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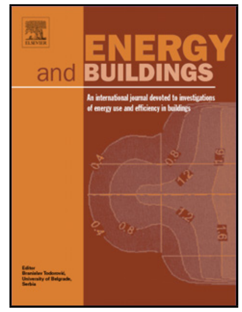

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Evaluation of Clean Air Delivery Rates and Operating Cost Effectiveness for Room Air Cleaner and Ventilation System in a Small Lecture Room

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Highlights:

- The CADRs of the ventilation and the room air cleaner was newly derived
- The CADR of the room air cleaner was higher than that of the ventilation
- The room air cleaner must be more cost-effective than the ventilation system

Abstract

In general, room air cleaners are rated according to clean air delivery rate (CADR). However, ventilation systems have not yet been assessed using a metric similar to CADR. This study establishes a new mass balance equation that compares the CADRs of a ventilation system and a room air cleaner. Experiments and CFD simulations were conducted to evaluate and compare the CADRs of room air cleaners and ventilation system in the view of removing particles from indoor air. In addition, the operating cost effectiveness of ventilation system and room air cleaner was investigated. The results showed that the room air cleaners showed their performance independently, even when two or more room air cleaners were operated simultaneously. In the ventilation system, an air filter with MERV11 or higher rating was recommended to reduce the indoor particle concentration when 100% outdoor air was supplied. It was possible to select an air filter with MERV11or lower rating when the recirculation airflow rate was increasing up to 70%. The CADR of the room air cleaner was higher than that of the ventilation system regardless of the particle size and the filter performance when the airflow rate was same. The operating cost effectiveness (CADR/kW) of the room air cleaner was higher than that of the ventilation system at the same airflow rate. Therefore, the room air cleaner must be more cost-effective than the ventilation system for reducing particle concentration indoors.

Keywords: Air Cleaner, Clean Air Delivery Rate (CADR), Operating Cost Effectiveness, Particle, Ventilation

1. Introduction

Ventilation and air cleaning techniques have been used for indoor spaces to improve indoor air quality [1]. Ventilation has been conventionally used to control the concentration of the particles and toxic gases, particularly, toxic substances. Indoor air cleaning has received an increasing amount of attention as a cost-effective method to reduce the concentration of indoor particles [1, 2]. However, each of these techniques has weaknesses. Ventilation is challenging due to the energy consumption in buildings and the introduction of dirty outdoor air that is present in many cities, and air filters with modern technology cannot be used to remove toxic gases for long periods of time.

Many studies have been carried out to reduce the indoor particle concentration by using ventilation and indoor air cleaner. Recently, a study to determine the proper ventilation rate and filter grading was carried out by analyzing the mass balance and fan power equations to reduce both the particle concentration and the fan energy consumption in the home [3]. The energy-saving potentials of a ventilation system with an air cleaning unit and demand control were investigated in a multi residential building [4]. The impact of the air distribution method in ventilated rooms on the aerosol particle dispersion and removal was investigated through experiments and CFD simulation [5]. Fischer et al. investigated which time-varying ventilation strategy was good to reduce indoor particle concentration [6]. Persily provided a summary of ventilation metrics, measurement methods, and numerous field studies of ventilation rates in order to understand building performance in terms of energy consumption and indoor air quality [7].

Moreover, the primary effect (i.e., concentration reduction) and secondary effect (energy use and byproduct emissions) of indoor air cleaners were described by Siegel [1]. Noh and Oh showed that the CADR of room air cleaner can be expressed as the product of the effective air cleaning ratio (EACR), filtration efficiency, and flow rate [2]. Many indoor air cleaners were rated and compared according to clean air delivery rate (CADR) [8]. Sultan et al. tested various air cleaners that used different technologies and found that air cleaners with a HEPA filter and an electrostatic precipitator exhibit the best performance [9]. Shaughnessy and Sextro discussed the proper CADR to describe the room area and air cleaning effectiveness for different room sizes and air cleaner CADR ratings [10]. Novoselac and Siegel assessed the effect that the CADR of a portable air cleaner and its location had on the overall particle concentration in a residential zone [11]. Zuraimi et al. evaluated the effectiveness of portable air cleaners in removing airborne NaCl particles as an analogue for the influenza virus and applied an IAQ mass balance model to evaluate the performance of the system in controlling residential exposure and mitigating the risk of infection [12].

Even though many studies have been carried out to date, rarely has air cleaning performance of ventilation systems been compared to that of indoor air cleaners. Moreover, the operating cost effectiveness of ventilation system and room air cleaner was not compared until now.

This study evaluates and compares the performance of indoor air cleaner and ventilation system in removing indoor particles in a small lecture room. A mass balance equation with two different CADRs of indoor air cleaner and ventilation system was newly derived from the conventional mass balance equation. Experiments and CFD simulations were carried out to validate the new mass balance equation when the room air cleaners operated only. Mutual interference of room air cleaners was investigated when two or more room air cleaners are simultaneously operating. The certified CADRs of room air cleaners were re-assessed in a real scale lecture room regarding indoor particle removal. The CADRs of the ventilation system were then compared to those of room air cleaners with respect to the filter performance, ratio of the indoor to outdoor particle concentration, and the particle size. Finally, the operating cost effectiveness of ventilation system and room air cleaner was investigated and discussed.

2. Clean Air Delivery Rates and Operating Cost Effectiveness

2.1 Clean Air Delivery Rates

Fig. 1 shows the modeled processes that have an effect on indoor particle concentration. The ventilation system, room air cleaning device, infiltration, particle deposition, particle generation, ventilation effectiveness and effective air cleaning ratio (EACR) are depicted.

Here, the EACR refers to the predicted air mixing performance of an air cleaning device in a room, and it is rated on a scale from 0 to 1 [2].

The mass balance equation for particles can be expressed as in Eq. (1). For convenience, the expression for particle size, d_p (μm), is omitted in Eq. (1) through Eq. (5).

$$\begin{aligned} V\frac{dC_{in}}{dt} &= \varepsilon_r\left[P_{vent}\cdot\left(\dot{Q}_{out}\cdot C_{out}+\dot{Q}_{re}\cdot C_{in}\right)-\left(\dot{Q}_{out}+\dot{Q}_{re}\right)\cdot C_{in}\right] \\ &\quad+\varepsilon_{ac}\left[P_{ac}\cdot\dot{Q}_{ac}\cdot C_{in}-\dot{Q}_{ac}\cdot C_{in}\right] \\ &\quad+P_{inf}\cdot\dot{Q}_{inf}\cdot C_{out}-\dot{Q}_{exf}\cdot C_{in}-V\cdot\dot{S}_{dep}\cdot C_{in}+\dot{G} \end{aligned} \tag{1}$$

where, C_{in} is the indoor particle concentration (#/m^3), C_{out} is the outdoor particle concentration (#/m^3), $\dot{Q}_{out}$ is the outdoor airflow rate (m^3/min), $\dot{Q}_{re}$ is the recirculation airflow rate (m^3/min) as shown in Fig. 1, $\dot{Q}_{ac}$ is the airflow rate of the room air cleaner (m^3/min), $\dot{Q}_{inf}$ is the infiltration airflow rate (m^3/min), $\dot{Q}_{exf}$ is the ex-filtration airflow rate (m^3/min), P_{vent} is the penetration efficiency of a ventilation filter (-), P_{ac} is the penetration efficiency of the room air cleaner (-), P_{inf} is the penetration efficiency of particles due to outdoor air infiltration (-), V is the volume of a room (m^3), $\dot{S}_{dep}$ is the deposition rate of the particles in room, $\dot{G}$ is the generation rate of the particles in a space (#/min), t is the time (min), ε_r is the ventilation effectiveness (-), and ε_{ac} is the EACR of the room air cleaner (-). In general, there is a difference between the infiltration airflow rate and the ex-filtration airflow rate, but in this study, both airflow rates are assumed to be the same. The same applies to the in/out airflow rates for ventilation system.

