Study on evaluation of ventilation effectiveness of occupied space in smoking room with the highly-efficient ventilation system

T. Endo
Kanto Gakuin University, Japan

T. Kurabuchi
Tokyo University of Science, Japan

ABSTRACT

An investigation to understand the actual conditions of smoking spaces was conducted, and it became clear that the introduction of a highly-efficient ventilation system is necessary, in addition to the securing of a sufficient ventilation volume. In addition, case studies using CFD and experiments were conducted on the effects of introducing a highly-efficient ventilation system to smoking rooms. As a result, a unidirectional ventilation system with a floor to ceiling airflow, such as a vertical tornado system, is highly effective for the improvement of the air environment in smoking rooms, when compared to ordinary mixing ventilation systems.

1. INTRODUCTION

In order to prevent environmental tobacco smoke (ETS) exposure from passive smoking, the Ministry of Health, Labour and Welfare has formulated the Guidelines for Measures on Smoking in the Workplace, in which certain standards are set concerning the installation of smoking rooms in order to promote a smoking ban and the separation of smoking areas. On the other hand, there is concern regarding the deterioration of the air environment in smoking spaces. In this study, an investigation was conducted on existing smoking rooms in which large ventilation volumes were secured and the possibility of introducing highly-efficient ventilation systems into the smoking rooms, based on

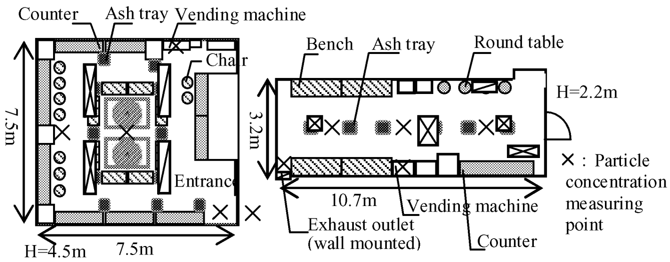


Fig. 1 Floor plans of the target smoking rooms (Left: building A, Right: building B)

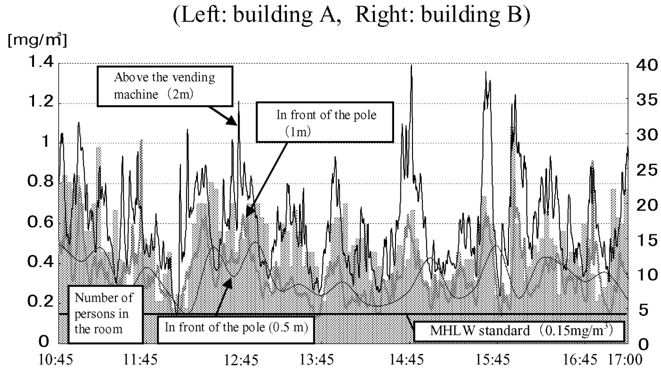


Fig. 2 Changes of particle concentration and number of persons in the room (building A, vertical distribution)

Table 1. Target smoking rooms outline

	Building A	Building B
Dimensions [m]	7.5*7.5*4.5	3.2*10.7*2.2
Volume [m^3]	253	75.3
Floor area [m^2]	56	34.2
Design discharge air volume [m^3/h]	4300	4300
Design ventilation rate [times/h]	17	57
Number of users [persons]	Approx. 950	Approx. 1450
Average number of persons in the room [persons]	14.0	15.3
Average occupancy density [persons/m^2]	0.25	0.45
Average particle concentration [mg/m^3]	0.46	0.56

the fact that the indoor particle concentrations substantially exceeded the standard value of 0.15 mg/m^3. Upon confirming the reproducibility of the CFD concerning the indoor air contaminant level distribution of the smoking rooms, a case study was conducted through the use of CFD which simulated the smoking and length of stay of smokers, and experiments were conducted in order to study a highly-efficient ventilation system. The following is a report of the results of the study.

