in Fig. 1. Air flow in this space was visualized, the direction and velocity of air flow were measured, and the inter-zonal air exchange rate was measured. Results of these measurements were compared to results of CFD analysis of the same space to verify that CFD analysis was consistent with actual findings. Air flow was visualized by generating smoke in the room with a water and glycol-based smoke generator, and then visualizing air flow around the door during door opening and closing (height of Nd:YV04 laser beam : 1.2 from the floor). The direction and velocity of air flow were measured to ascertain variations in air flow around the door due to door opening and closing using 3D ultrasonic anemometer. Measurement was done 0.1 m (h = 1.2 m) from the edge of the door (projecting into the corridor) when the door was fully open. The inter-zonal air exchange rate was measured by uniformly dispersing sulfur hexafluoride (SF_6) as a tracer gas in the room. The door was closed 0 times/h (natural ventilation), 6 times/h, 12 times/h, and 60 times/h. The inter-zonal air exchange rate (Eq. 1) was calculated based on the concentration decay as a result of the door being closed a certain number of times. All of the measurement units are shown in Table 1.

$$Q = \frac{V}{\Delta t} \cdot \ln \frac{C_S}{C} \tag{1}$$

Here, Q [m^3/h] is the inter-zonal air exchange rate, C_s [kg/m^3] is the initial concentration of contaminants, C [kg/m^3] is the concentration of those pollutants in the room after time t [h], and V [m^3] is the room volume.

Boundary conditions for CFD analysis are shown in Table 2. The turbulence model used was a high Reynolds number k-epsilon model, and the differencing scheme used was a MUSCL scheme. To realize door opening motion, CFD analysis was considered the calculation of time-dependent and overset mesh technique. The initial concentration of contaminant was also set to 1 in indoor and 0 in corridor to calculate the inter-zonal air exchange rates by CFD analysis. The interval for door opening and closing was set to 0~4 sec (door opening) → 4~6 sec (door opened) → 6~10 sec (door closing) → 10~12 sec (door closed).

2.2 Evaluation of ways to decrease leakage of pollutants from a smoking room

Smoke from smoking area is affect non-smoking area by including human breathing, attached clothes, induced airflow by the human moving, and door opening/closing. Therefore there is need to install exhaust fan or air cleaner system, and there is need to maintain the acceptable concentration limit of carbon monoxide, carbon dioxide and particulate matter. In Japan, the design guideline for smoking room has proposed by Ministry of Health, Labour and Welfare, and it is recommended to maintain the air velocity more than 0.2m/s at the door of smoking area by installing an exhaust fan. However, the design guideline is non-binding standards and non-engineered recommendation. In this study, we evaluated the effects of air curtain and exhaust fan to decrease leakage of pollutants from a smoking room, and conducted quantitative analysis about the transport rates of pollutants.

(1) Air curtain effects under different thermal conditions

Air curtains are commonly used as virtual barriers in doorways separating two different thermal or contaminant environments. At the smoking room, an air curtain can considerably reduce the

spreading of cigarette smoke, heat loss, and draughts between two adjacent spaces without impeding human traffic through the doorway. To evaluate the effects of air curtain at the smoking room, the extent of pollutant leakage due to the air flow from an air curtain was studied by CFD analysis.
The schematic of smoking room model is shown in Fig. 5. The volume of a smoking room is 15.625 cubic meters and the adjacent space is a corridor of 12.500 cubic meters. Details of the door and door louvers are also shown in Fig. 5, and the interval for door opening and closing was set to 0~2 sec (door opening) → 2~4 sec (door opened) → 4~6 sec (door closing). For this investigation, we also used a 6m/s vertically downwards blowing air curtain model. Boundary conditions and calculation cases for CFD analysis are shown in Tables 3, 4. The CFD analysis was calculated the pollutant leakage in air curtain operation and non-operation with temperature difference between smoking room and corridor. The temperature of smoking room was fixed to 20°C, and the temperature of corridor was set to 40°C from 0°C at 5°C intervals for investigation. Pollutant leakage was also calculated when the smoking room had a sliding door and a swinging door.

(2) Exhaust fan effects under isothermal conditions

The extent of pollutant leakage due to the air flow from an exhaust fan was studied in a smoking room in which negative room pressure was maintained (Fig. 5). Pollutant leakage was studied when the room had a sliding door and a swinging door. The calculation cases for CFD analysis are shown in Table 5. The steady state was calculated and then the unsteady state resulting from door movement was calculated. The inter-zonal air exchange rate was assessed for a smoking room with an air exchange rate of 5 times/h, 12 times/h, 30 times/h, and 77 times/h. The air exchange rate of 77 times/h is a value of the design guideline proposed as the air velocity 0.2m/s at the door of smoking room. In addition, human movement was also added to instances with an air exchange rate of all cases.