As shown in Eq. (1), the ventilation effectiveness and the EACR were used in order to consider the air mixing characteristics of ventilation system and room air cleaner, and to make correct predictions of the particle decay rates in indoor air. The air mixing characteristics of room air cleaners were defined as the EACR in Ref. [2] or the short-circuit factor in Refs. [13, 15, 16].

The first and second terms in the right hand side of Eq. (1) can be manipulated in respect to the indoor particle concentration, C_{in}, and therefore Eq. (1) changes as follows.

$$\begin{aligned} V\frac{dC_{in}}{dt} &= -\varepsilon_r \cdot \left[\left(1-P_{vent}\frac{C_{out}}{C_{in}}\right) \cdot \dot{Q}_{out} + \left(1-P_{vent}\right) \cdot \dot{Q}_{re} \right] \cdot C_{in} - \varepsilon_{ac} \cdot \left(1-P_{ac}\right) \cdot \dot{Q}_{ac} \cdot C_{in} \\ &\quad + P_{inf} \cdot \dot{Q}_{inf} \cdot C_{out} + \dot{Q}_{exf} \cdot C_{in} - V \cdot \dot{S}_{dep} \cdot C_{in} + \dot{G} \\ &= -\left[\varepsilon_r \cdot \left(1-P_{vent}\frac{C_{out}}{C_{in}}\right) \cdot \dot{Q}_{out} + \varepsilon_r \cdot \left(1-P_{vent}\right) \cdot \dot{Q}_{re} + \varepsilon_{ac} \cdot \left(1-P_{ac}\right) \cdot \dot{Q}_{ac} \right] \cdot C_{in} \\ &\quad + P_{inf} \cdot \dot{Q}_{inf} \cdot C_{out} - \dot{Q}_{exf} \cdot C_{in} - V \cdot \dot{S}_{dep} \cdot C_{in} + \dot{G} \end{aligned} \tag{2}$$

$$CADR_{vent} = \varepsilon_r \cdot \left[\left(1-P_{vent}\frac{C_{out}}{C_{in}}\right) \cdot \dot{Q}_{out} + \left(1-P_{vent}\right) \cdot \dot{Q}_{re} \right] \tag{3}$$

$$CADR_{ac} = \varepsilon_{ac} \cdot \left(1-P_{ac}\right) \cdot \dot{Q}_{ac} \tag{4}$$

$$V\frac{dC_{in}}{dt} = -\left[CADR_{vent} + CADR_{ac} + \dot{Q}_{exf} + V \cdot \dot{S}_{dep} \right] \cdot C_{in} + P_{\mathrm{inf}} \cdot \dot{Q}_{\mathrm{inf}} \cdot C_{out} + \dot{G} \tag{5}$$

In Eqs. (3) and (4), $CADR_{vent}$ and $CADR_{ac}$ indicate the clean air delivery rates of the ventilation system and the room air cleaner (m^3/min), respectively. In Eq. (2), the terms for the infiltration and ex-filtration have been left untouched since a specific airflow pattern cannot form as a result of infiltration and ex-filtration, such as for a ventilation system and a room air cleaner.

As shown in Eq. (3), the CADR of ventilation system can be defined as a function of the ventilation effectiveness, the penetration efficiency of the ventilation filter, the ratio of outdoor to indoor particle concentrations, the outdoor airflow rate, and the recirculation airflow rate, whereas the CADR of room air cleaner, shown in Eq. (4), can be expressed as the product of the EACR, the penetration efficiency of room air cleaner, and the airflow rate of room air cleaner. When the CADR is higher than zero, it means that the ventilation system or the room air cleaner can reduce the particle concentration in indoor air. Oppositely, when the CADR is lower than zero, it means that the indoor particle concentration will increase. From Eqs. (3) and (4), the CADRs for ventilation system and room air cleaner can be compared to each other.

From Eq. (5), the transient solution of the mass balance equation, Eq. (1), can be obtained as follows.

$$
\begin{aligned}
C_{in}(d_p,t) = {} & C_{in}(d_p,0)\cdot exp\left[-\frac{1}{V}(CADR_{vent}(d_p)+CADR_{ac}(d_p)+\dot{Q}_{exf}+V\cdot\dot{S}_{dep}(d_p))\cdot t\right] \\
& +\left\{1-exp\left[-\frac{1}{V}(CADR_{vent}(d_p)+CADR_{ac}(d_p)+\dot{Q}_{exf}+V\cdot\dot{S}_{dep}(d_p))\cdot t\right]\right\} \\
& \times\frac{P_{\boldsymbol{inf}}(d_p)\cdot\dot{Q}_{\boldsymbol{inf}}\cdot C_{out}(d_p)+\dot{G}(d_p)}{CADR_{vent}(d_p)+CADR_{ac}(d_p)+\dot{Q}_{exf}+V\cdot\dot{S}_{dep}(d_p)}
\end{aligned}
\tag{6}
$$

where, d_p is the particle size (μm). Under the steady state condition, the indoor particle concentration will be determined by the second term of the right hand side in Eq. (6).

2.2 Operating cost effectiveness

The operating cost effectiveness was simply defined as the CADR per electric power consumption in this study. Therefore, the higher the operating cost effectiveness is, the more the energy-efficient technology is. The CADRs of the ventilation system and the room air cleaner was obtained from Eqs. (3) and (4), respectively. The electric power consumption of room air cleaner was generally rated at the highest airflow rate and presented on the body in Korea. Therefore, the rated electric power consumption was directly used. The electric power consumption of ventilation system was assumed as the fan power draw of a heat recovery ventilator since the application of a heat or energy recovery ventilation system with filter has been used as a good solution to supply the fresh outdoor air and to eliminate indoor contaminants from the lecture room.

3. Research Methods

3.1 Experiments

Fig. 2(a) and (b) show the schematic and photo of the test room that was used as a lecture room at University of Seoul to investigate the variations in the particle decay rates according to the number and the type of operating room air cleaners. The test room had dimensions of 6.5 m (L) x 7.0 m (D) x 2.7 m (H). Three different room air cleaners were used for all tests. All room air cleaners were obtained from their manufacturer and were in a new condition. The airflow rates, the filtration efficiencies, and the CADRs were certified by the Korea Air Cleaning Association (KACA) standard [17], and the power consumptions of the tested air cleaners are presented in Table 1. The locations of inlets and outlets were different according to the room air cleaners. In the case of AC1, the cleaned air was discharged forward and the indoor air was sucked in from the back side. In the case of AC2, the cleaned air was discharged laterally and the indoor air was sucked in from the back side. In the case of AC3, the cleaned air was discharged forward and the indoor air was sucked in from the left and right sides.

In experiments, the room air cleaners were placed at three different locations, as shown in Fig. 2. The locations of the room air cleaners were fixed in all tests, and the influence of the mutual interference of the operating room air cleaners on the CADR was examined by varying the number of operating room air cleaners from 2 to 3. In fact, there were no inlets or outlets for ventilation in the room. These were virtually made to simulate airflow patterns and the air age in the CFD simulations.

An optical particle counter (Grimm, Model 1.109) was used to measure the concentration decay of the 0.3 μm-sized particles at the center of the test room. The sampling period was set to 1 minute, and all data were sequentially sampled over 1 hour. Outdoor particles were used as test particles. The outdoor particles were sufficiently supplied through natural ventilation, i.e., by opening all windows and doors, and the initial particle concentration in the room was of over 10^7 particles/m^3 in the room. After that, all windows and doors were closed and the room air cleaners were operated. The particle concentrations were measured after 10 minutes to carry out tests after a constant airflow pattern had formed from the room air cleaners. All tests were repeated over three times to guarantee the reliability of the experiments.