2. INVESTIGATION OF EXISTING SMOKING ROOMS

2.1 Outline of Measurements

Measurements were taken of smoking rooms of buildings in Tokyo, with each room being measured for 2 days. Indoor and outdoor particle concentrations were measured by 7 particle counters, and the number of users in each room per day (the number of people entering and leaving the rooms being counted), smoking durations, amount of time spent in the rooms, and the average number of cigarettes smoked were visually counted by observers stationed outside the rooms. The floor plans of the target rooms are shown in Fig. 1. Building A had 2 ceiling air inlets and 2 ceiling exhaust outlets and building B had 4 ceiling air inlets (2 external air inlets, 2 inlets from outdoor pathways), 1 ceiling exhaust outlet, and 1 wall exhaust outlet. In building B, chairs were only placed in the back of the room so as to direct the smokers toward the exhaust outlet at the end of the room. Overviews of the smoking rooms are given in Table 1. The exhaust air volume was measured by means of a tracer gas after opening hours for general users had ended in building B to confirm that the exhaust air volume was approximately the same as the design value.

2.2 Measurement Results

The time-series changes of the particle concentration and the number of people in the room of building A are shown in Fig. 2. Since building A has a high ceiling and the air is only exhausted through the ceiling, a tendency was observed in which the higher the measuring point was, the stronger the particle concentration. In both buildings, a significant correlation was observed between changes in the number of people in the room and changes in the particle concentration, and the average particle concentrations exceeded the standard value prescribed by the Ministry of Health, Labour and Welfare (0.15 mg/m^3), as shown in Table 1. From this result, it appears that an increase in the ventilation is not a sufficient response in spaces where large amounts of contaminants are generated; instead, a highly-efficient ventilation system must be introduced (other detailed results are described in ref. Endo 2008)

3. STUDY OF A HIGHLY-EFFICIENT VENTILATION SYSTEM

3.1 CFD outline

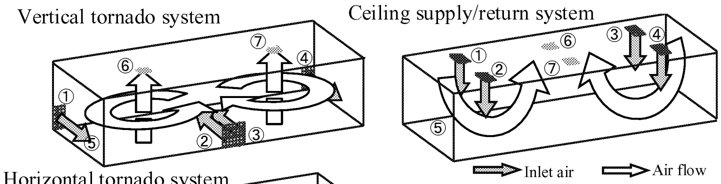
In general, a ceiling supply/return system is adopted as the air conditioning system of a smoking room. In such cases, however, indoor air basically becomes a uniform mixture condition. On the other hand, ventilation efficiency is expected to improve if indoor airflow is turned into a one-way plug flow by separating the diffuser and inlet. At this time, we examined the introduction of a tornado ventilation system that generates a swirl flow in the rooms (Fig. 3). A vertical tornado ventilation system generates a swirl flow which has an axis in the vertical direction of the room, thus forming a flow field running in a floor to ceiling direction. A horizontal tornado ventilation system generates a flow field that runs in a front to back direction across the room by means of a swirl flow which has an axis in a horizontal direction. Three cases of these ventilation systems and a common type ceiling supply/return system were studied by means of CFD. The values shown in Fig. 3 based on the results of the actual measurements were used for the dimensions of the room and the inlet/outlet. A high Reynolds number k-ε model was used as the turbulence model, and the SIMPLE method was used as the calculation algorithm. As for the difference schemes, QICK was used for u, v, and w and MARS for k and ε. Additionally, in analyzing the indoor air flow, heating elements simulating the human body, shown in Fig. 4, were used in order to reproduce the generation of thermals and contamination from human bodies (Ito, 2006, [2]). The number of the first mesh around the human body model was 2783, and a wall function was applied to reduce the computation load. Mesh segmentation for high precision convection heat transfer prediction was not performed. The surface temperature of the model was set as 34 deg., the convection heat transfer coefficient α_c was set as 4 W/(m^2*K), and 0.96 m^3/h per body of contaminated air at 32 deg. was generated from the mouth of the human body (Hayashi, 2000). Based on the obtained computation results, IAQ evaluation was conducted using the air change efficiency ε^a and contaminant removal effectiveness (CRE) ε^c (Table 2) as indexes of the ventilation efficiency. ε^a is an indicator of the indoor air exchange capacity that does not assume the existence of contaminated air, whereas ε^c is an indicator of how low the retention of contamination is in cases in which actual contamination generation is assumed.

