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Effects of Hospital Ward Curtains on Ventilation in a Four-bed Hospital Ward

Jung-Hun Noh[1,2], Jungsuk Lee[1], Kwang-Chul Noh[3], Young-Won Kim[4], Se-Jin Yook[1*]

[1] *School of Mechanical Engineering, Hanyang University, Seoul 04763, Korea*
[2] *R&D Center for Research & Business Cooperation Mechatronics Team, Institute for Advanced Engineering, Yongin 17180, Korea*
[3] *Air Lab, Gwangju 61478, Korea*
[4] *Applied Optics and Energy Research Group, Korea Institute of Industrial Technology (KITECH), Gwangju 61012, Korea*

ABSTRACT

Various highly infective pathogens that are present in hospital wards can spread through the air and infect patients. To remove pathogens effectively in order to reduce infections, the efficient ventilation of hospital wards is critical. This study used age of air data to analyze the ventilation efficiency within hospital wards. The validity of the numerical analysis method was verified by comparison with the age of air data obtained from an experimental test on a four-bed hospital ward. The verified numerical analysis method was used to establish the airflow within a hospital ward in relation to the use of ventilation systems, air cleaners, and individual patient curtains. The efficiency of ventilation according to each factor was compared using age of air data. Considerable differences in the age of the air were identified, depending on the location of the patient with respect to both the air cleaner and the inlet/outlet duct of the ventilation system. Furthermore, individual curtains were found to interfere with air circulation, reducing ventilation efficiency and increasing the age of the air at the location of each patient.

Keywords: Age of air; Ventilation system; Air cleaner; Hospital ward; Patient curtain.

INTRODUCTION

Since most of the patients in a hospital ward require long-term care, secondary infections can occur due to airborne viruses in the ward (Beggs, 2003). Effective ventilation is very important in reducing the possibility of such airborne infection. Therefore, improvement of indoor air quality through the reduction of fine dust concentration is an area of active research, and numerous studies have been conducted on the analysis of airflow in interior spaces. Recently, in the Republic of Korea, knowledge based on studies considering both the indoor propagation of airborne pathogens and the ventilation of hospital wards has increased in response to the number of occurrences of Middle East Respiratory Syndrome.

Ventilation and air-purification technologies are widely used to improve the quality of indoor air (Noh and Oh, 2015; Ciuzas *et al.*, 2016; Siegel, 2016). Numerous studies have been conducted on reducing the concentrations of indoor airborne particulates using ventilation systems and air purification devices. Ning *et al.* (2006) investigated the effect of the flow rate of a ventilation system on particle number concentration decay after indoor smoking. Gao and Zhang (2010) conducted a numerical study to investigate the effect of room air cleaners on contaminant exposure reduction. Research has been conducted on mass flow rates and fan power ratios to determine appropriate ventilation rates and filter ratings for energy efficient reduction of indoor particulates (Noh and Hwang, 2010). Further research has considered energy efficiencies associated with ventilation systems and air cleaners in multi-unit residential buildings (Cho *et al.*, 2015). Research has also been conducted using CFD simulations and experimental methods to assess the impact of air distribution methods on the quality of indoor air in spaces with ventilation systems (Jurelionis *et al.*, 2015). Fischer *et al.* (2015) conducted a study on operational strategies for ventilators for optimum reduction of the concentration of indoor airborne particulates depending on the hour of the day. Noh and Yook (2016) investigated the air quality in a lecture room by operating a ventilation system and multiple air cleaners. Persily (2016) summarized the impact of ventilation rates on indoor air quality measurements by analyzing numerous reports of field studies. Zhang *et al.* (2016) tested different types of ventilation systems to enhance ventilation performance in factories.

Recently, following confirmation of the risk of infection

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[*] Corresponding author.
Tel.: +82-2-2220-0422; Fax: +82-2-2220-2299
E-mail address: ysjnuri@hanyang.ac.kr

from airborne pathogens within hospital wards, numerous studies have investigated the removal or reduction of pollutants using ventilation systems. Research has been performed on indoor airflows and pollutant diffusion characteristics in relation to various ventilation strategies inside negative pressure isolation rooms simulating a hospital ward (Cheong and Phua, 2006). Qian *et al.* (2008) tested a downward ventilation design to investigate the exhaust of exhalation pollutants to reduce cross-contamination in a two-bed hospital ward. Other studies have examined the levels of exposure of a person to indoor pollutants depending on the locations and properties of those pollutants under different ventilation conditions (Rim and Novoselac, 2010). The effect of the use of air conditioners equipped with high efficiency particulate air (HEPA) filters on the reduction of microbe concentration in a hospital was investigated (Chuaybamroong *et al.*, 2008). Numerical analysis and experimental research have been performed to determine whether microorganisms might concentrate and/or become deposited after entering a hospital ward via the ventilation system's inlet, assuming a situation where a patient is in bed (King *et al.*, 2013). The influences of horizontal and vertical ventilation systems on the removal of bacteria-carrying particles in an operating room was investigated (Sadrizadeh *et al.*, 2014). In these earlier studies, however, only the effect of ventilation systems installed in the ceilings or on the walls of hospital wards was investigated, i.e., the effect of individual curtains and/or air cleaners on the air quality in a hospital ward was not considered. Thus, the findings of such studies are limited to only some of the situations that could occur in an actual hospital ward.

The age of the air can be used to compare the indoor air quality controlled by ventilation systems. Li *et al.* (2003) investigated the effects of the air mixing process of ventilation systems and the presence of ducts on indoor air quality by using the age of the air. Tian *et al.* (2011) calculated mean local air age to observe air quality in an office at different conditions of heat inflow through a ventilation system. Wu and Ahmed (2012) used the mean age of the air to investigate the effect of air supply mode on aircraft cabin ventilation. Noh and Oh (2015) observed local air age to evaluate and compare the performance of room air cleaning devices used for removing particles. Cheng and Lin (2015) obtained the distribution of the local mean age of the air to check the feasibility of stratum ventilation for a room occupied by people in multiple rows.

