A study on the effect of the airflow rate of the ceiling type air-conditioner on the ventilation performance

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SUMMARY

We performed a study on the effect of the discharge airflow rate of the ceiling type air-conditioner on ventilation performance in the lecture room with the mixing ventilation. The experiments and CFD were conducted for analyzing ventilation performance. The concept of mean air age and indoor CO_2 concentration were used for evaluating ventilation performance. We made the CO_2 generation model in the simulation and calculated a lot of cases with respect to the airflow rate of air conditioner and the ventilation flow rate. And the selected experimental measurements were performed in the lecture room of the same layout as the numerical one for verifying simulation results. Mean air age is gradually increased, but CO_2 concentration is oppositely decreased in the occupied zone with the increment of the discharge airflow rate of the ceiling type air-conditioner. This result shows that both of mean air age and residual life time must be considered for evaluating ventilation performance when the contaminants are generated indoors. And the increment of discharge airflow of the ceiling type air-conditioner can induce the piston effect and push the contaminants out of the occupied zone. From this result, it is found out that that ventilation performance can be increased when the momentum source like an air-conditioner is used in the room with the mixing ventilation.

INTRODUCTION

Recent studies [1-4] showed that many buildings have poor indoor air quality, and especially CO_2 concentrations measured in the room exceeded the present guideline [5]. In this case, the role of ventilation is very important as the strategy for more comfortably indoor environment because CO_2 cannot be removed by present air cleaning systems. Accordingly, various researches on the improvement of ventilation performance as well as ventilation itself have been carried out. In the view of IAQ, Lee and Chang [2] investigated the indoor and outdoor air quality of the five classrooms at five different schools in Hong Kong and pointed that PM_{10} and CO_2 concentration exceeded the HKIAQ limits due to the high outdoor PM_{10} concentration and inadequate ventilation respectively. Daisey et al. [3] reviewed the literature on IAQ, ventilation and health symptoms in schools and showed that ventilation was inadequate in many classrooms, possibly leading to health problems. Noh and Oh [4] performed the numerical study on the comparison of ventilation performance with variations of indoor momentum source such as air-conditioners, air cleaners and ceiling fan for displacement and mixing ventilations. They found out that ventilation performance is getting better or worse with variations of the intensity and the location of momentum source due to that the intensity and the location of momentum source affect the residence time of air in the room.

However, there are hardly ever studies on effect of the air discharge intensity of the personal air-conditioning systems such as indoor air-conditioners, air cleaners, and fans in school buildings on the ventilation effectiveness until now. Therefore we performed the experiments and numerical simulations in a lecture room with a ceiling type air-conditioner and a ventilation system. With variations of the air discharge rate of the ceiling type air-conditioner and occupancy, CO_2 concentrations and local mean air-ages during class hours were investigated and the effect of the air discharge intensity of a ceiling type air-conditioner on ventilation effectiveness was analyzed.

RESEARCH METHODS

Model descriptions

Fig. 1 shows the schematic design of a real lecture room which is presently used in one of universities in Korea. The dimensions of this room are 11.2m (L) x 6.65m (D) x 2.4m (H). This lecture room has 3 windows and 2 doors. The lecture room was generally occupied by 20 to 30 people including a lecturer and students when the experiments were carried out. In order to control the thermal loads in the lecture room, the ceiling type 4-way cassette air-conditioner. It is located at the center of this room. The discharge airflow of this air-conditioner is discretely varied from $0m^3$/hour to 1600 m^3/hour, while the discharge angle is fixed to 30 degrees when the experiments were conducted. The ventilation system is composed of 4 supply diffusers, 4 exhaust ones, and a heat exchanger. Locations of supply and exhaust diffusers are determined to optimize the ventilation effectiveness.