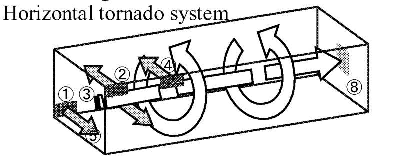
3.2 Results of CFD

The actual smoking rooms measured were made into rather simple models (Fig. 5) in order to check the consistency between the CFD results and the actual measurement results. The number of people in the room was set as 15, which is the average value of the actual measurement results, and the concentration at each point was made non-dimensional by dividing it by the concentration at the outlet of the measuring point (4), and was compared with the actual measurement results. It was confirmed that the contamination distribution basically corresponded to the actual measurements (Table 3, Fig. 6).

3.2.1 Air change efficiency

CFD was performed for the study model of Fig. 3, setting 0, 4, 8 and 12 as the number of users in the room. The results of the study of air change efficiency are shown in Fig. 7. In an empty room, the horizontal tornado system showed a value as high as ε^a= 0.87, and the ventilation condition was similar to plug-flow ventilation. On the other hand, the air change





Room volume	92.16 [m³]
Dimensions	9.6×4.0×2.4[m]
Ventilation volume per 1 m^2	50 [m³/h・m²]
Ventilation volume	1920[m³/h]
Ventilation rate	20.83 [times/h]

		Dimensions[m]	Air flow[m^3/h]	Wind speed[m/s]
①～④	SA	0.4*0.4	405	0.35
⑤	Door air flow [1]	2.0*2.0	300	0.21
⑥⑦	EA	0.4*0.4	Vertical tornado system, Ceiling supply/return system	
⑧	EA	0.8*0.8	Horizontal tornado system	

Fig. 3 Outline of the ventilation system and the studied model

Table 2. Indexes used for evaluation of the study model

Air change efficiency ε^a

$$\varepsilon^a = \tau_n / 2\overline{\tau}$$

$0 \leqq \varepsilon^a \leqq 1$, 0.5 in a uniform mixture condition
Upper limit 1 with plug flow

Contaminant removal effectiveness (CRE) ε^c

$$\varepsilon^c = Ce / \overline{C}$$

1 in a uniform mixture condition
When the number is greater, CRE is higher.

Nominal time constant τ_n

$$\tau_n = V/Q$$

Occupied area CRE ε^{co}

$$\varepsilon^{co} = Ce / \overline{C^o}$$

The concentration of the room is evaluated withεc in the Occupied area
Occupied area : space within 1.8 m or less of the floor and 0.6 m or more of the wall or air condi-

Q : Ventilation volume
V : Room volume
Ce : Emission concentration
$\overline{\tau}$: Average age of air in the room
$\overline{C}$: Indoor average concentration
$\overline{C_o}$: Occupied area average concentration

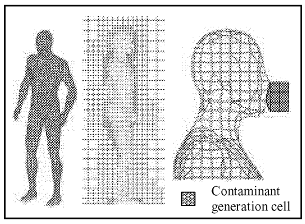
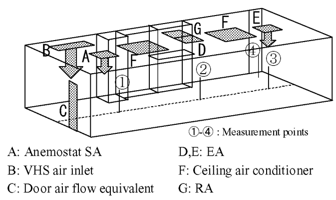