In this study, therefore, the age of the air was calculated using a numerical analysis method to evaluate the efficiency of ventilation within hospital wards. Using these data, the effects of general ventilation systems, air cleaners, and structural changes in hospital wards on ventilation efficiency were evaluated. Additionally, an air cleaner was operated in a hospital ward to evaluate its impact on air quality, and the use or absence of individual patient curtains was considered both in calculating the age of the air and in evaluating the efficiency of ventilation.

NUMERICAL METHOD

The age of the air can be used to compare the degree of impact of several factors on ventilation within hospital wards. Fig. 1 shows a conceptual diagram that illustrates this concept. The time taken for air to pass through a specific location (Point A), after entering a certain space through the inlet and before exiting through the outlet, is called the residence time. The time taken for air to reach a specific location after entering a certain space through the inlet is called the age of the air. The time taken for air that was in a specific location to exit through the outlet is called the residence lifetime. If applying this concept to ventilation systems, it can be said that the age of the air is the time taken for clean air, supplied via the ventilation inlet, to reach a specific location; the lower this value, the better the ventilation efficiency.

To verify the reduction of the concentration of airborne particulates in relation to the operation of ventilation systems and air cleaners in hospital wards, the structure of a four-bed hospital ward (Ministry of Health and Welfare, Republic of Korea), which is the usual configuration of a hospital ward in Korea, was adopted for the numerical analysis and experimental model. Fig. 2 shows the structure of the four-bed hospital ward used in this study, in which each bed has individual curtains installed to protect patient privacy. The inlet/outlet of the ventilation system used for air circulation, heating, and cooling is installed in the ceiling. Additionally, an air cleaner, intended to improve the air quality of the ward, is installed near a wall.

To estimate the age of the air using a numerical analysis method, the indoor airflow produced by the ventilation system and the air cleaner must be analyzed. The airflow was assumed to be three-dimensional, steady, incompressible, and turbulent. The governing equations used in the airflow analysis are shown below, and the standard *k*-*ε* model was used for turbulent flow analysis.

- Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u} \right) = 0. \tag{1}$$

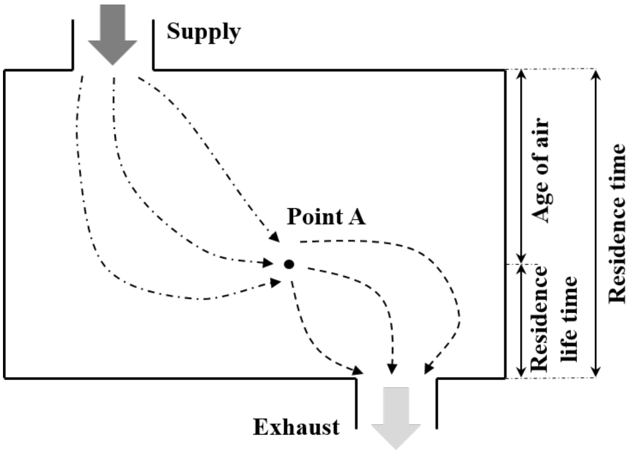

Fig. 1. Concept of the age of air.

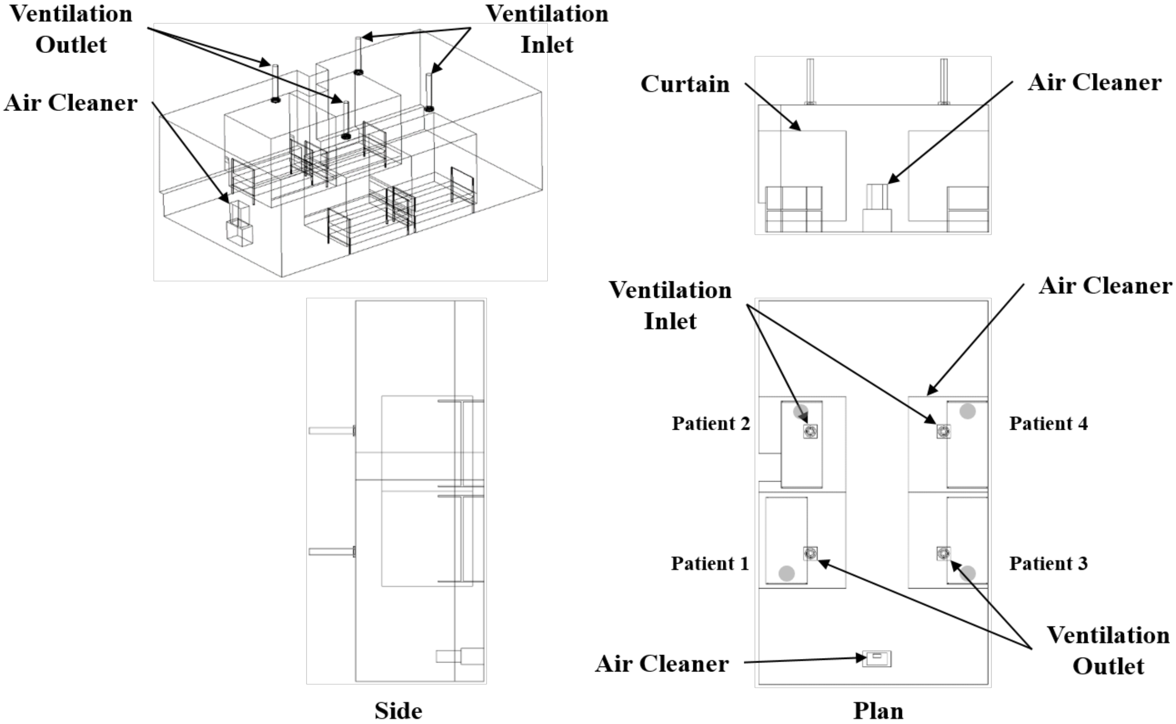

Fig. 2. Structure of the four-bed hospital ward used in this study.