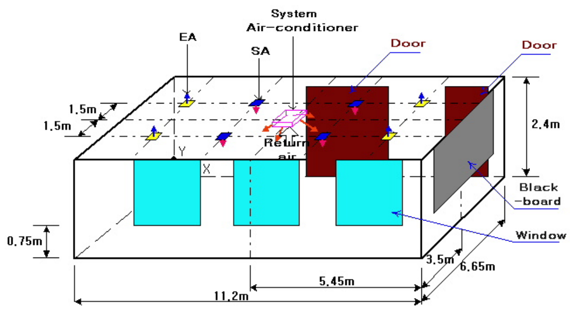


Fig. 1 Layout of the lecture room

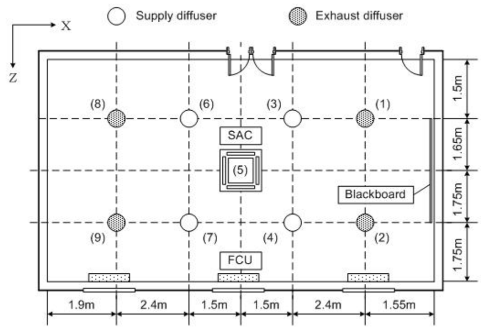


Fig. 2 Measuring points of the lecture room

Experiments

We measured CO_2 concentration and mean air age in the lecture room with respect to the discharge airflow rate of the ceiling type 4-way cassette air-conditioner. The discharge airflow rate was varied from 0 to $1600m^3$/hour and ventilation rate was fixed to be $800m^3$/hour when experiments were carried out. Based on the previous study [1], the discharge angle of the ceiling type 4-way cassette air-conditioner is fixed to be 30 degrees. As shown in Fig. 2, 9 measuring points were selected to analyze the local or the room-averaged performance for ventilation effectiveness. Sampling probes were placed at 1.1m high from the bottom. The experiments for each case were repeated over three times in the same case. All the measured values of indoor CO_2 were compensated according to the outdoor CO_2 variation. In the case of CO_2 concentrations, all experiments were conducted during the class hours and 20 people were asked not to move around. To examine the mean air age, all experiments were conducted after the class hours. SF_6 gases were released in the supply duct and were sampled at the same points like the case of CO_2 measurement. IAQ monitor (Graywolf, model IAQ-410; USA), Thermal comfort data logger (Innova, model 1221; Denmark), The multi gas monitor (Innova, model 1314; Denmark) were respectively used for CO_2 measurement, velocity and air temperature, and SF_6 measurement

CFD simulations

We adopted this numerical model with appropriate boundary conditions as a prediction tool for a couple of operating conditions. We considered the discharge airflow rate of 4-way cassette air-conditioner and the number of people as the control variables. All the occupants with hexagonal shapes sitting on were modelled as the rectangular objects with 1.2m height and the volume of $1.62m^3$. The CO_2 concentration emitted from occupants' mouth was selected to be $0.014m^3$/hour [5].

The flow in the lecture room was assumed to be 3D steady and incompressible [4]. The standard k-ε turbulence model was applied and the airflow transport can be described by the following time-averaged Navier-Stokes equation:

$$div(\rho \mathbf{V}\Phi - \Gamma_{\Phi,eff}\, grad\ \Phi) = S_{\Phi} \tag{1}$$

Where ρ is the air density (kg/m^3), $\Gamma_{\Phi,eff}$ is the effective diffusion coefficient (kg/m·s), V is the air velocity vectors (m/s), S is the source term of the general flow property, and Φ is any one of the components shown in Table 1. When Φ=1, the general equation becomes the continuity equation. The effective diffusion coefficients and the source terms for different Φ are listed in Table 1. Also, Wall boundary conditions were treated as shown in Table 2.

Table 1 Terms, coefficients and constants in Eq. (1)

Equations	Φ	$\Gamma_{\varphi,eff}$	S_φ
Continuity	1	0	0
Momentum	U_i	μ_{eff}	$-\partial P/\partial x_i + g_i(\rho-\rho_0)$
Turbulence kinetic energy	k	μ_{eff}/σ_k	$P_k - \rho\varepsilon + G_k$
Turbulence kinetic energy dissipation rate	ε	$\mu_{eff}/\sigma_\varepsilon$	$\varepsilon(C_1P_k - C_2\varepsilon)/k + C_3G_k\varepsilon/k$
Concentration	C	μ_{eff}/σ_C	S_C

$P_k=\mu_t(U_{i,j} + U_{j,i})U_{i,j}$, $\mu_{eff} = \mu_t + \mu$, $\mu_t = C_\mu \rho k^2/\varepsilon$,
$(\sigma_k, \sigma_\varepsilon, \sigma_C, C_1, C_2, C_3) = (1.0, 1.314, 1.0, 1.44, 1.92, 1.0, 0.09)$