3 RESULTS

3.1 Verification of the results of CFD analysis

The visualized air flow at different times during door opening and closing and the results of CFD analysis are shown in Fig. 2. The standard k-ε turbulence model used in CFD analysis used the Reynolds average, so precise changes in turbulence characteristics over time could not be reproduced. However, flow characteristics around the door were similar to that actually visualized. Measurements of the flow rate variation in the x and y directions (the ensemble average determined based on 50 measurements) at the measurement site are shown in Fig. 3. These measurements were compared to the results of CFD analysis. Measurements and results of CFD analysis differed by 0.1 m/s or less. Measurements and CFD analysis yielded quite similar characteristics of flow rate variation over time as well. Concentration decay as a result of the number of times the door was opened or closed per hour was measured, as shown in Fig. 4(a). The absolute rate of inter-zonal air exchange minus the effects of the rate of natural air exchange was compared to the results of CFD analysis, as shown in Fig. 4(b). The number of times the door was opened or closed per hour was proportional to the absolute rate of inter-zonal air exchange. The measured absolute rate of inter-zonal air exchange (0.49 m^3) as a result of opening and closing the door once differed little (0.06 m^3) from the result of CFD analysis (0.43 m^3), so the results roughly coincided.
Comparison of the 3 measurements mentioned and CFD analysis verified that measurements and results of CFD analysis differed little. Results of CFD analysis were highly consistent with actual measurements.

3.2 Evaluation of ways to decrease leakage of pollutants from a smoking room

(1) Evaluation results on air curtain effect

The results of CFD analysis with corridor temperature in air curtain non-operation are shown in Fig. 6, and the results of CFD analysis in air curtain operation are shown in Fig. 7. The results in air curtain non-operation show that the leakage rates of pollutant from smoking room was increased with increasing the difference of air temperature between smoking room and corridor because the drive force was increased by difference of air density. By contrast, the results in air curtain operation show that the leakage rates of pollutant was high than air curtain non-operation cases irrespective of the difference of air temperature because the turbulence diffusivity was increased due to the air flow from an air curtain.
The results of the cumulative inter-zonal air exchange rate in all calculation cases are shown in Fig. 8. Although using sliding door limited the inter-zonal air exchange rate more than using of swinging door under isothermal condition, it was totally ineffective under thermal condition. Moreover, although the air curtain operation was ineffective when the temperature differential between smoking room and corridor is little, the air curtain operation was predictably effective when the temperature differential is large. That is more effective under cooling mode than heating mode of smoking room.

(2) Evaluation results on exhaust fan effect

The results of CFD analysis with a sliding door and a swinging door, an air exchange rate of 5 times/h by exhaust fan, and no human movement are shown in Fig. 9, and the results of CFD analysis with an air exchange rate of 5 times/h and 77 times/h, and human movement are shown in Fig. 10. The sliding door resulted in less pollutant concentration leaking into the corridor than did the swinging door, but a large concentration of pollutants leaked when a person left the smoking room and entered the corridor. The cumulative effective air exchange in 6 sec with air change rates is shown in Fig. 11. Based on the calculated results, a sliding door resulted in a lower inter-zonal air exchange rate, and the small amount of pollutant leakage into the corridor was verified quantitatively. In addition, the effective air exchange rate for the smoking room approximated an exponential function with $Q_{eff}=0.493e^{-0.029n}$ when the room had a swinging door and $Q_{eff}=0.063e^{-0.023n}$ when it had a sliding door. Moreover, the inter-zonal air exchange rate increased when human movement was included, and the sliding door resulted in a greater rate of increase in the inter-zonal air exchange rate.

4 CONCLUSIONS

This study predicted the inter-zonal air exchange rate commensurate with door opening and closing and human movement, and this study examined ventilation to effectively prevent pollutant leakage from a smoking room. Based on the results, this study yielded the following conclusions:

(1) There was little difference between actual measurements and results of CFD analysis, so CFD analysis was verified to be consistent with actual findings.
(2) The air curtain operation was ineffective to decrease the inter-zonal air exchange rate when the temperature differential between two adjacent spaces is little, the air curtain operation was predictably effective when the temperature differential between two adjacent spaces is large. Moreover, it is more effective under cooling mode than heating mode.
(3) Use of a sliding door in a room with an exhaust ventilation system limited the inter-zonal air exchange rate more than use of a swinging door. However, the inter-zonal air exchange rate increased when human movement was combined with use of a sliding door.