- Momentum conservation equation:

$$\frac{\partial\left(\rho\vec{u}\right)}{\partial t}+\nabla\cdot\left(\rho\vec{u}\vec{u}\right)=-\nabla p+\nabla\cdot\left(\mu\nabla\vec{u}\right). \tag{2}$$

- Transport equation for k (standard k-ε model):

$$\frac{\partial\left(\rho\kappa\right)}{\partial t}+\nabla\cdot\left(\rho\kappa\vec{u}\right)=\Delta\left[\left(\mu+\frac{\mu_t}{\sigma_\kappa}\right)\nabla\kappa\right]+G_\kappa+G_b -\rho\varepsilon-Y_M\,. \tag{3}$$

- Transport equation for ε (standard k-ε model):

$$\frac{\partial\left(\rho\varepsilon\right)}{\partial t}+\nabla\cdot\left(\rho\varepsilon\vec{u}\right)=\nabla\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]. +C_{1\varepsilon}\frac{\varepsilon}{\kappa}\left(G_\kappa+C_{3\varepsilon}G_b\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa} \tag{4}$$

The governing equation used to estimate the age of the air simultaneously with the airflow analysis is as follows.

- Concentration transport equation (age of air):

$$\nabla\cdot\left(\rho\tau_p\vec{u}\right)=\nabla\left[\left(\frac{\mu}{\sigma_1}+\frac{\mu_t}{\sigma_t}\right)\nabla\tau_p\right]+\rho, \tag{5}$$

$$\tau_{p,num}=\int_0^\infty\frac{C_p(t)}{C_0}dt. \tag{6}$$

Here, τ_p is the ratio of particulate concentration at a specific location integrated as a function of time and it refers to the age of the air (Bartak *et al.*, 2001). The indoor temperature and pressure were assumed to be 20°C and 101.3 kPa, respectively. The operational flows of the ventilation system and air cleaner were set to 0.088 and 0.124 $\mathrm{m}^3\ \mathrm{s}^{-1}$, respectively, reflecting the specifications of the commercial products used in the experiment. The convergence criteria used to solve the governing equations was set to 10^{-4}. The boundary conditions comprised the velocity inlet conditions at the inlet of both the ventilation system and the air cleaner, velocity outlet conditions at the outlet of both the ventilation system and the air cleaner, and no-slip conditions at all walls. Hexahedral and tetrahedral grids were used in combination to create the grids, and the number of grids adopted, determined through a grid dependence test, was approximately 4.76 million. Table 1 shows six cases regarding various configurations of the ventilation system, air cleaner, and curtains. Each case was analyzed numerically and the age of air values of each case were calculated and compared.

Table 1. Cases regarding various configurations of the ventilation system, air cleaner, and curtains.

Case	Ventilation	Air Cleaner	Curtain
I	On	Off	without
II	Off	On	without
III	On	Off	with
IV	Off	On	with
V	On	On	without
VI	On	On	with

EXPERIMENTAL METHOD

Tests were conducted to verify the accuracy of the numerical analysis method. In general, headboards are placed in a way that they face the walls in actual hospital wards. However, a space with the same structure as a four-bed hospital ward could not be provided in the present study's experimental setup, due to the limited laboratory space. Therefore, the test was conducted on a space of similar size with patient beds and curtains, as shown in Fig. 3(a), by placing one side of each ward bed up against the wall. Fig. 3(b) shows a schematic of the air circulation. To supply clean air, a pre-filter (MERV 8) and a HEPA filter (MERV 16) were installed inside a filter box. Collection efficiency was measured to be 22.12% for the pre-filter and 99.86% for the HEPA filter. The air supplied through the inlet of the ventilation system was first passed through the filter for fine dust removal. The flow rate of air supplied by the ventilation system was 0.088 $m^3 s^{-1}$, which corresponded to the air exchange rate of 2.5 per hour. The air from inside the simulated hospital ward was recovered through the outlet and discharged outside without recirculation. The simulated hospital ward had two inlets and two outlets installed in the ceiling. In addition to the ventilation system, an air cleaner was also installed within the experimental space. The flow rate of air supplied by the air cleaner was 0.124 $m^3 s^{-1}$. As shown in Fig. 3(a), two condensation particle counters (Model CPC-0701, HCT Co., Ltd., Republic of Korea) were used at seven locations to measure the number concentration of airborne particles. Sampling probes for the inhalation of aerosols were installed vertically with their inlets 1 m above the floor. Since not only viruses but also particles on which viruses can be parasitic are various in size in actual hospital ward environments, the laboratory simulating a four-bed hospital ward was filled with atmospheric air containing particles of various sizes before turning on the ventilation system and the air cleaner.

To ensure consistency, the following experimental procedure was repeated for each case.

i) Windows were open to allow external air to enter while the ventilation system and the air cleaner were turned off (90 min).
ii) Windows were closed to stabilize the flow of the indoor air (20 min) − [Step A].
iii) The flow of the indoor air was stabilized after turning on the ventilation system and/or the air cleaner (10 min) − [Step B].
iv) A constant flow of indoor air was maintained (60 min) − [Step C].

Among the cases shown in Table 1, Case I was repeated three times using the prescribed experimental procedure, and the condensation particle counters were placed at measurement locations to observe the changes in particle number concentration over time.