Fig. 4 Heating element model

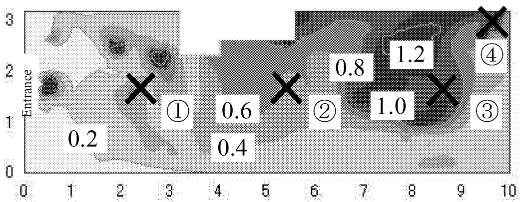


Room volume	75.3 [m³]
Dimensions	10.7×3.2×2.2 [m]
Ventilation volume	4300 [m³/h]
Ventilation rate	57.3 [times/h]

Fig. 5 CFD study model of an existing smoking room

Table 3. Result of contaminant concentration made non-dimensional

	①	②	③	④
Experiment	0.56	0.67	0.76	1
CFD	0.47	0.56	0.81	1



Distribution of the contamination concentrations made non-dimensional by dividing them by the emission concentrations.

Fig. 6 CFD study result of contamination distribution in an existing smoking room

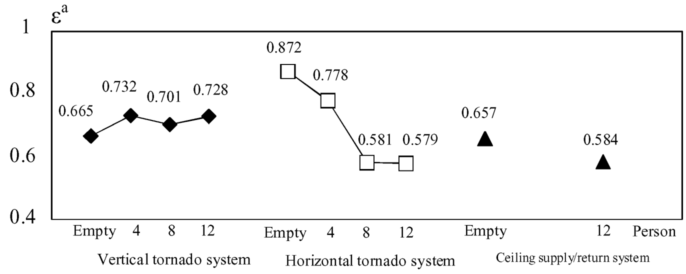


Fig. 7 Air change efficiency ε^a

efficiency of both the vertical tornado system and the ceiling supply/return system was approximately $\varepsilon^a = 0.65$. In the case of assuming there are 12 people in the room, the air change efficiency for the horizontal tornado system decreased significantly to $\varepsilon^a = 0.58$. This was due to the swirl flow from front to back of the room generated while the room was empty being disrupted by thermals generated from the human body models, as shown in Fig 8. On the other hand, the air change efficiency of the vertical tornado system increased to $\varepsilon^a = 0.73$. This is believed to be due to the contribution of thermals to the formation of an upward plug-flow (Fig. 9). The air change efficiency of the ceiling supply/return system decreased, as in the case of the horizontal tornado system.

3.2.2 Contaminant removal effectiveness (CRE)

The results of CRE calculations performed based on the results of contamination concentration distribution are shown in Fig. 10, and the contamination concentration of each point divided by the exhaust concentration and made non-dimensional is shown in Fig. 11. The CRE of the horizontal tornado system was $\varepsilon^c = 1.00$, which is the same value as that of the uniform mixture condition. This is due to the disruption of the swirl flow, as was confirmed when examining the room air change As for the ceiling supply/return system, although it assumes a uniform mixture condition of indoor air, its CRE showed a relatively high value of $\varepsilon^c = 1.62$, due to the convection flow of contaminants to the floor. Compared to these systems, the vertical tornado system showed a higher CRE of $\varepsilon^c = 3.25$. In addition, it was confirmed that the CRE was higher in occupied areas than it was in the overall area in all cases. This shows that the average particle concentration in occupied areas was lower than that of the entire room. The vertical tornado system showed an especially high value of $\varepsilon^{co} = 4.89$, a result from which it can be expected that there will the effect of improving the air environment to which users of smoking rooms are exposed.