Table 2 Boundary Conditions for the numerical calculation

Inlet: $k_{in} = \frac{3}{2}(u_{in} \cdot I)^2,\ \varepsilon_{in} = C_\mu^{3/4} k^{3/2} l,\ I = 0.1,\ l = 0.5 \times D_h,\ C_{in} = 500\,ppm$

Outlet: $\frac{\partial u}{\partial x} = 0,\ \frac{\partial k}{\partial x} = 0,\ \frac{\partial \varepsilon}{\partial x} = 0,\ \frac{\partial T}{\partial x} = 0,\ \frac{\partial C}{\partial x} = 0$

Wall: $u = v = w = 0,\ \frac{\partial k}{\partial x} = \frac{\partial k}{\partial y} = \frac{\partial k}{\partial z} = 0,\ \frac{\partial C}{\partial x} = \frac{\partial C}{\partial y} = \frac{\partial C}{\partial z} = 0$

Where, D_h is the width of inlet

The mean air age and boundary conditions were calculated by the following equation induced from equation (2) and (3) [6]:

$$div(\rho \mathbf{V} \tau - \Gamma_\tau \; grad \;\; \tau) = 1 \quad (2)$$

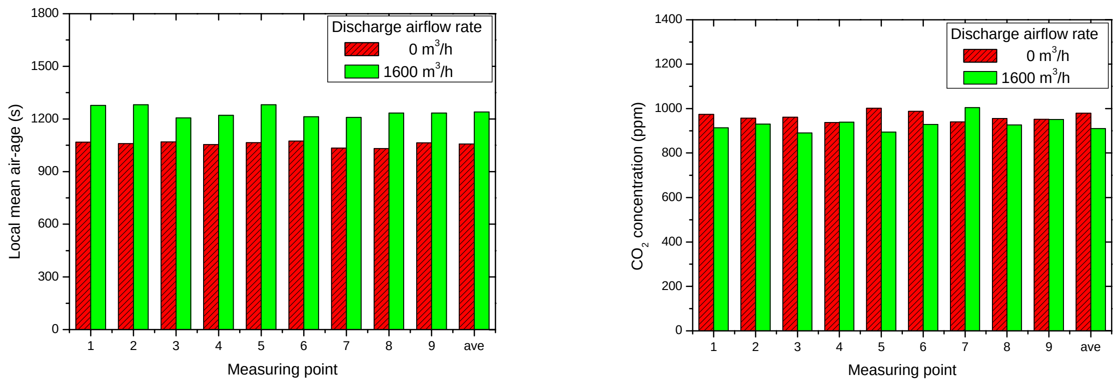
$$inlet : \tau = 0, \;\; outlet : \frac{\partial \tau}{\partial x_i} = 0 \quad (3)$$

Where, τ is the mean air age (s). x_i represent the 3D coordinates. The governing equations were solved by SIMPLE algorithm and 2nd order upwind scheme was used to discretize the convection term in equation (1). STAR-CD was employed to compute the airflow, temperature, and concentration distributions. The number of cells for numerical calculation is about 750,000 and the standard log-wall functions of Launder and Spalding were adopted for the next grid points to the surface.

RESULTS

Experiments

Fig. 3(a) shows mean air age distribution for two different discharge airflows of 4-way cassette air-conditioner. When the 4-way cassette air-conditioner was not in operation, mean air age was measured in the range of 1030~1075 seconds. When the 4-way cassette air-conditioner was operated at the discharge airflow rate of 1600m^3/hour, the mean air ages were in the range of 1200~1280 seconds. These results shows that when the discharge airflow rate of the ceiling type air-conditioner, which is one of the indoor momentum sources, is increased, mean air age can be also increased. The reason is that the operation of the ceiling type air conditioner intervene the air current and makes the outdoor fresh air move a longer way. Therefore this indicates that the indoor air quality may be deteriorated as the discharge airflow is increased.