3.2 CFD simulation

In general, the particle concentration is not evenly distributed in a space where an air cleaning device is in operation. The CADRs measured at the center of the test chamber would not represent the mean value, as pointed out in Ref [2]. However, the average particle concentrations and the CADRs can be approximately predicted when the air mixing characteristics of ventilation system and room air cleaner were known in a room through CFD simulation. Therefore, CFD simulation was adopted to calculate the air mixing characteristics. The EACR or the ventilation effectiveness were calculated as the ratio of the nominal time constant to the air age induced by the room air cleaner or the ventilation system, respectively [2, 18, 19]. In order to obtain the EACR and the ventilation effectiveness, the air age was numerically calculated for the lecture room.

In the CFD simulation, the flow was assumed to be steady and incompressible. The standard k-ε turbulence model was used. The STAR-CCM+ simulation software, version 8.02.011 was employed to compute the velocity field and the air age distributions. The grid dependency tests were performed and the number of grid was more than 550,000 in all simulation cases.

4. Results and Discussion

4.1 CADRs of the room air cleaners with no ventilation

Fig. 3 shows examples of the indoor particle decay when the number of operating room air cleaners varied. By considering the most penetrating particle size (MMPS) of general filters, the concentration of the 0.3 μm particles was monitored. Each of the data was normalized by the initial concentration of the 0.3 μm particles. The particle concentrations rapidly decreased with an increment of the operating room air cleaners. The tendency of the particle decay was similar for all cases. Table 2 shows the EACRs, the real CADRs, and the removal rates of deposition and ex-filtration according to the number and the kind of operating room air cleaners. The EACRs were obtained from CFD simulations. The real CADR was used to be distinguished from the certified CADR. The real CADRs of the room air cleaners were calculated using Eq. (4). The real CADRs increased arithmetically with the increment in the number of the operating air cleaners. This means that the room air cleaners operated independently, even when two or more room air cleaners simultaneously operated in the lecture room.

The particle removal rates of the deposition and ex-filtration were calculated from the first term in Eq. (5).The particle removal rates of the deposition and ex-filtration varied with the experimental cases. The average and the standard deviation of the particle removal rates were 3.145 m^3/min and 0.313 m^3/min, respectively. Also, the particle removal rates of the deposition and ex-filtration can be estimatedby a reasonable assumption. The deposition removal rate of 0.3-μm particles was calculated to be of about 0.1 m^3/min in the lecture room since the deposition rate of the 0.3-μm particles was known to be of about 0.05/hour [2, 14, 20]. According to previous research [21], the infiltration or the ex-filtration rates were surveyed within the range from 1.0 to 1.5/hour over 80% of the lecture rooms in Korea. From this information, the removal rates of the ex-filtration were predicted to be in the range from 2.05 to 3.08m^3/min. The sum of the deposition and the ex-filtration removal rates that were calculated from the reasonable estimation was nearly equal to the average removal rates of the deposition and ex-filtration presented in Table 2 when the ex-filtration was assumed to be of about 1.5/hour.

Table 3 shows the measured and predicted particle decay rates in the lecture room. The measured particle decay rates were obtained by curve fitting for particle concentration data sets. The errors of the particle decay rates stayed at under 0.004. Both of two different predicted particle decay rates were obtained from the assumption that the particle removal rates of the deposition and ex-filtration were 0.1 m^3/min and 3.08 m^3/min, respectively. The predicted results obtained from the real CADR were in good agreement with the measured ones. This result showed that the indoor particle decay rates would be approximately predicted through information of the real CADR, the deposition rate, the ex-filtration rate, and the volume of a room. On the other hand, the measured particle decay rates were not in agreement with the predicted particle decay rates obtained from the certified CADRs enumerated in Table 1. In all cases, the predicted particle decay rates obtained from the certified CADRs were larger than the measured ones.

Figs. 4(a) and (b) show the distributions of the velocity and the air age in the case where three room air cleaners are in operation and the ventilation system is off. The velocity distribution showed that the airflow patterns formed by a room air cleaner partially disturbed those formed by the others. However, the cleaned air discharged from an air cleaner was not directly introduced to the inlets of the other air cleaners as can be seen from the air age distribution. Therefore, it was thought that the room air cleaners operated independently when two or more room air cleaners simultaneously operated in the lecture room as mentioned earlier.

As shown in Table 2, the EACRs varied with the kind of room air cleaners. That is, the location of the inlet and the outlet, as shown in Figs. 4(a) and (b), led to the different EACRs. The EACR was relatively large when the direction of the discharge and the suction were the same (AC1). The results suggested that the location of the inlet and the outlet of a room air cleaner must be important factors for determining the ability of the indoor air to mix by the room air cleaner. Nevertheless, the EACRs were similar in this study when two or more room air cleaners operated simultaneously.

4.2 Comparison of the CADRs between the room air cleaner and the ventilation system

The CADR of the ventilation system can be obtained when the ventilation effectiveness is known in the lecture room. To obtain the ventilation effectiveness in the lecture room, the CFD simulations were carried out. Figs. 5(a) and (b) show the distributions of the velocity and the air age when the ventilation system operates and the room air cleaners are off. The ventilation airflow rate was selected to be of 6 m^3/min in order to meet the airflow rate that is discharged from the room air cleaner, AC1. As shown in Figs. 5(a) and (b), the ceiling-based air supply diffusers and air return grilles were modelled for the supply air to be evenly distributed throughout the lecture room. From the CFD simulation, the mean air age and the ventilation effectiveness that were obtained were about 1,345s and 0.68, respectively. The ventilation effectiveness was placed in the typical range from 0.63 to 0.82 that was surveyed in previous studies [22]. The ventilation effectiveness of the lecture room was slightly lower than the EACRs of the room air cleaners.

In order to find the CADR for the ventilation system, the penetration efficiency of the ventilation filter and the outdoor or recirculation airflow rate should be known. The ventilation filters with a performance of MERV08, MERV11, or MERV14 were considered to assess the removal of the particles introduced from outdoor air. Two different air supply concepts were considered in this study. The one is 100% outdoor air supply to the lecture room and the other is the supply of 30% outdoor air and 70% recirculation air.

Figs. 6(a) and (b) show the variations in the CADRs of the ventilation system for the ratio of the indoor to the outdoor particle concentration and the performance of the ventilation filter when 100% outdoor air of 6 m^3/minis supplied to the lecture room. Also, the CADR of the room air cleaner with the discharge airflow rate of 6 m^3/min and the removal rate of the deposition and ex-filtration in the lecture room were depicted. For the 0.3-μm particles, the penetration efficiencies for MERV08, MERV11, and MERV14 were determined as 0.95, 0.80, and 0.26, respectively [23, 24]. For the 3.0-μm particles, the penetration efficiencies for MERV08, MERV11, and MERV14 were determined as 0.35, 0.03, and 0.0, respectively [23, 24]. The CADRs of the ventilation system gradually increased with the increase in the ratio of the indoor to outdoor (I/O) particle concentration. The CADRs of the ventilation system increased with the increase in the particle size. In addition, a higher collection efficiency for the particles guaranteed a higher CADR. The highest CADR of the ventilation system was of 3.48 m^3/min for the 3.0-μm particles, which was determined by the product of the ventilation effectiveness and the ventilation airflow rate.

When the I/O ratio was the same as the penetration efficiency of the particle size, the CADR of the ventilation system for the given particle size became zero as shown in Eq. (3). For example, the CADR for the ventilation system of the 0.3-μm particles became zero when an I/O ratio was equal to 0.95 and 0.80, respectively, for the MERV08 or MERV11 filters used in the ventilation system. Therefore, the indoor concentration of 0.3-μm particles would increase in the 100% outdoor air supply system when the MERV8 filter was used and the I/O ratio of 0.3-μm particles was lower than 0.95. According to the previous study [25], the I/O ratio of lower than 0.95 for 0.3-μm particles can be frequently taken place in buildings. This means that the indoor air quality in the view of particle concentration can be deteriorated when the ventilation filter having a performance of lower than MERV11 is used. Similarly, Noh and Hwang [3] pointed out that the ventilation filters witha higher than MERV11 were recommended to reduce the indoor particle concentration in a residential housing unit. Fig. 6(b) shows that particles larger than 3.0 μm are not easily transferred to indoor air when the ventilation filter having MERV11 or a higher performance is adopted because these filters can almost perfectly screen large particles that are included in outdoor air.