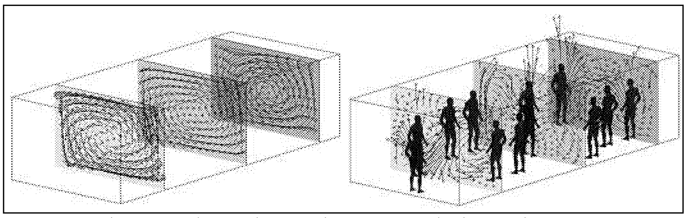


Fig. 8 Horizontal tornado system wind speed vector

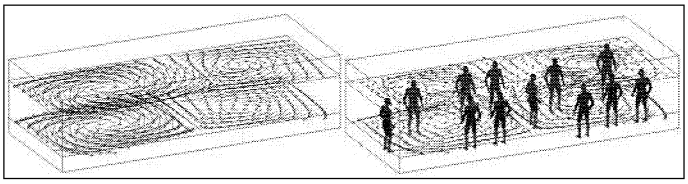


Fig. 9 Vertical tornado system wind speed vector

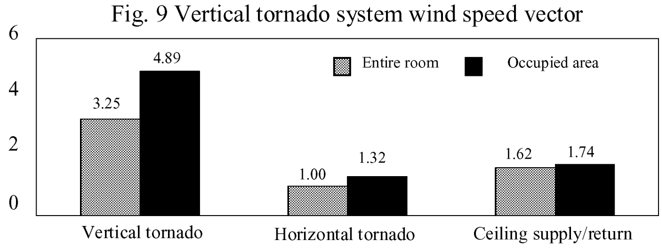


Fig. 10 CRE ε^c, ε^{co}

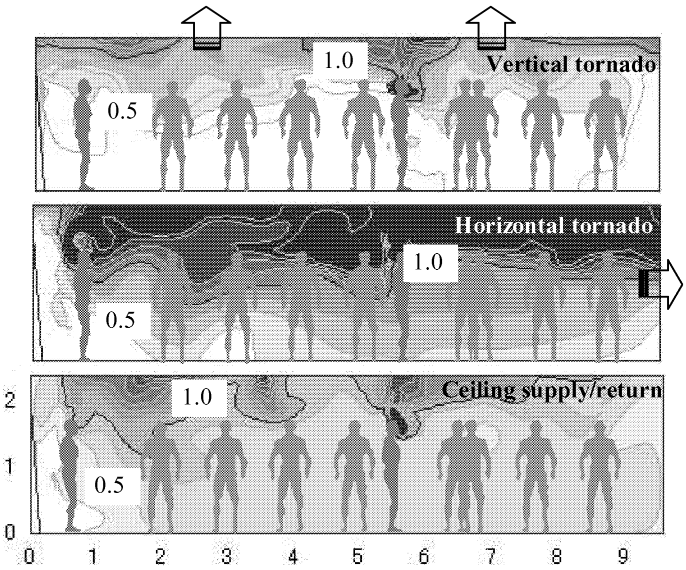


Fig. 11 Distributions of contamination normalized by the exhaust air concentrations

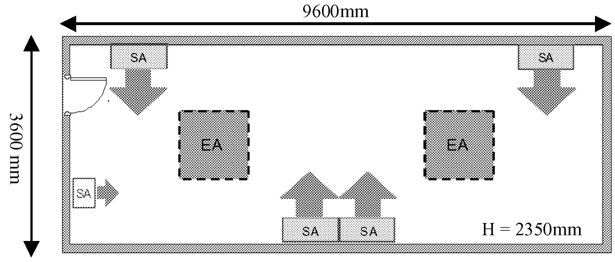


Fig. 12 Test room floor plan (layout for the vertical tornado system)

3.3 Reproduction experiment outline

The highly-efficient ventilation system suggested by the CFD was reproduced in a full-scale test room to study the air change efficiency and the CRE. The experiment was conducted using the performance testing device for Next Generation Air-Conditioning System Laboratory of the Kanto Gakuin University. The outline of the test room is shown in Table 4 and the overview of the test room when implementing the vertical tornado system is shown in Fig. 12. The ventilation rate was set as 25 times/h. The ceiling supply/return system was designed to supply air from 8 anemostat diffusers installed on the ceiling surface and to exhaust from 2 locations on the ceiling surface. The vertical tornado system and the horizontal tornado system were the same as the CFD conditions described in Fig. 3. In a total of 54 locations, 18 locations in the horizontal direction, and 3 locations in the vertical locations of the room, the age of the air was measured using the decay method (using SF6 as a tracer gas) to obtain the air change efficiency. In experiments in occupied rooms, 12 heating elements made with flexible ducts (zinc coated steel) and incandescent bulbs (60 W+40 W) were used as alternatives for human bodies for the locations of the CFD. The surface area and surface temperature of the heating elements were set so as to meet the CFD conditions. Cigarettes were placed on the heating elements, and CRE was calculated based on the particle concentration of secondhand smoke. The measuring points were the same as the measuring points for the age of the air. The external appearance and the cigarettes placed on the heating elements are shown in Fig. 13.