(a) mean air age (b) CO_2 concentration

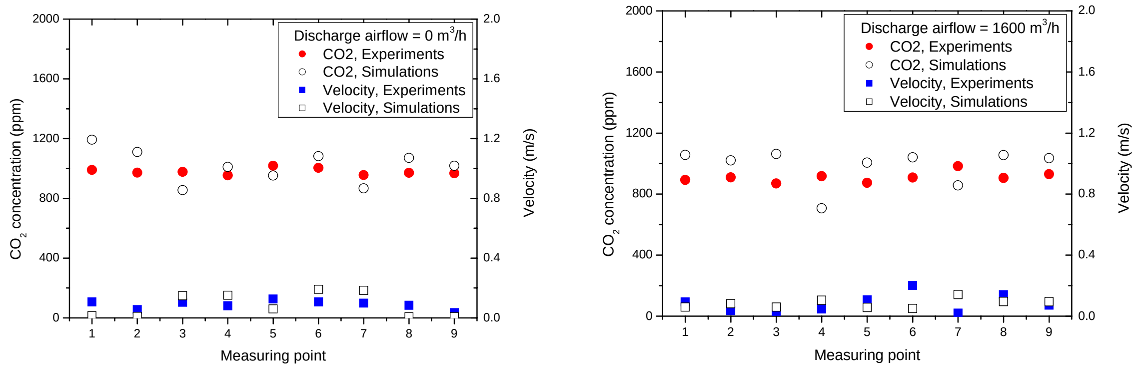
Fig. 3 Experimental results for mean air age and CO_2 concentration at the measuring points with the different discharge airflow of 4-way cassette air-conditioner

Fig. 3(b) shows the locally-averaged CO_2 distributions, which were measured at y=1.1m, with two different discharge airflow rates. When the 4-way cassette air-conditioner was not in operation, CO_2 concentrations were measured in the range of 950~1020ppm. When the 4-way cassette air-conditioner was operated at the discharge airflow rate of 1600m^3/hour, CO_2 concentrations were measured in the range of 870~980ppm. Unlike mean air age distributions as shown in Fig. 3(a), CO_2 concentration get to be somewhat decreased as the discharge airflow rate of the ceiling type air-conditioner is increased. This phenomenon had been

reported by the previous numerical and experimental studies [4]. This reason is that the operation of the ceiling type air conditioner can make the mixing effect of indoor contaminants increased and the residual life time of indoor contaminants decreased.
From these results it was revealed that both of the mean air age and the residual life time must be considered to evaluate the ventilation performance when the contaminants are generated from the indoor.

Validation of CFD model

A part of results from measurements were used for validating the following numerical calculations. Numerical simulations were designed to sufficiently meet the experimental work. Numerical simulations of flow patterns and CO_2 concentrations were compared with measurements at the section of 1.1m high above the bottom in a full-scale room.



(a) discharge airflow is 0m^3/h (b) discharge airflow is 1600m^3/h

Fig. 4 Comparison of experimental results and numerical ones for CO_2 and velocity at the measuring points

Fig. 4 shows the comparison of experimental results and numerical ones for velocities and CO_2 concentrations at the measuring points when the discharge airflow rate is 0m^3/h and 1600m^3/h. There were slight differences between experiments and simulations. In the case of CO_2 concentration, the locally-averaged concentrations were measured nearly the same as the room-averaged value in the experiments regardless of the discharge airflow rate. Their maximum differences of them were under 17% and the agreement was acceptable. In the case of velocity, all values were under 0.25m/s and satisfied an acceptable condition in the occupied zone. From these results we could make sure that the numerical model is sufficient to carry out the applications for evaluating the ventilation effectiveness with variations of the discharge airflow rate of the ceiling type air-conditioner.

Assessment of ventilation effectiveness

Fig. 5 shows the variation of indoor CO_2 concentration in the occupied zone with respect to the discharge airflow rate of the ceiling type air-conditioner, the occupancy and the ventilation rate. Regardless of the occupancy and ventilation rate, CO_2 concentrations is gradually decreased as the discharge airflow rate is increased from 0 to 800m^3/h, while their values are rarely changed in the case that the discharge airflow rate is over 800m^3/h. This result demonstrates that a minimum value exists with the increment of the discharge airflow rate. Fig. 6 shows CO_2 distributions at the plane of z=3.2m with respect to the discharge airflow rate of the ceiling type 4-way cassette air-conditioner. As the discharge airflow rate is larger, this deviation of indoor CO_2 concentration becomes smaller in the occupied zone. It is due to that increment of the discharge airflow rate will lead the indoor air to be more mixed as