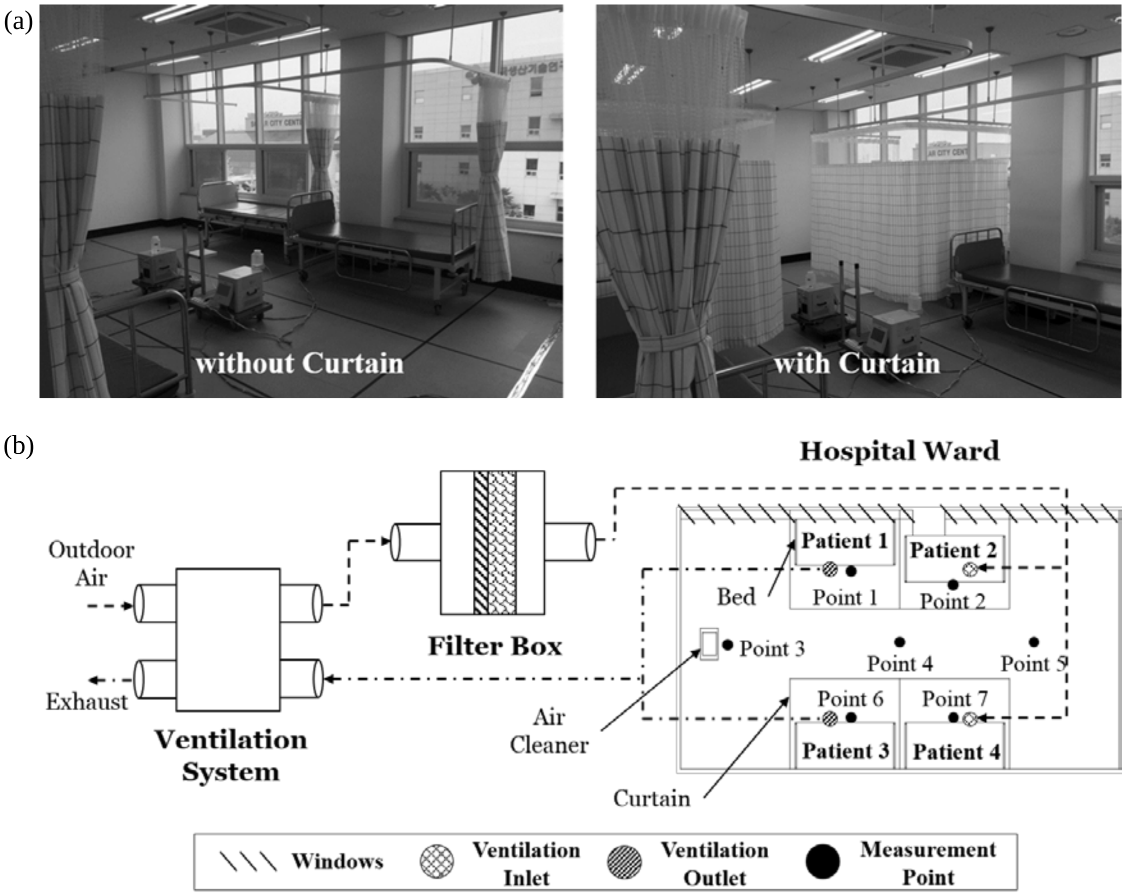

Fig. 3. Experimental setup: (a) photos of the simulated four-bed hospital ward; (b) schematic of air circulation.

It was observed that the indoor particle concentration decreased exponentially over time once the ventilation system and/or the air cleaner were activated. Therefore, the following equation was used to draw indicators that could be compared with the age of the air:

$$C_p(t) = A\exp\left(-\frac{t}{\tau_{p,\exp}}\right) + y_0. \quad (7)$$

If defining the initial number concentration of indoor particles as C_0, and defining the number concentration that converged to a constant value, in response to the operation of the ventilation system and/or the air cleaner, over a long period as C_∞, they can be expressed as:

$$C_p(0) = \mathrm{C}_0, \quad (8)$$

$$C_p(\infty) = \mathrm{C}_\infty. \quad (9)$$

Using Eqs. (8) and (9), Eq. (7) can be expressed as follows:

$$C_p(t) = \left[C_0 - C_\infty\right]\exp\left(-\frac{t}{\tau_{p,\exp}}\right) + C_\infty. \quad (10)$$

Dividing both sides of Eq. (10) by the initial concentration (C_0) and then integrating as a function of time produces a formula that defines the age of the air:

$$\int_{t=0}^{t=\infty} \frac{C_p(t)}{C_0}dt = \int_{t=0}^{t=\infty} \frac{C_0 - C_\infty}{C_0}\exp\left(-\frac{t}{\tau_{p,\exp}}\right)dt + \int_{t=0}^{t=\infty} \frac{C_\infty}{C_0}dt. \quad (11)$$

Here, assuming the filtration efficiency of the ventilation system is 1.0, and setting the convergence value of the indoor particle number concentration after a long period to 0 ($C_\infty = 0$), results in the following:

$$\int_{t=0}^{t=\infty} \frac{C_p(t)}{C_0}dt = \tau_{p,\exp}. \quad (12)$$

This is the age of the air determined based on the experimental results. This means that the age of the air can be calculated through experiment by finding the fitted curve of Eq. (7), after measuring the indoor particle number concentration over time.

RESULTS AND DISCUSSION

As an example of one of the experimental results, Fig. 4(a) shows the change of the particle number concentration over time, as measured at Point 4 inside the simulated hospital ward space shown in Fig. 3. During the first 20 min after window closure (Step A), a slow decrement in the indoor particle number concentration was observed. The reason for this was presumably that particles became deposited on the floor and/or walls via gravitational settling and diffusion. After 20 min of measurement, the ventilation system with the pre-filter (MERV 8) and the HEPA filter (MERV 16) was turned on and the indoor airflow was stabilized over 10 min (Step B). At this point, in the case shown in Fig. 4(a), the air cleaner was turned off and curtains were not used. After turning on the ventilation system, it was verified that the indoor particle number concentration started to decrease abruptly. Subsequently, constant indoor airflow was maintained over 60 min (Step C), and it was observed that the indoor particle number concentration decreased exponentially. Fig. 4(b) shows the particle number concentration of Steps B and C normalized with the particle number concentration at the point when Step B started, together with the fitted curve. Here, the fitted curve is in the form of Eq. (7). It was verified that this fitted curve could express the results of the decreasing particle number concentration in Steps B and C. From this fitted curve, the age of the air was calculated using Eq. (12).

The age of air values derived experimentally at other indoor locations using the same method are shown in Fig. 5, together with the values of the age of the air calculated by numerical analysis. The age of the air was low near the ventilation inlet (Points 2, 5, and 7) where clean air was supplied, whereas near the ventilation outlet (Points 1, 3, and 6), through which the air was discharged after circulating within the indoor space, the age of the air was high. The absolute values of air age were different between experimental data and numerical results, maybe because the effect of particle size was not considered. However, it was found that the tendency of spatial distribution of the age of the air coincided in both the experimental and the numerical analysis results. Thus, it was verified that the numerical analysis method, established in this study, could be used to qualitatively evaluate the age of air distribution.