3.4 Experimental Results

3.4.1 Air change efficiency

The results of the air change efficiency are shown in Fig. 14. The CFD results were as previously listed. Due to differences in the gap dimensions, etc., effectiveness was low overall. In the figure, graphs that use the results of the

Table 4. Test room overview

Room volume	81.2 [m^3]
Dimensions	^{W}9.6 m × ^{D}3.6 m × ^{H}2.35 m
Ventilation volume	Approx.2,000 [m^3/h]
Ventilation rate	Approx.25 [times/h]
Nominal time constant	144 [s]

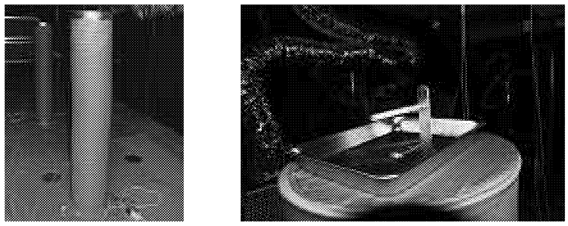
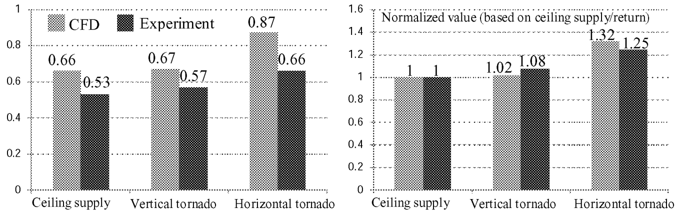
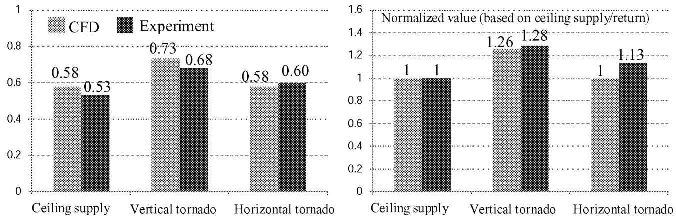


Fig. 13 Heating elements and placement of cigarettes

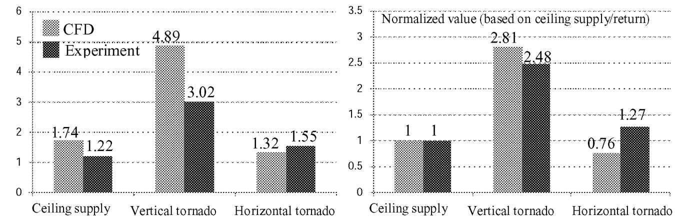


Air change efficiency/empty room



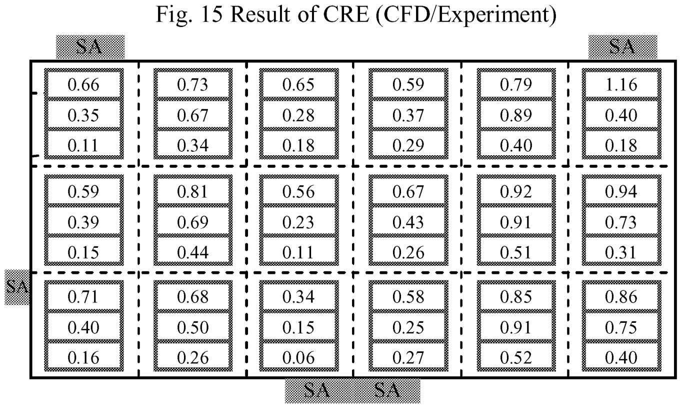
Air change efficiency/with heating elements