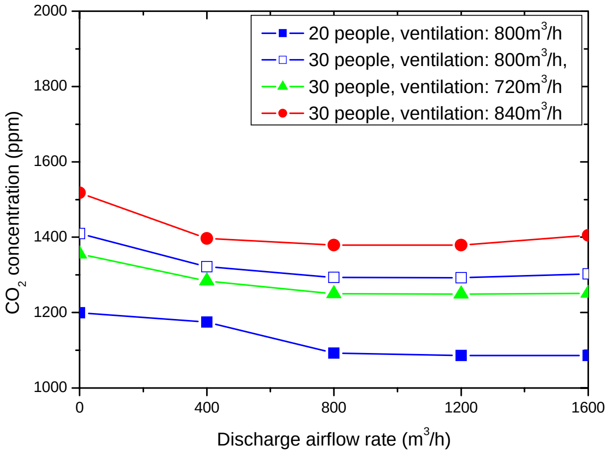
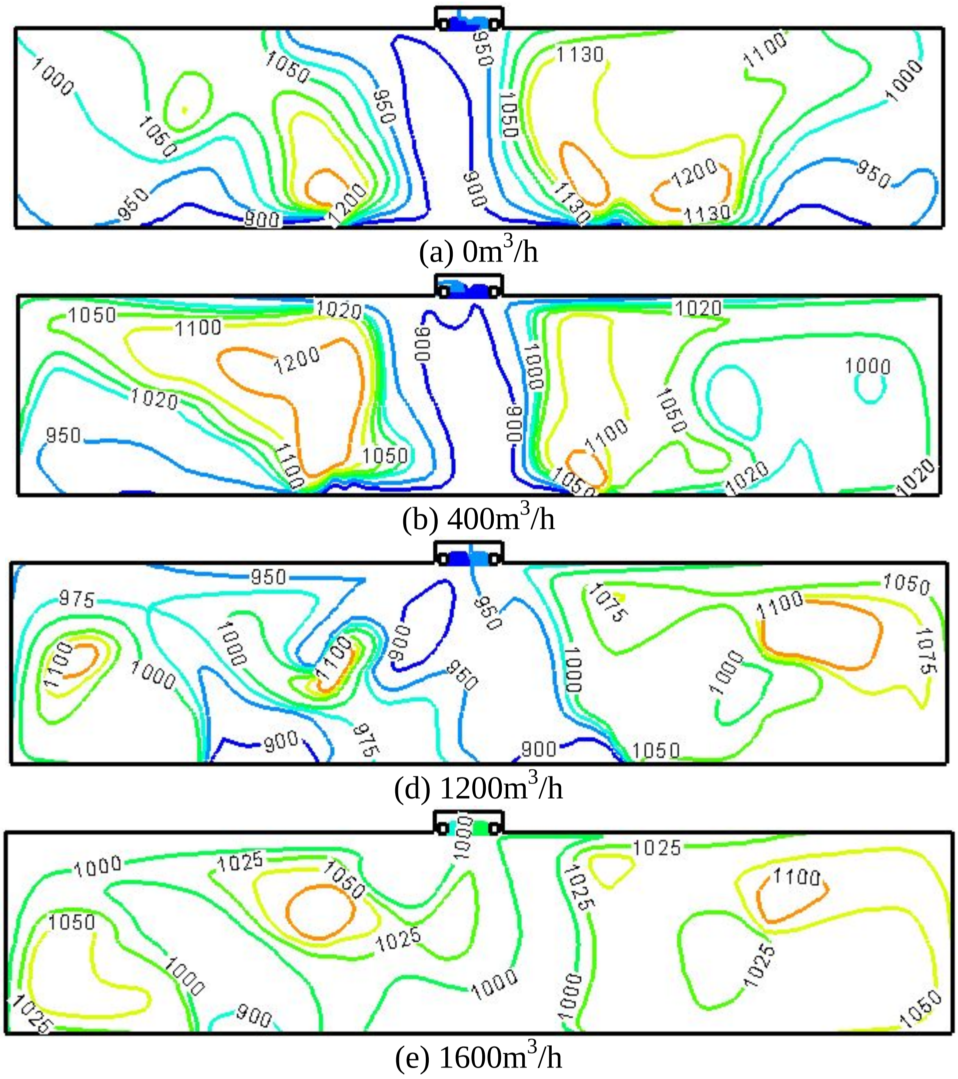