The CADR of the room air cleaner was higher than that of the ventilation system at the same airflow rateregardless of the particle size and the filter performance when 100% outdoor air was supplied at 6 m^3/min. The reason was that the EACR, which was the air mixing characteristic metric by the room air cleaner, was higher than the ventilation effectiveness of the ventilation system and the filtration efficiency of the room air cleaner was higher than that of the ventilation system. Also, the removal rate of the deposition and ex-filtration in the lecture room was higher than the CADRs of the ventilation system when 100% outdoor air was supplied at 6 m^3/min.

Figs. 7(a) and (b) show the variations in the CADRs of the ventilation system for the ratio of the indoor to the outdoor particle concentration and the performance of the ventilation filter when 30% outdoor air of 6 m^3/min and 70% recirculation air are supplied to the lecture room. As the recirculation airflow rate to the lecture room increased, the CADRs for ventilation system also increased as compared with the results displayed in Figs 6(a) and (b). It was due to the fact that the increase of the recirculation air reduced the influence of the outdoor particle concentration. Therefore, it was possible to select the relatively lower performance filter at the same I/O ratio when the recirculation air was supplied to the lecture room. At the I/O ratio of 0.85, for example, MERV08 filter could be used to reduce the indoor particle concentration with the scheme of 30% outdoor air and 70% recirculation air, whereas MERV11 filter was needed when the 100% outdoor air was supplied.

Regardless of the increment of the recirculation air, the CADR of the room air cleaner was superior to that of the ventilation system at the same airflow rate. Also, the particles larger than 3.0 μm are not easily transferred to indoor air when the ventilation filter having MERV11 or a higher performance is adopted. Consequently, most of large particles that were measured in the indoor air, including bacteria and fungi, were presumed to be originated from occupants, pets, and other indoor sources (such as burning) or to have been re-suspended from the floor or other surfaces, except for the case when the ventilation filter of lower than MERV11 was used.

4.3 Operating cost effectiveness of the room air cleaner and the ventilation system

Table 4 shows the operating cost effectiveness of the ventilation system and the room air cleaner when the ventilation system supplies 100% outdoor air of 6 m^3/min at I/O ratio of unity and the room air cleaner discharges the cleaned air of 6 m^3/min, respectively. In Table 4, the electric power consumption of the ventilation system, i.e. a heat or energy recovery ventilator with the airflow rate of about 6 m^3/min, referred to the rated or estimated values in the previous studies [3, 26].

The operating cost effectiveness of the ventilation system increased as the filter performance became higher. The operating cost effectiveness of the room air cleaner (AC1 in Table 1) was higher than that of the ventilation system regardless of the particle size and filter performance. The reason was that the CADR of the room air cleaner was high and the electric power consumption of the room air cleaner was very low as compared to those of the ventilation system. The operating cost effectiveness of the room air cleaner was 6~7 times higher than the maximum operating cost effectiveness of the ventilation system with MERV14. Even though the I/O ratio increases and then the CADR of the ventilation system also increases, the operating cost effectiveness of the room air cleaner will be still higher than that of the ventilation system. From these results, the room air cleaner is more cost-effective for reducing particle concentrations indoors.

5. Conclusions

The performance of room air cleaners and ventilation systems was investigated in terms of the removal of indoor particles by taking a theoretical approach, conducting experiments, and running CFD simulations. A mass balance equation considering the CADRs of the ventilation system and room air cleaner was newly derived, and the CADRs for the room air cleaners and ventilation system were evaluated and compared at various conditions. In addition, the operating cost effectiveness was investigated. The experiments and simulations allowed the following conclusions to be drawn.

The room air cleaners showed their performance independently, even when two or more room air cleaners were simultaneously operated in the lecture room in our case studies. However, additional investigations are necessary by considering various lecture room size and airflow rate. The air mixing characteristics, i.e., EACR, of the room air cleaners varied according to the locations of the inlet and outlet. The EACR was relatively larger when the directions of the discharge and suction were the same. The CADR of the room air cleaner was higher than that of the ventilation system since the air mixing characteristics and the filtration efficiency of room air cleaner were superior. The operating cost effectiveness (CADR/kW) of the room air cleaner was higher than that of the ventilation system at the same airflow rate since the ventilation system had a larger pressure drop and a lower CADR than the room air cleaners. Therefore, the room air cleaner is considered to be more cost-effective than the ventilation system for reducing particle concentration indoors, e.g., in the small lecture room considered in this study.

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Fig. 1 Schematic of a mass balance model in a room with ventilation system and indoor air cleaner

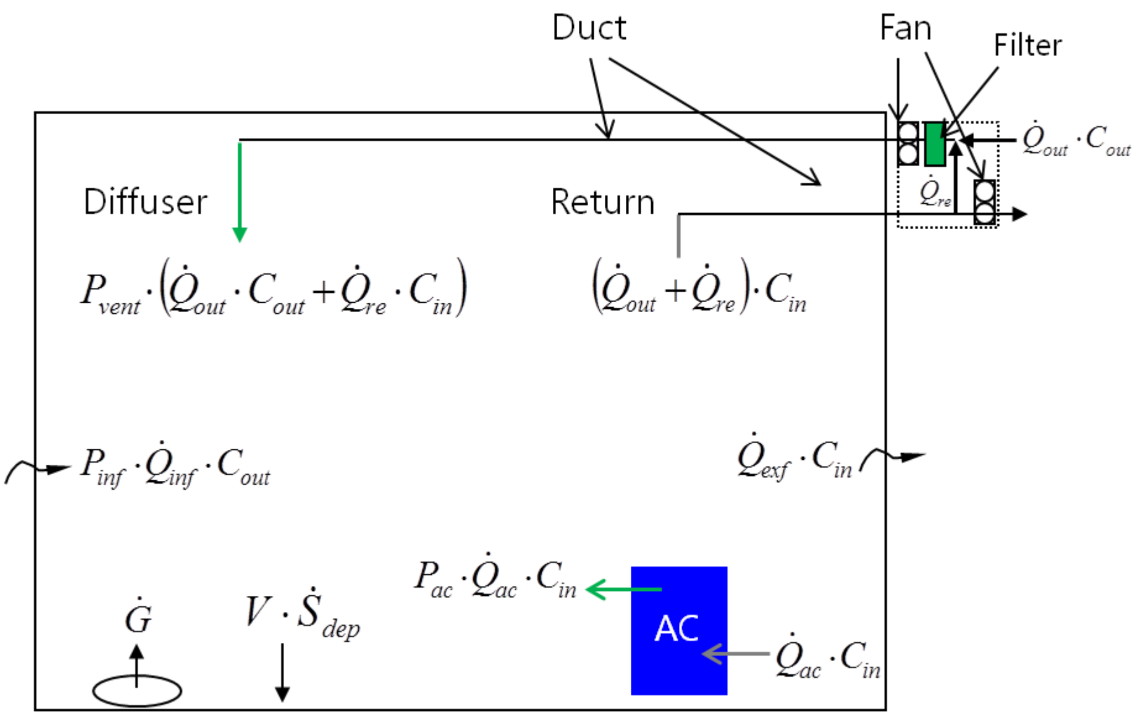
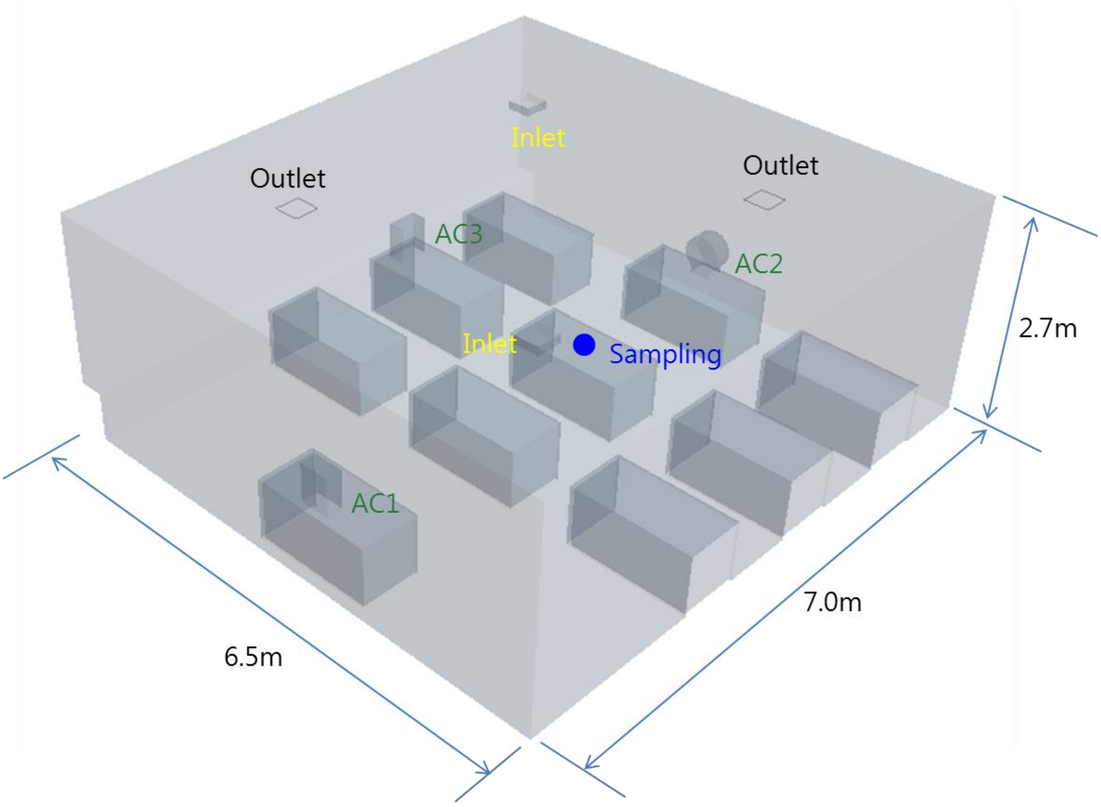