Fig. 14 Result of air change efficiency (CFD/Experiment)



CRE/with heating elements

Fig. 15 Result of CRE (CFD/Experiment)



Top column: 1400 mm high, middle column: 600 mm high, bottom column: 100 mm high

Fig. 16 Horizontal contamination distribution made non-dimensional using the exhaust concentrations ceiling supply/return system as the benchmark are also shown. When the room was empty, the air change efficiency of the horizontal tornado system was more than 1.25 times that of the ceiling supply/return system, which was the most effective result, as in the CFD. As for the air change efficiency when the heating elements were introduced, the effectiveness of the vertical tornado system was 1.28 times that of the ceiling supply/return system due to the effect of thermals generated by the heating elements, which was the most effective result, as in the CFD.

3.4.2 Contaminant removal effectiveness (CRE)

The CRE results (using the heating elements) are shown in Fig. 15 (the CFD results are also as previously listed). The vertical tornado system showed an effectiveness of ε^{co} = 3.02, approximately twice that of other systems. Although the value was lower than that of the CFD results, it was approximately 2.5 times the efficiency of the ceiling supply/return system, which is close to the CFD result. An example of a contamination distribution result (vertical tornado system) made non-dimensional by dividing the contamination concentrations by exhaust concentrations is shown in Fig. 16. As in the CFD, a relation between the concentration and the vertical direction was also observed in the experiment, showing that the air environment became cleaner in the lower section of the room.

4. CONCLUSIONS

An investigation to understand the actual conditions of smoking spaces was conducted, and it became clear that the introduction of a highly-efficient ventilation system is necessary, in addition to the securing of a sufficient ventilation volume. In addition, case studies using CFD and experiments were conducted on the effects of introducing a highly-efficient ventilation system to smoking rooms. As a result, a unidirectional ventilation system with a floor to ceiling airflow, such as a vertical tornado system, is highly effective for the improvement of the air environment in smoking rooms, when compared to ordinary mixing ventilation systems.

NOTES

[1] Assuming a louver attached to the side of the door and a wind speed that satisfies the condition requiring the “taking of necessary measures to ensure that the velocity of air flow from a non-smoking area to a designated smoking area, etc., is 0.2 m/s or higher,” prescribed in the “Guidelines for Measures on Smoking in the Workplace” issued by the Ministry of Health, Labour and Welfare.

[2] From the computation at this time, only the convective heat transfer has been coupled without coupling radiation and all sensible heat generation has become convection heat that causes thermals from the human bodies to be overrated.

REFERENCES

Endo, T., Kurabuchi, T. and Asari, Y., (2008). Study on Improvement of Air Environment of Smoking Rooms by Introduction of Highly-Efficient Ventilation System, part 2 Actual Measurements and CFD Reproduction Test in a Full-scale Test Room. Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan. (in press).

Hayashi, T., Kato, S., Murakami, S. and Zeng, J., (2000). CFD Analysis of Passive Smoking by Means of Micro Climate Around the Human Body. Journal of architecture, planning and environmental engineering, Transactions of AIJ No. 533, pp.17–21.

Ito, K., Hotta, T., (2006). Development of Virtual Mannequins and Their Grid Library for CFD Analysis. Transactions of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (technical paper) No. 113, pp.27–34.

Ministry of Health, Labour and Welfare, (2005). Report on the “Study Committee for Promotion of Effective Smoking Area Separation,” Ministry of Health, Labour and Welfare.

Ministry of Health, abour and Welfare, Report on the criteria decision board on the effect of segregated smoking, Ministry of Health, Labour and Welfare.