Fig. 5 The variation of indoor CO_2 concentration in the occupied zone with respect to the discharge airflow rate of the ceiling type air-conditioner, the occupancy and the ventilation rate



(a) $0m^3/h$

(b) $400m^3/h$

(d) $1200m^3/h$

(e) $1600m^3/h$

Fig. 6 CO_2 distributions at the plane of z=3.2m with respect to the discharge airflow rate of the ceiling type 4-way cassette air-conditioner mentioned above. Also, it is shown that the maximum area of indoor CO_2 concentration is gradually going up and their value is smaller as the discharge airflow rate is increased. This means that the discharge airflow of the ceiling type air-conditioner can induce the piston effect and push the contaminants out of the occupied zone. But, this effect is gradually diminished with the increment of the discharge airflow intensity as shown in Fig. 6.

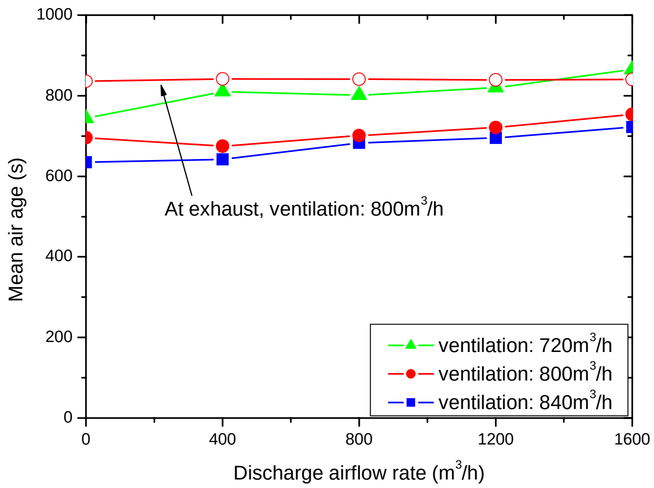


Fig. 7 The variation of mean air age in the occupied zone with respect to the discharge airflow rate of the ceiling type air-conditioner, the occupancy and the ventilation rate

Fig. 7 shows the variation of mean air age in the occupied zone and exhaust with respect to the discharge airflow rate of the ceiling type air-conditioner and the ventilation rate. Regardless of the ventilation rate, mean air age is gradually increased as the discharge airflow rate is increased. This calculation result shows qualitative similarity with the experiment. But, these numerical values of mean air age were not approximated to the experimental ones and there differences were about 200 seconds. It is due to that molecular weight of SF_6 is about 5 times heavier than one of air and the supply airflow rate was smaller than the exhaust one of $800m^3/h$. While, mean air age at exhaust is almost constant even though the discharge airflow rate is increased. This means that the residence time is not changed with the discharge airflow rate of the ceiling type air-conditioner. When the mean air age is increased and the residence time is constant like these cases, the residual life time should be decreased by the definition of air age. Therefore, the contaminant concentration like CO_2 emitted from indoor sources must be decreased with the decrement of the residual life time. These results show that the increment of mean air age does not always make indoor air quality deteriorated. Again, both of mean air age and residual life time are important parameters to be considered for evaluating ventilation performance when the contaminants are generated indoors.

CONCLUSIONS

The effect of the discharge airflow rate of the ceiling type air-conditioner on ventilation performance was studied. Mean air age is gradually increased, but CO_2 concentration is oppositely decreased in the occupied zone with the increment of the discharge airflow rate of the ceiling type air-conditioner. This result shows that both of mean air age and residual life time must be considered for evaluating ventilation performance when the contaminants are generated indoors. And the increment of discharge airflow of the ceiling type air-conditioner can induce the piston effect and push the contaminants out of the occupied zone. This shows that the ventilation performance can be increased when the momentum source like an air-conditioner, air cleaner, and fan is used in the room with mixing ventilation.

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