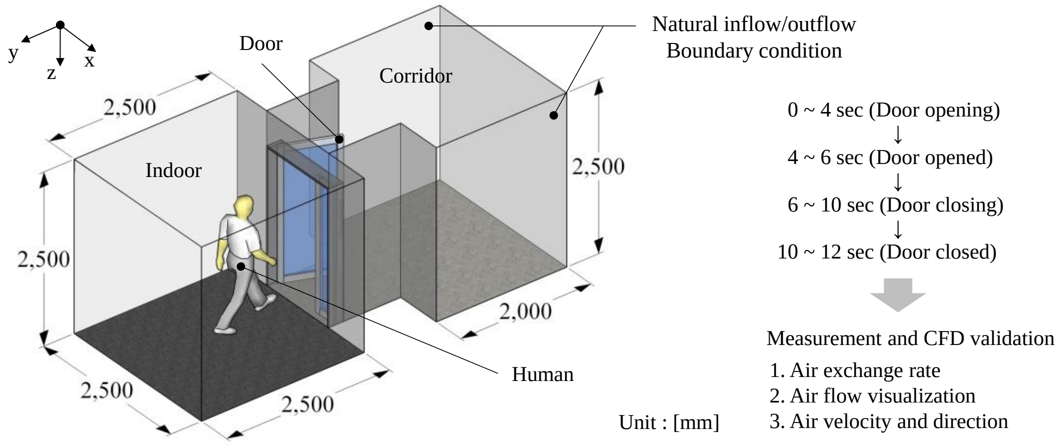


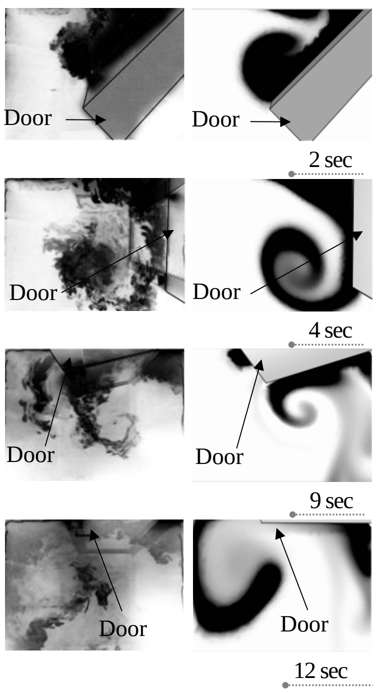
Figure 1: Schematic of calculation model

Table 1: Measurement units

Item	Contents
Air exchange rates	Multi-gas monitor (INNOVA 1312), Multipoint sampler (INNOVA 1303), SF_6
Air flow visualization	Water and glycol-based smoke generator, Nd:YV04 laser at 532 nm
Air velocity and direction	3D ultrasonic anemometer

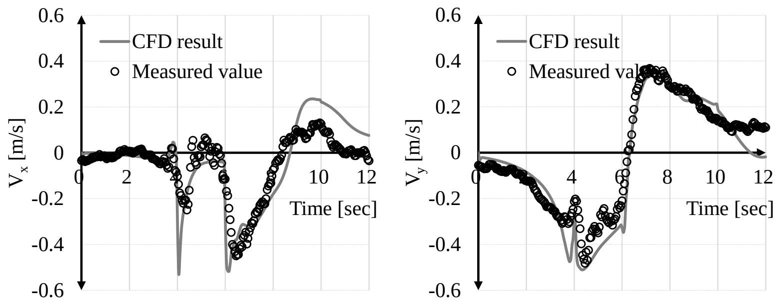
Table 2: Boundary condition for CFD analysis

Item	Contents
Indoor	2500(x) × 2500(y) × 2500(z) mm
Swing door	800(x) × 50(y) × 2100(z) mm (0.084 m^3, adiabatic) π/8 rotational motion (0~4sec : door opening, 6~10sec : door closing)
Turbulence model	High-Reynolds number k-epsilon model
Meshes (Moving object)	About 3,000,000 (Overset mesh technique)
Time dependent	Transient calculation (Courant number < 1)
Scheme	MUSCL scheme
Coefficient of mass diffusivity (SF_6)	1.6×10^{-5} m^2/s
Initial condition of SF_6 gas	C_s (indoor) = 1.0, C_s (corridor) = 0.0
Thermal condition	Isothermal condition