Fig. 2 Schematic and photo of the test room used to analyze CADRs of room air cleaners and ventilation system

(a) Schematic



(b) Photo

Fig. 3 Examples of indoor particle decays when the number of operating room air cleaners varied; Each of the data was normalized by the initial concentration of the 0.3 μm particles.

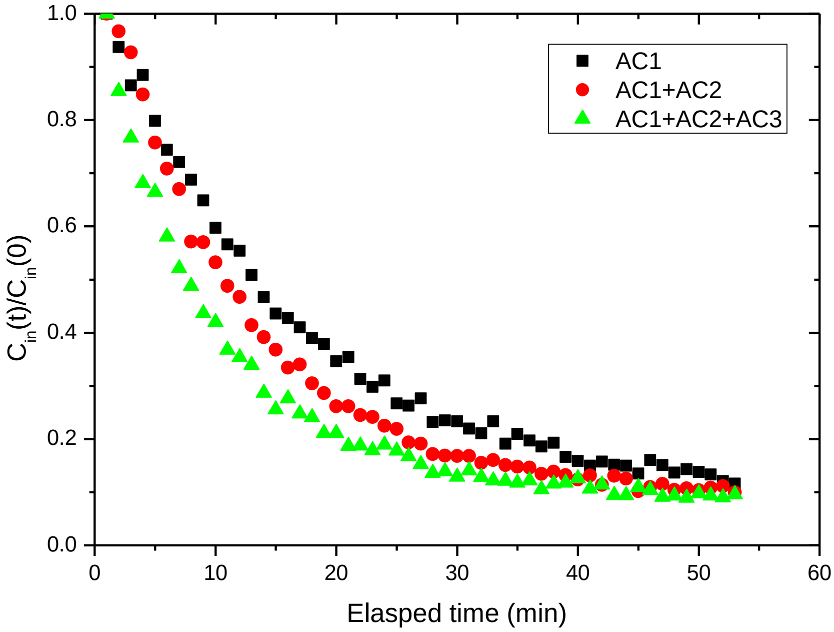
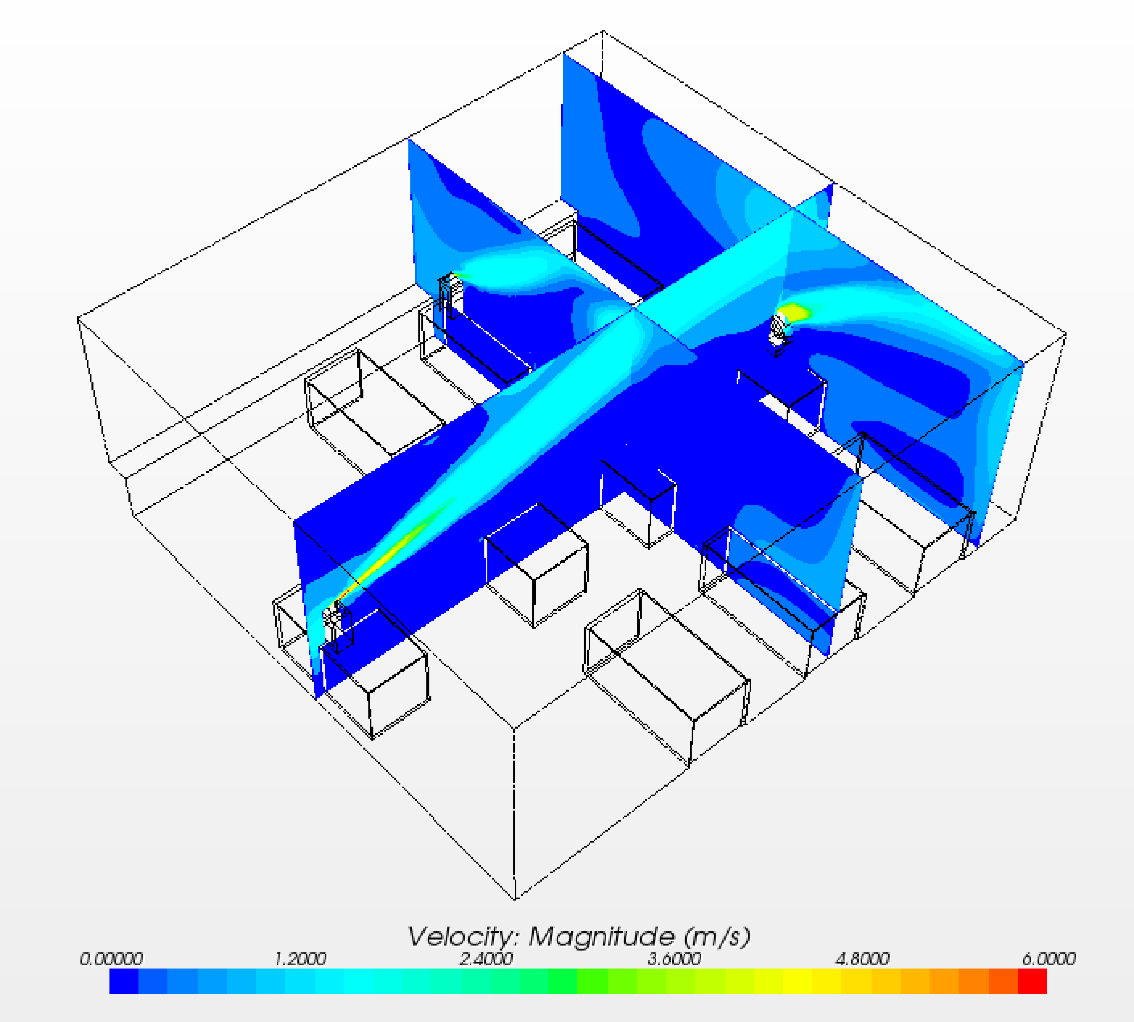


Fig. 4 Distributions of the velocity and the air age in the case where three room air cleaners are in operation but the ventilation system is off.