The verified numerical method was used to analyze the age of the air in the simulated four-bed hospital ward shown in Fig. 2. Fig. 6 shows the airflow and age of air distributions obtained for Case I (use of ventilation system only without personal curtains) and Case II (use of air cleaner only without personal curtains). In Case I, clean air entered through the ventilation inlets and spread downward into the room. Therefore, high airflow occurred only near the inlet, where the age of the air was low. Thus, Patients 2 and 4 (located near the ventilation inlet) were supplied with relatively clean air, compared with Patients 1 and 3 (located near the ventilation outlet), who received air that had remained within the indoor space for a longer period. Such air has a higher chance of being contaminated with pathogens. In Case II, air supplied by the air cleaner rose and moved along the ceiling of the hospital ward, circulating and spreading within the room. The age of the air at the locations of Patients 2 and 4 (farthest from the air cleaner) was higher than at the locations of Patients 1 and 3 (near the air cleaner). The reason why the maximum and average age of air values in Case II were lower than in Case I was because the flow rate of the air cleaner (0.124 $\mathrm{m}^3\ \mathrm{s}^{-1}$) was higher than that of the ventilation system (0.088 $\mathrm{m}^3\ \mathrm{s}^{-1}$).

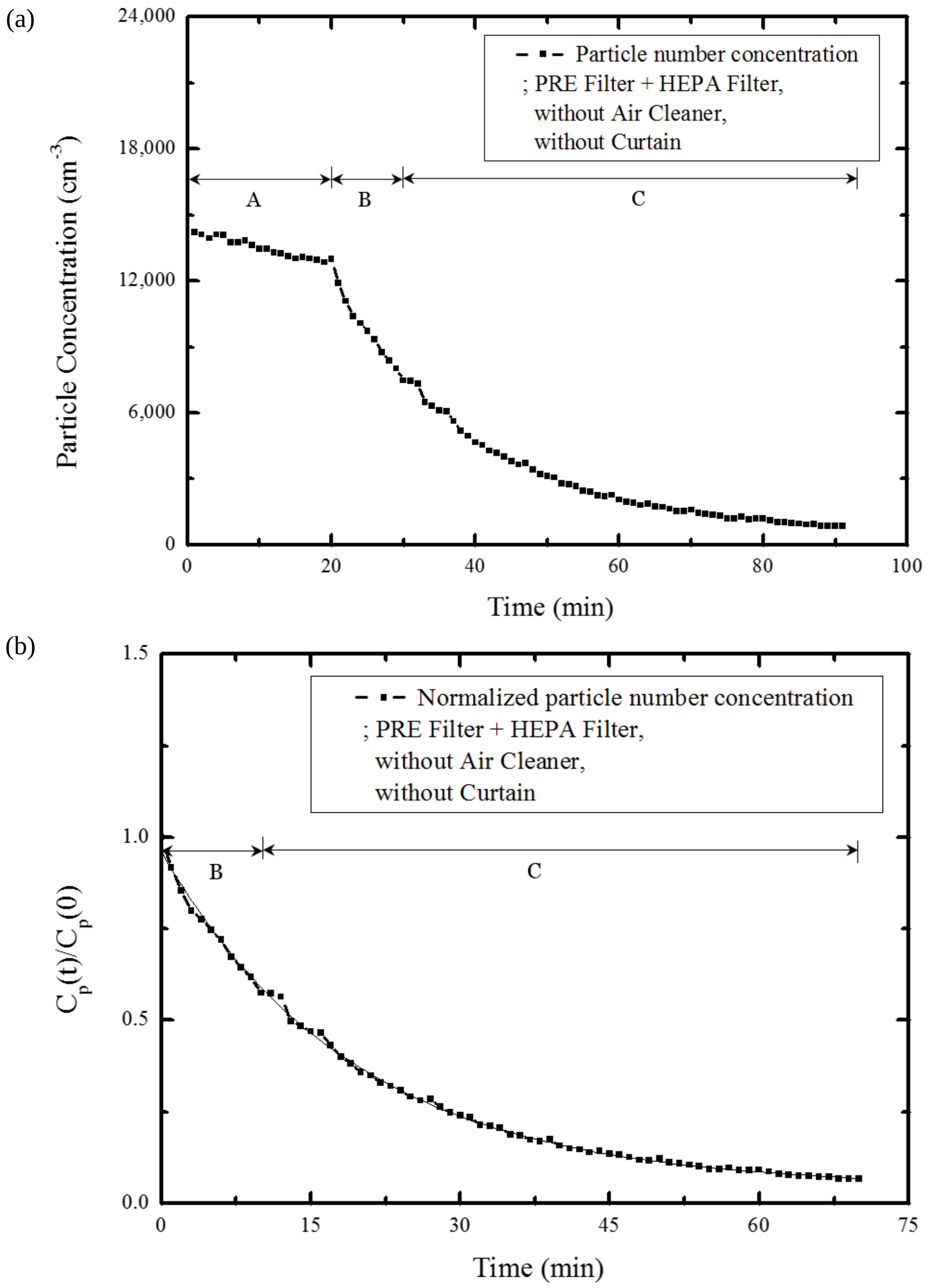

Fig. 4. Example of particle concentration measurement results: (a) change over time of the particle number concentration as measured at Point 4 inside the simulated hospital ward; (b) particle number concentration of Steps B and C normalized with the particle number concentration at the point when Step B started.