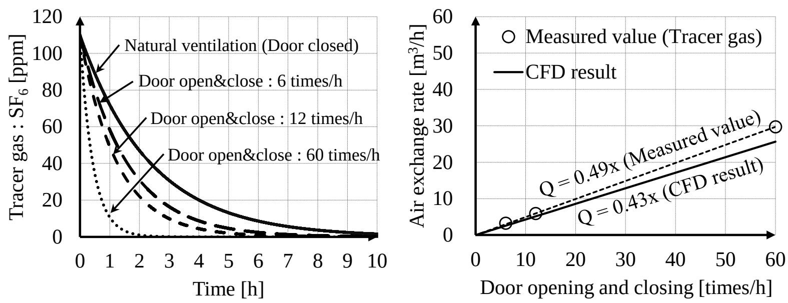
(a) measure (b) CFD

Figure 2: Airflow visualization



(a) air velocity in x-direction (b) air velocity in y-direction

Figure 3: Air velocity and air direction by 3D ultrasonic anemometer



(a) tracer gas decay (b) air exchange rate

Figure 4: Air exchange rate by tracer gas method

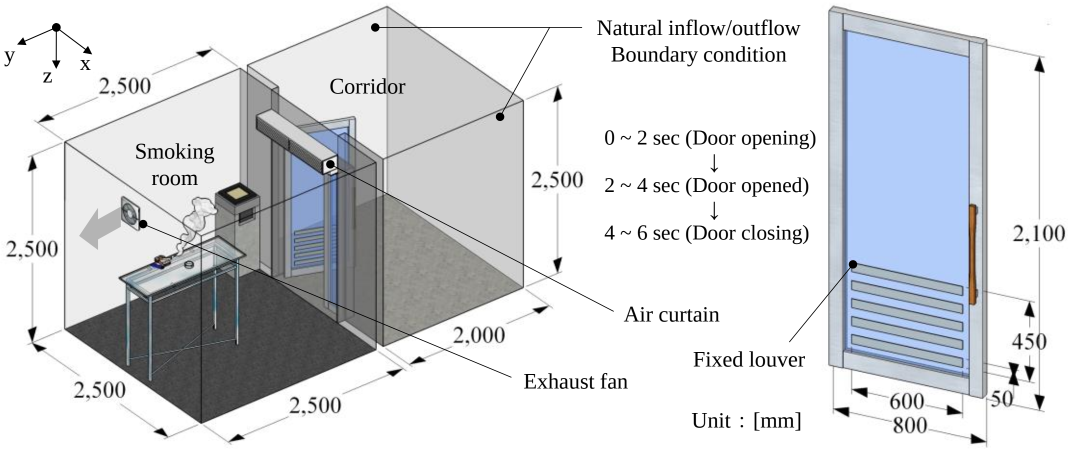


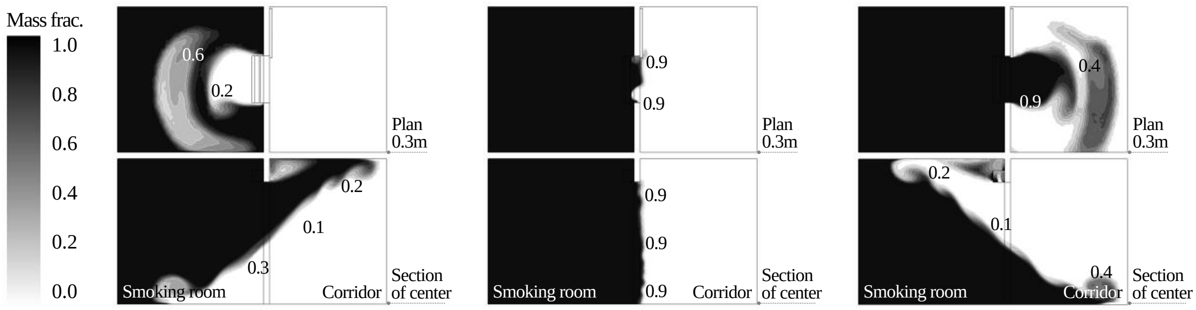
Figure 5: Schematic of smoking room model and detail of door