(a) Velocity



(b) Air age

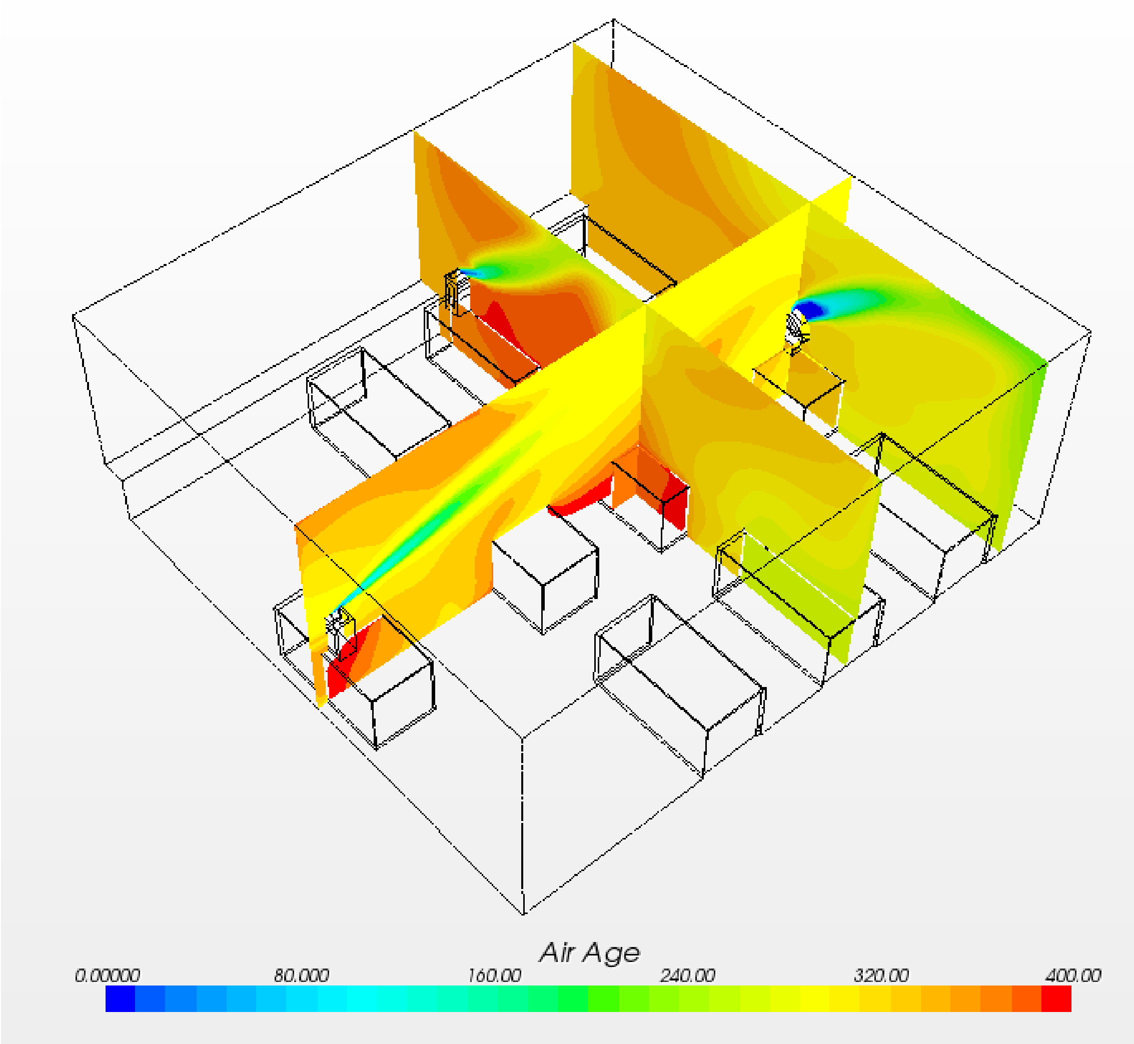
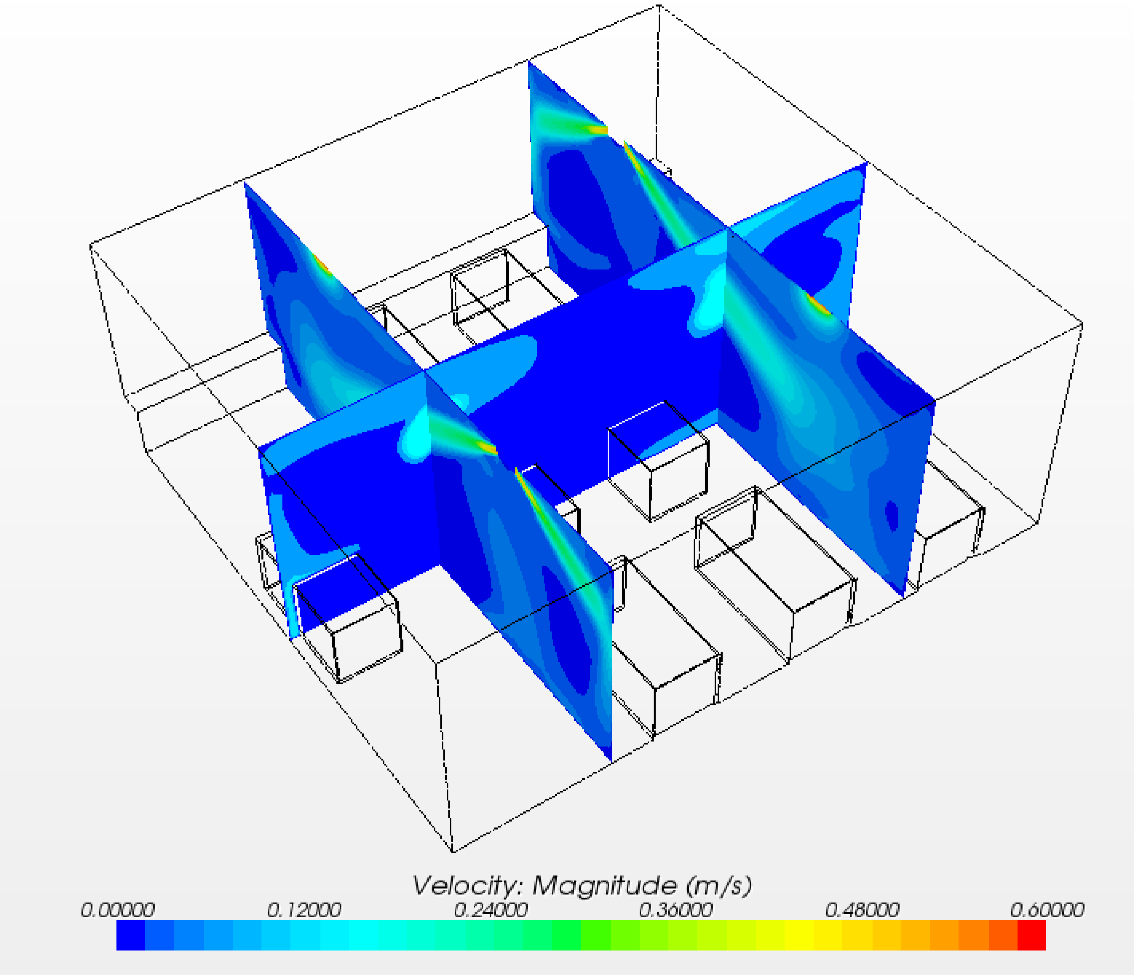


Fig. 5 Distributions of the velocity and the air age when only ventilation operates.