Fig. 7 shows the airflow and age of air distributions of Case III (use of ventilation system only with personal curtains) and Case IV (use of air cleaner only with personal curtains). In Case III, air could not circulate smoothly because the curtains were unfolded. Thus, clean air supplied via the ventilation inlet could not reach the location of each patient quickly, i.e., the age of air was increased. In Case III, at the locations of Patients 2 and 4 (near the ventilation inlet), a lower age of air was estimated because of the use of the curtains. At the locations of Patients 1 and 3 (near the ventilation outlet), a higher age of air was estimated in Case III. This was because the air of the personal space of each patient with unfolded curtains stagnated because of improper ventilation. In such a case, pathogens inside a hospital ward might not be discharged smoothly, increasing the chances of additional infection. In Case IV, clean air supplied by the air cleaner was also unable to reach the location of each patient easily because of the use of the curtains. In this case, the age of the air at the location of each patient was higher than when the curtains were withdrawn.

Fig. 8 shows the comparison of the age of the air at the location of the head of each patient (see Fig. 2) between or

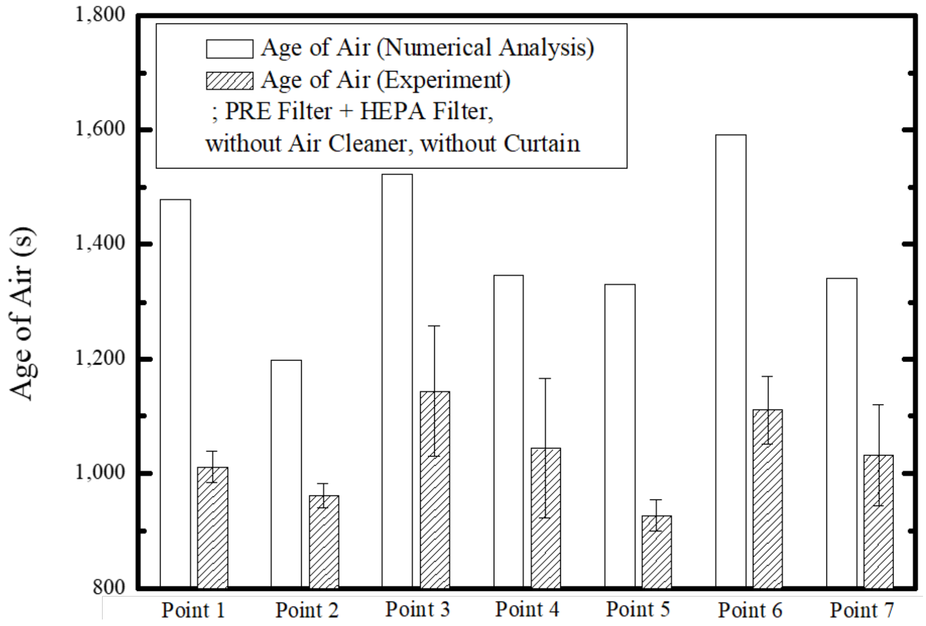

Fig. 5. Comparison of the tendency of age of the air between numerical results and experimental data.

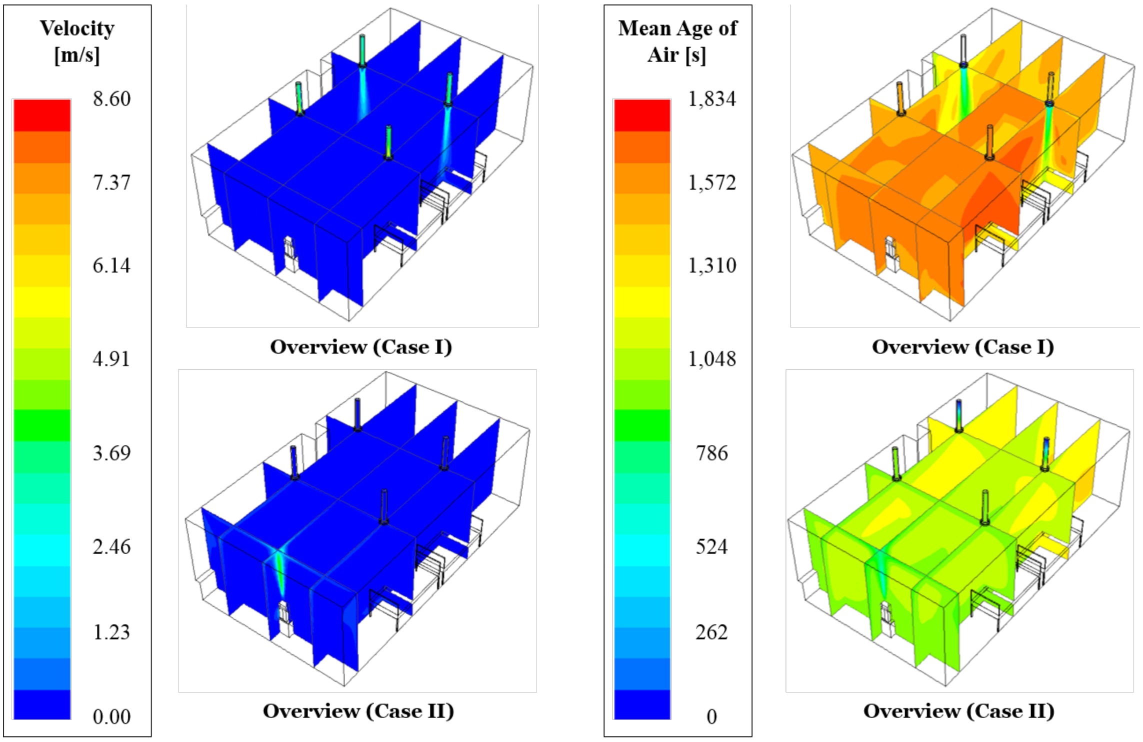

Fig. 6. Airflow and age of air distributions obtained for Case I and Case II.

among the cases listed in Table 1. In addition to the age of the air, the flow rate of the supply of clean air is also indicated. The mean age of the air was calculated to compare the degree of ventilation throughout the hospital ward, and the local age of the air at the location of each patient's head was determined to compare the degree of ventilation at specific locations. As can be seen in Fig. 2, the structure of the hospital ward was asymmetric with regard to the building pillars. This structure affected the airflow and it produced an asymmetric distribution of the age of the air.