Table 3: Boundary condition

Item	Contents
Smoking room	2500(x) × 2500(y) × 2500(z) mm
Corridor	2500(x) × 2000(y) × 2500(z) mm
Human	690(x) × 27(y) × 1700(z) mm (0.053 m^3, adiabatic)
Door	800(x) × 50(y) × 2100(z) mm (0.084 m^3, adiabatic)
Fixed louver of door	600(x) × 50(z) mm (5 columns)
Exhaust Fan	300(y) × 300(z) mm
Air curtain (Inlet of air curtain)	800(x) × 200(y) × 200(z) mm (800(x) × 30(y) mm, v = 6.0 m/s)
Time dependent	Transient calculation after steady calculation

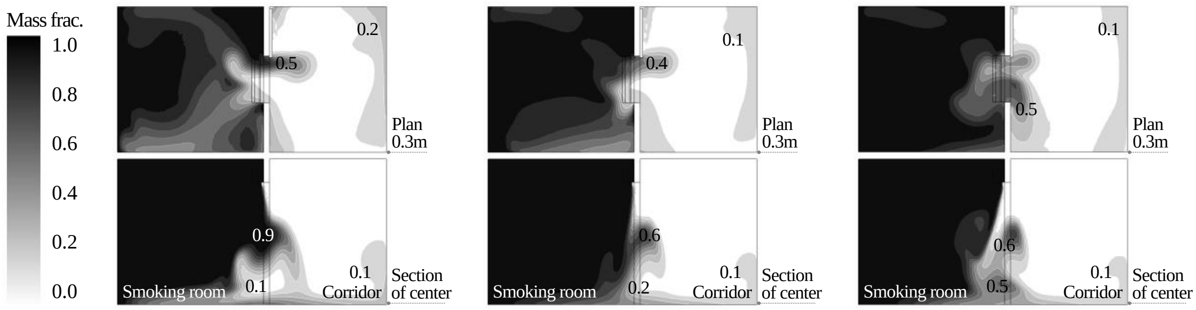
Table 4: Thermal calculation cases (36 cases)

Item	Contents
Smoking room temperature	20 ºC (fixed)
Corridor temperature	0, 5, 10, 15, 20, 25, 30, 35, 40 ºC (9 cases)
Door type	Swing door, Slide door (2 cases)
Air curtain operation	On / Off (2 cases)



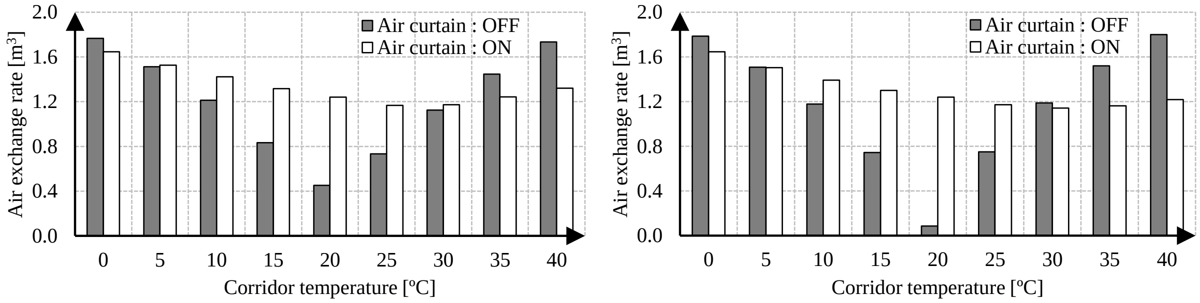
(a) Room : 20 ºC, Corridor : 0 ºC (b) Room : 20 ºC, Corridor : 20 ºC (c) Room : 20 ºC, Corridor : 40 ºC

Figure 6. Calculated results with corridor temperature in air curtain non-operation (at 4 seconds)



(a) Room : 20 ºC, Corridor : 0 ºC (b) Room : 20 ºC, Corridor : 20 ºC (c) Room : 20 ºC, Corridor : 40 ºC

Figure 7. Calculated results with corridor temperature in air curtain operation (at 4 seconds)