(a) Velocity



(b) Air age

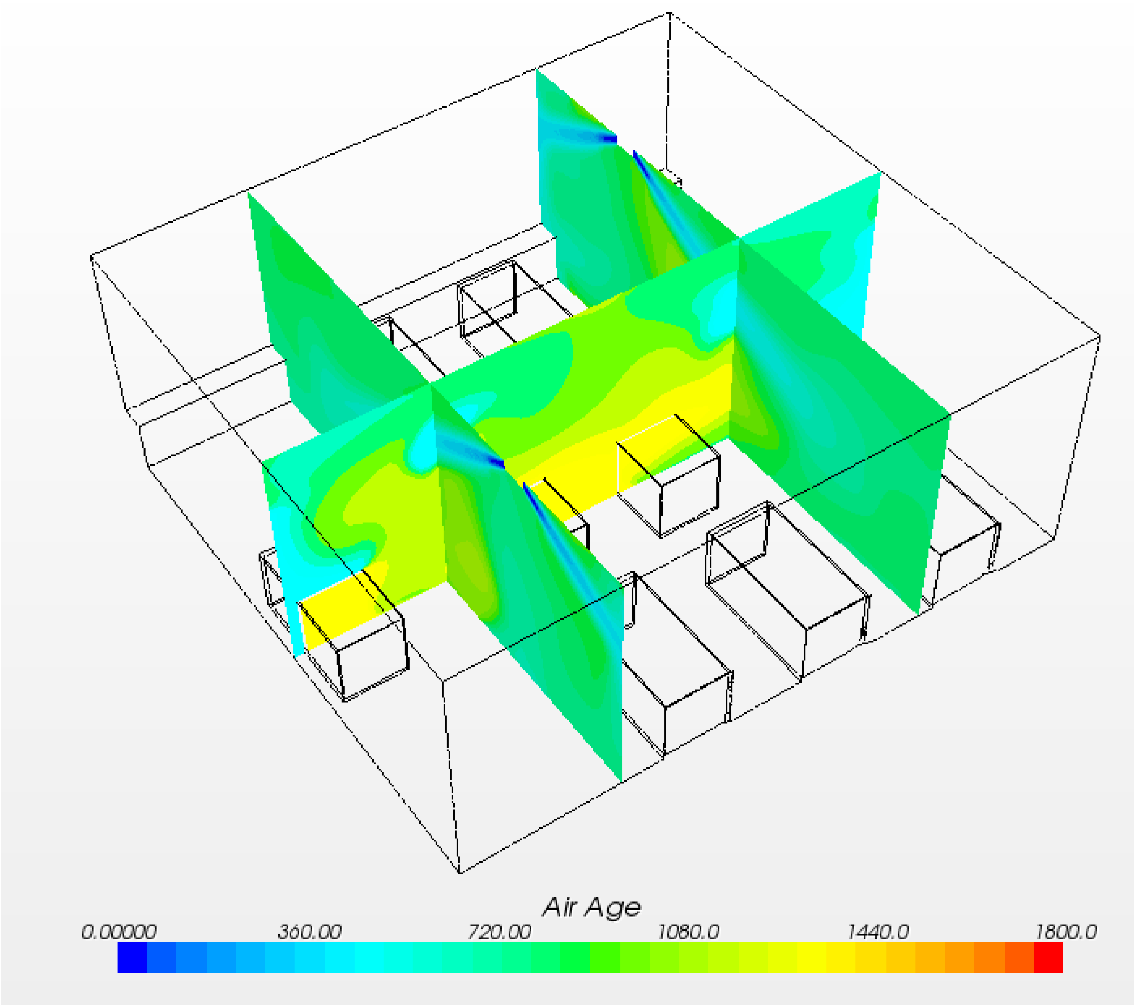
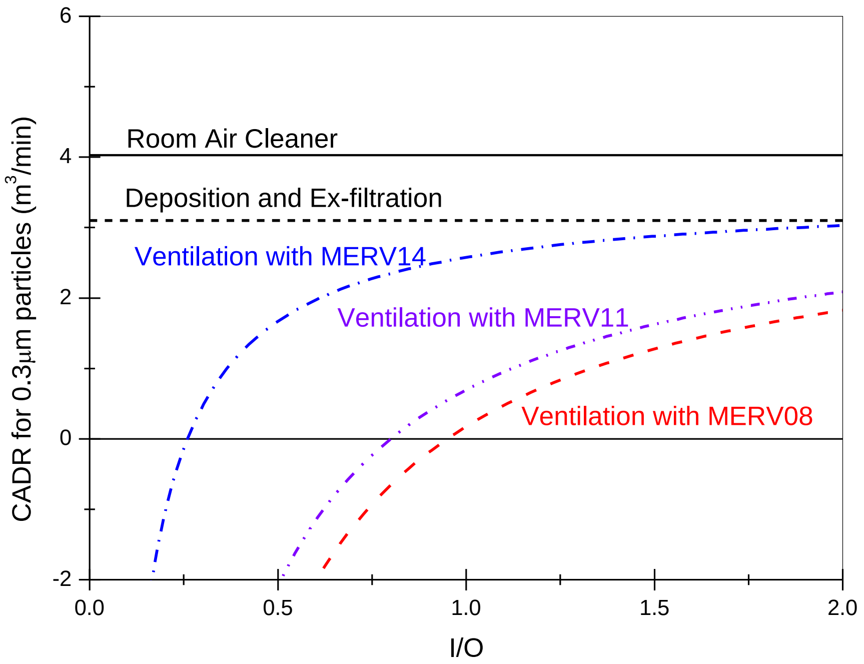


Fig. 6 Variations in the CADR of the ventilation for the ratio of the indoor to the outdoor particle concentration and the performance of ventilation filter when 100% outdoor air of 6 m^3/min is supplied to the lecture room.