Fig. 8(a) compares the age of the air of Case I (use of ventilation system only), Case II (use of air cleaner only), and Case V (use of both devices) without curtains. The age of the air was found to decrease as the total flow rate of supplied clean air increased. Comparison of Cases II and V indicates that ventilation efficiency within hospital wards could be improved only to a certain extent by increasing the total flow rate of clean air supplied. Fig. 8(b) compares

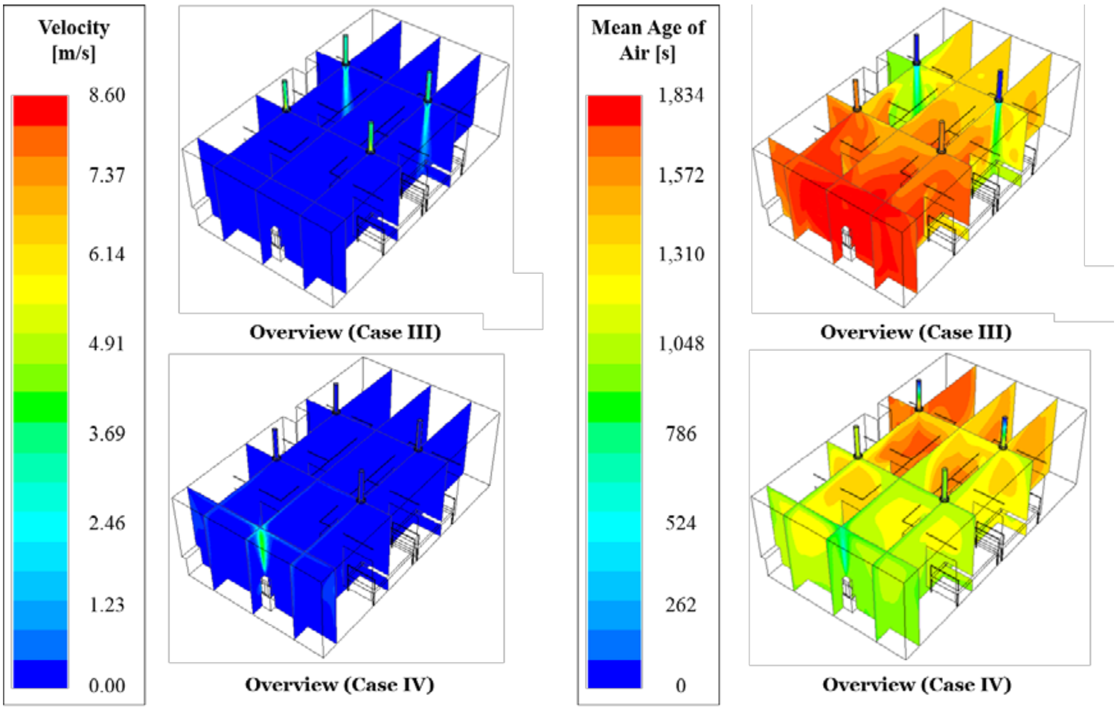

Fig. 7. Airflow and age of air distributions obtained for Case III and Case IV.

the effect of curtain use when using only the ventilation system. The mean age of the air within the hospital ward was 1.4% higher in Case III (with curtains) than Case I (without curtains) under the same flow rate conditions. Locally, the age of the air for Patient 1 (6.8%) and Patient 3 (2.1%), located near the outlet of the ventilation system, increased. Conversely, the age of the air for Patient 2 (9.0%) and Patient 4 (7.3%), located near the inlet of the ventilation system, decreased. Thus, ventilation efficiency declined because curtains interfered with the path of the airflow from the ventilation system, preventing clean air from circulating smoothly to the location of each patient. Furthermore, because of the structural asymmetry of the building in this study, it was verified that the rates of the age of air increments and decrements associated with the use of curtains differed. Fig. 8(c) compares the results obtained for cases with and without curtains when only the air cleaner was activated. As in the previous cases, in Case IV (with curtains), the circulation of air was restricted, which meant the mean age of the air increased (10.8%) more than in Case II (without curtains). The reason for this was that when the curtains were unfolded, the flow of clean air from the air cleaner could not be supplied directly to the patient. Instead, it circulated around other parts of the ward, causing the age of the air at the location of each patient to become higher than when curtains were not used. Locally, the age of the air for Patient 1 (15.3%) and Patient 2 (20.1%), located near the building pillars, increased significantly. The age of the air for Patient 3 (5.7%) and Patient 4 (6.0%), located on the opposite side of the ward, also increased but to a lower degree. Fig. 8(d) compares the results obtained for cases with and without curtains when both the ventilation system and the air cleaner were activated simultaneously. It was verified that the mean age of the air was lower than when only one of the devices was in operation. It was found that in Case VI (with curtains), the age of the air increased at all patient locations in comparison with Case V (without curtains).

CONCLUSION

In this study, the age of the air was calculated by predicting the flow of air within a hospital ward using a numerical analysis method. In addition, the age of the air was determined through experiment by measuring the reduction of the particle number concentration within a simulated hospital ward. The results of the numerical analysis and the experiment agreed in terms of the age of air tendencies according to different locations within the simulated hospital ward, thus verifying the validity of the numerical analysis method. The numerical analysis method was used to simulate a four-bed hospital ward and estimate the age of the air depending on the use (or non-use) of curtains, ventilation systems, and air cleaners. It was verified that the ventilation of the ward was most efficient, i.e., the age of the air was reduced, when the ventilation system and air cleaner were used concurrently. It was further verified that curtains installed to protect patient privacy interfered with the circulation of the air, decreasing the efficiency of the ventilation. In addition, it was found that the age of the air differed according to the location of each patient in response to the structural asymmetry of the building. Thus, differences in the amount of clean air supplied to patients by the ventilation system and/or the air cleaner depended on the location of the patient. The local age of the air at a specific location was affected considerably by factors such as curtain