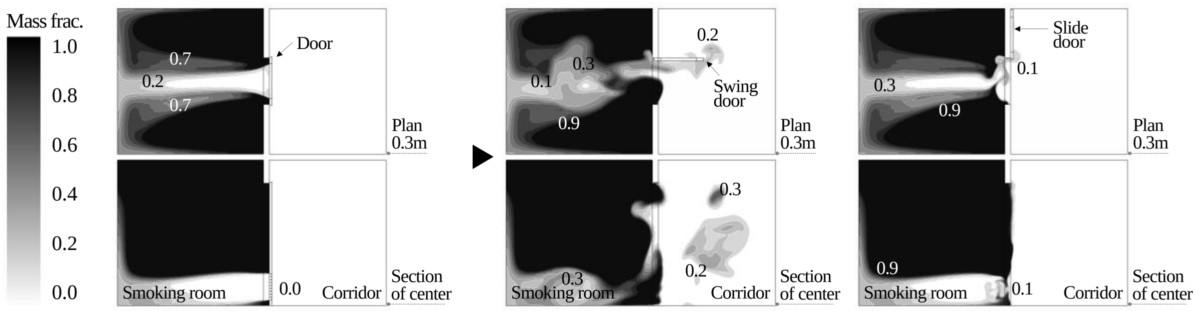


(a) swing door (b) slide door

Figure 8. Calculated results of cumulative inter-zonal air exchange rate with corridor temperature

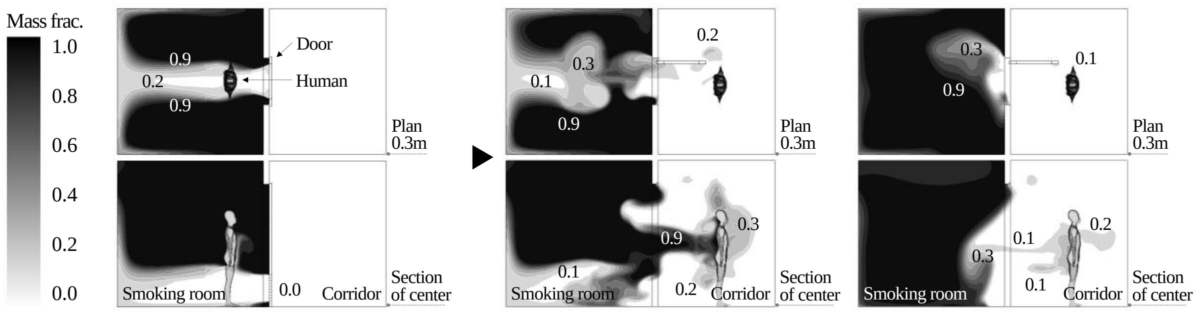
Table 5: Isothermal calculation cases (16 cases)

Item	Contents
Smoking room temperature	20 ºC (fixed)
Corridor temperature	20 ºC (fixed)
Air change rate (negative pressure)	5, 12, 30, 77 times/h (4 cases)
Door type	Swing door, Slide door (2 cases)
Human movement (1 m/s linear motion)	On / Off (2 cases)



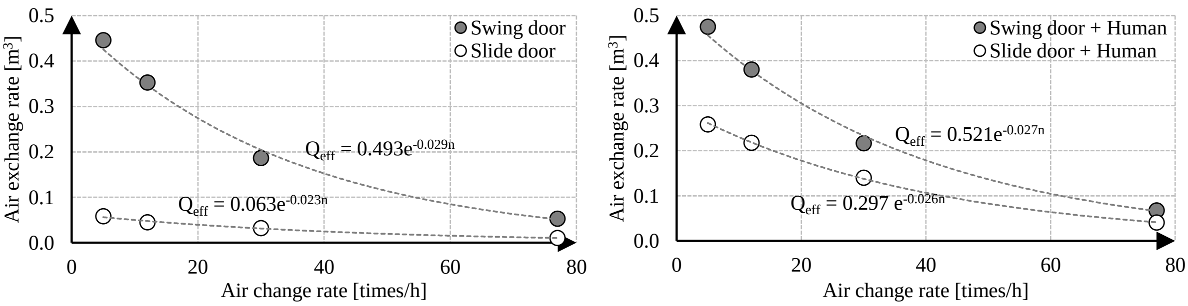
(a) t=0sec (steady) (b) t=4sec (transient, Left : swing door, Right : slide door)

Figure 9. Calculated results of contaminant distribution with door type (5 times/h)



(a) t=0sec (steady) (b) t=4sec (transient, Left : 5 times/h, Right : 77 times/h)

Figure 10. Calculated results of contaminant distribution with air change rate (swing door + human)



(a) door only (b) door + human

Figure 11. Calculated results of cumulative inter-zonal air exchange rate with air change rate

5 ACKNOWLEDGEMENTS

This study was made possible by the financial support received from Tokyo University of Science, Japan. We would like to thank students of Tokyo University of Science, for their generous cooperation.

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