(a) 0.3㎛



(b) 3.0㎛

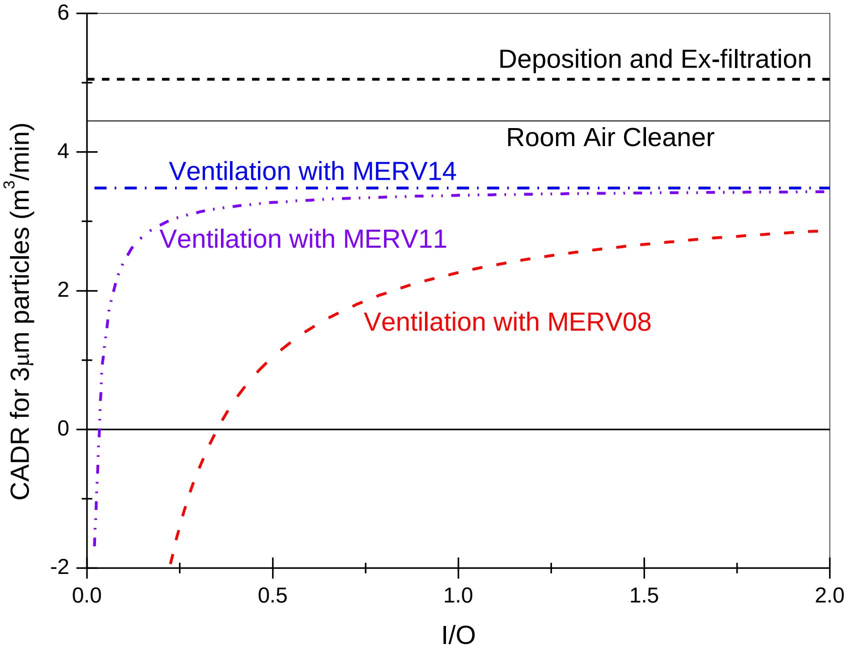
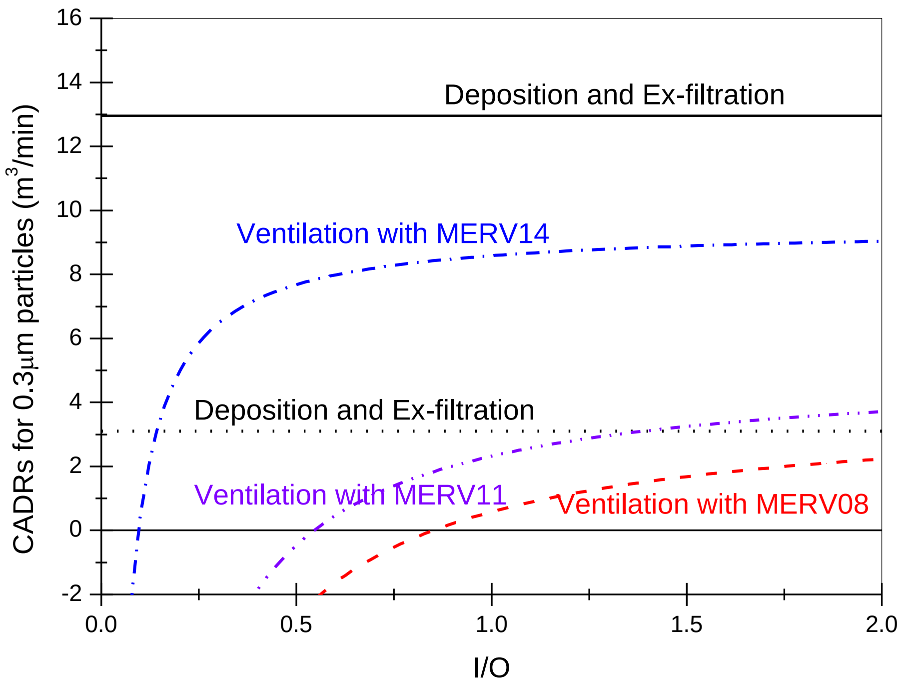
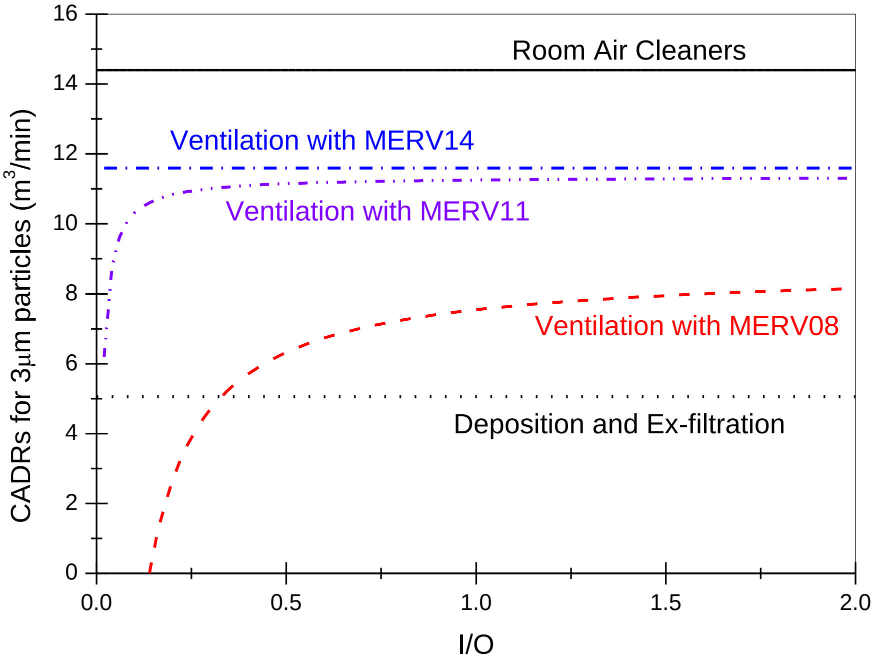

Deposition and Ex-filtration
Room Air Cleaner
Ventilation with MERV14
Ventilation with MERV11
Ventilation with MERV08
CADR for 3µm particles (m³/min)
I/O
6
4
2
0
-2
0.0
0.5
1.0
1.5
2.0

Fig. 7 Variations in the CADR of the ventilation for the ratio of the indoor to the outdoor particle concentration and the performance of ventilation filter when 30% outdoor air of 6 m^3/min and 70% recirculation air supplied to the lecture room.

(a) 0.3㎛



(b) 3.0㎛



Room Air Cleaners
Ventilation with MERV14
Ventilation with MERV11
Ventilation with MERV08
Deposition and Ex-filtration
CADRs for 3µm particles (m3/min)
I/O
0
2
4
6
8
10
12
14
16
0.0
0.5
1.0
1.5
2.0

Table 1 The characteristics of room air cleaners used in tests

Room air cleaners	Airflow rate (m^3/min)	Filtration efficiency (-)	Certified CADR (m^3/min)	Power consumption (kW)
AC1	5.9	0.907	5.25	0.034
AC2	5.5	0.877	4.90	0.040
AC3	3.2	0.86	2.54	0.026

Table 2 The EACRs, the real CADRs, and the deposition and ex-filtration removal rates according to the number and the kind of operating room air cleaners

Cases[1)]	EACR (-)	Real CADR[2)] (m^3/min)	Deposition and Ex-filtration (m^3/min)
AC1	0.754	4.03	3.72
AC2	0.683	3.29	3.07
AC3	0.720	1.98	3.06
AC1+AC2	0.723	7.34	2.98
AC1+AC3	0.720	5.83	2.81
AC1+AC2+AC3	0.725	9.37	3.23

1) Cases were classified from the number and the kinds of the operating room air cleaners.
2) The CADR were calculated using Eq.(3).

Table 3 Measured and predicted particle decay rates of the room air cleaners used in this study

Cases[1)]	Particle decay rates (min^{-1})		
	Measured in the lecture room	Predicted by real CADR	Predicted by certified CADR
AC1	-0.064 ± 0.002	-0.059	-0.068
AC2	-0.053 ± 0.001	-0.053	-0.066
AC3	-0.042 ± 0.001	-0.042	-0.047
AC1+AC2	-0.086 ± 0.001	-0.086	-0.108
AC1+AC3	-0.072 ± 0.002	-0.073	-0.089
AC1+AC2+AC3	-0.105 ± 0.004	-0.102	-0.129

Table 4 Operating cost effectiveness of the ventilation system and the room air cleaner; The ventilation system is assumed to supply 100% outdoor air of 6 m^3/min at I/O ratio of unity and the room air cleaner is assumed to discharge the cleaned air of 6 m^3/min.

Air cleaning method	Filter performance	CADR (m^3/min)		Electric power consumption (kW)	Operating cost effectiveness (CADR/kW)	
		0.3㎛	3.0㎛		0.3㎛	3.0㎛
Ventilation system	MERV08	0.174	2.262	0.164 to 0.324	0.54 to 1.06	6.98 to 13.79
	MERV11	0.696	3.376	0.164 to 0.352	1.98 to 4.24	9.59 to 20.59
	MERV14	2.575	3.480	0.164 to 0.425	6.06 to 15.7	8.19 to 21.22
Room air cleaner	90% @0.3㎛ 100% @3.0㎛	4.030	4.450	0.034	118.5	130.9