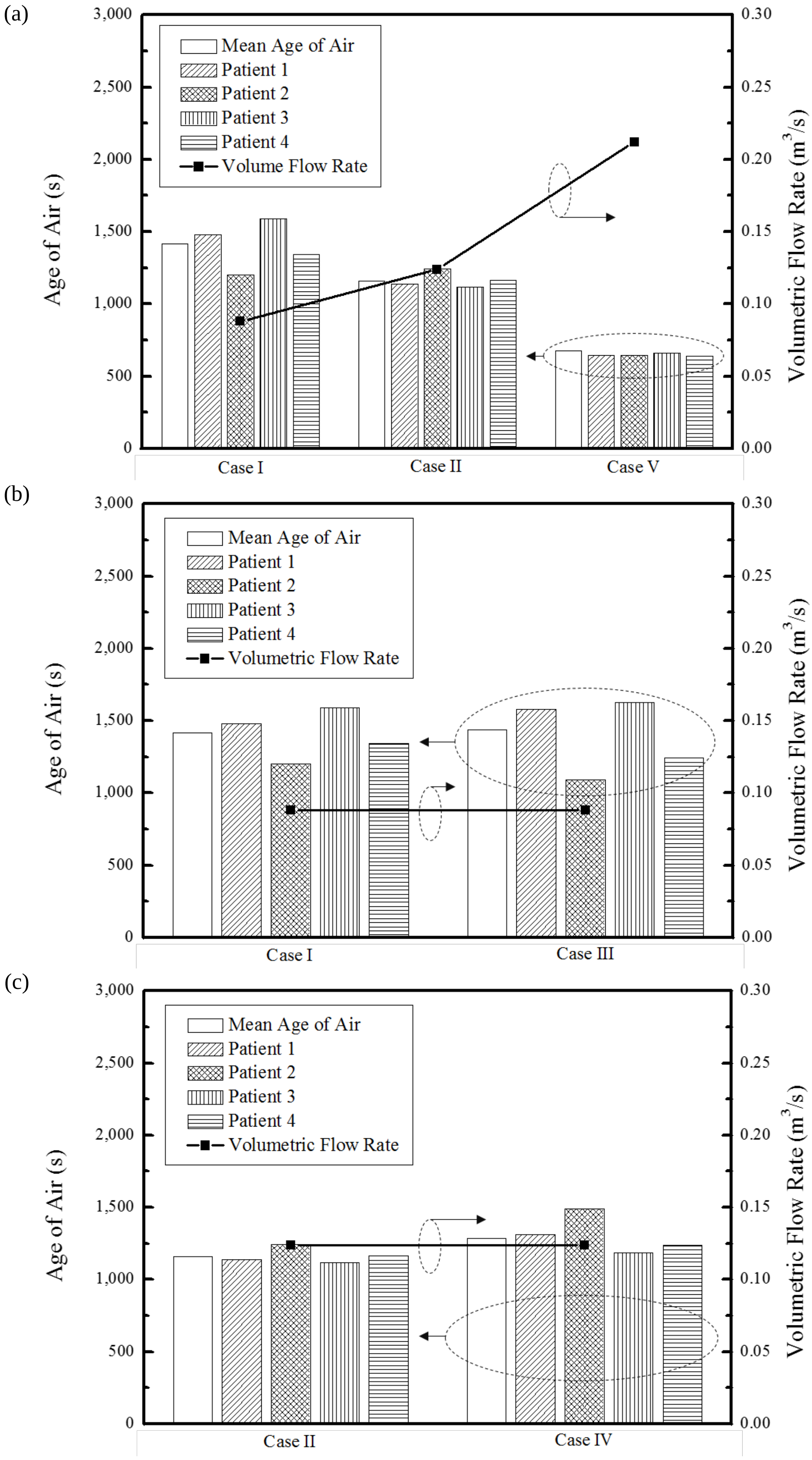

Fig. 8. Comparison of the age of the air at the location of the head of each patient between or among the cases listed in Table 1.

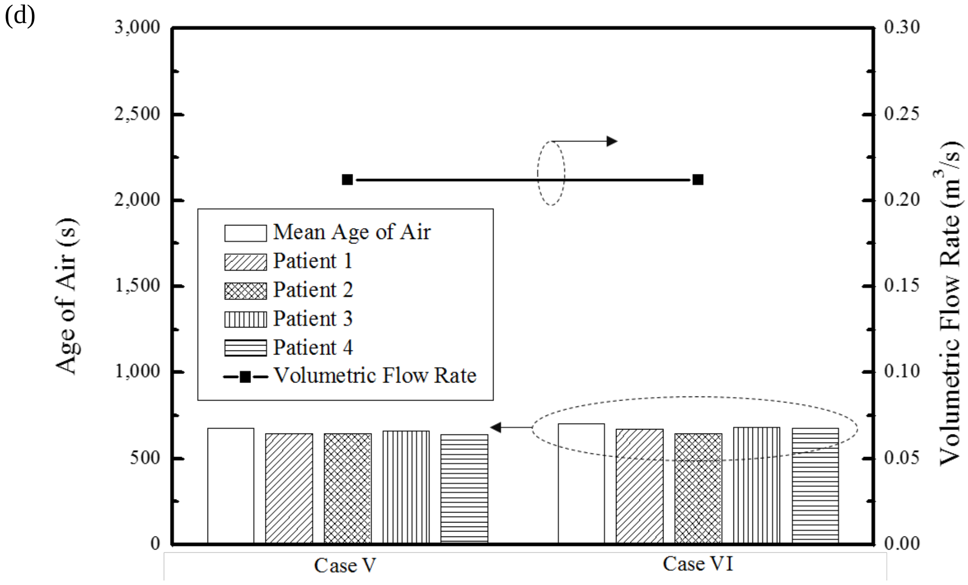

Fig. 8. (*continued*).

use and the interior structure of the building. Therefore, it is necessary to select appropriate locations for both the inlet/outlet ducts of ventilation systems and the air cleaners in order to improve the circulation of air within hospital wards. In some cases, the use of multiple air cleaners may be necessary. Moreover, in future studies, the effect of particle size on the air age distribution needs to be investigated.

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