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The Effect of Ventilation Rate and Filter Performance on Indoor Particle Concentration and Fan Power Consumption in a Residential Housing Unit

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Key Words

Filter performance · Indoor air quality · Particle · Residential housing · Ventilation

Abstract

This paper reports a study of the effect of ventilation rate and filters performance on indoor particle concentration and fan power consumption in a residential housing unit with a mechanical ventilation system. Through an adapted mass-balance model, indoor particle concentrations were calculated for various ventilation rates, filter performances and room sizes. Additionally, the influence of air-exchange effectiveness and cross-contamination around the exterior air vent on the indoor particle concentration was considered. Recirculation of indoor air was not considered. From the results, filters for which the performance was lower than MERV07 were found to be insufficient for reducing indoor particle concentrations below the levels obtained under no ventilation. A higher ventilation rate was needed for the given amount of indoor particle sources for a smaller size residential housing unit in comparison to the larger units. The minimum ventilation rate was less sensitive to variations in the air-exchange effectiveness inside the residential housing unit and the cross-contamination index around the exterior air vents. To satisfy the ventilation requirement for gaseous pollutants and keep the particle concentrations below those under no ventilation, a filter with a performance that would exceed MERV11 should be used when the size of the residential housing unit is in the range of 150–300 m^3.

Introduction

The increasing requirement for energy conservation of buildings, has increased the air-tightness of building further, and reduced ventilation rate. These would have an effect in deteriorating indoor air quality (IAQ) [1–6]. The reduced ventilation rate could bring about an increase in allergic and asthmatic diseases among both children and adults [7–10]. Seppänen and Fisk [7] showed that a low

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ventilation rate in offices could be associated with an increased risk of adverse health effects. Apte et al. [8] reported that increases in the ventilation rates in typical office buildings would significantly reduce the prevalence of several symptoms such as sore throat, irritated nose, combined mucous membrane symptoms, tight chest and wheezing. Bornehag et al. [9,10] studied the association between IAQ and the presence of asthma/allergies; they undertook detailed chemical, physical, biological and medical measurements in 200 homes with healthy children. The results showed that allergic symptoms were inversely related to the degree of ventilation.

The sick-building syndromes or other adverse health effects that are related to the ventilation rate could be originally caused by gaseous or particulate pollutants that are generated both indoors and outdoors [5,6]. The concentration of gaseous pollutants is higher in buildings than outdoors, but that of particulate pollutants is lower within buildings when compared to outdoors, as long as there are no sources of combustion and environmental tobacco smoke and no cleaning activities carried out indoors [11–15]. Therefore, ventilation and filtration are important, for simultaneously controlling gaseous and particulate pollutants, reducing the risks of sick building symptoms associated with poor IAQ and satisfying the health and wellbeing of the occupants.

However, an increase in the ventilation rate can lead to an increase in energy consumption due to the incremental pressure-loss in a mechanical ventilation system that comprises of a filter, duct and heat-exchanger. Thus, a few studies have been carried out to understand the effect of ventilation and filtration on IAQ [12,13,15–17], but the effect of the ventilation rate and filter performance on energy consumption has not been sufficiently considered.

The aim of this work was to investigate the effect of the ventilation rate and filter performance on both indoor particle concentration and fan power consumption in a residential housing unit that contains a mechanical ventilation system. For this purpose, the concentrations of indoor particles were theoretically calculated by adapting a mass-balance model, and the energy consumption was monitored for the various outdoor airflow rates, filter performances and room sizes. Additionally, the influence of the air-exchange effectiveness and the cross-contamination around the exterior air vent was considered. From the results on the concentration of indoor particles and fan power consumption, the proper filter performance for satisfying the minimum ventilation rate and diminishing the energy consumption in residential housing units was evaluated.

Methods

Ratio of Indoor to Outdoor Concentration of Particles

Figure 1 shows the modelled processes that could affect the indoor concentration of particulate pollutants. Recirculation of indoor air was not included for consideration in this study. This type of residential housing unit with a forced ventilation system has been mainly used in Korea to meet the ventilation requirement for newly built and remodelled apartment.

Under the assumption of a well-mixed indoor space and steady-state condition, the mass-balance equation would be as described by Equation (1):

$$V\frac{\mathrm{d}C_{in}}{\mathrm{d}t}=(\varepsilon_{CCI}(C_{in}-C_{OA})+C_{OA})[\varepsilon_{AEE}\cdot\dot{Q}_{OA}(1-\varepsilon_f)]+C_{OA}\dot{Q}_I P - C_{in}[\varepsilon_{AEE}\cdot\dot{Q}_{OA}+\dot{Q}_I+\dot{\beta}\cdot V]+\dot{S} \quad (1)$$

where C_{in} is the indoor concentration of particles (numbers·m^{-3}), C_{OA} is the outdoor concentration of

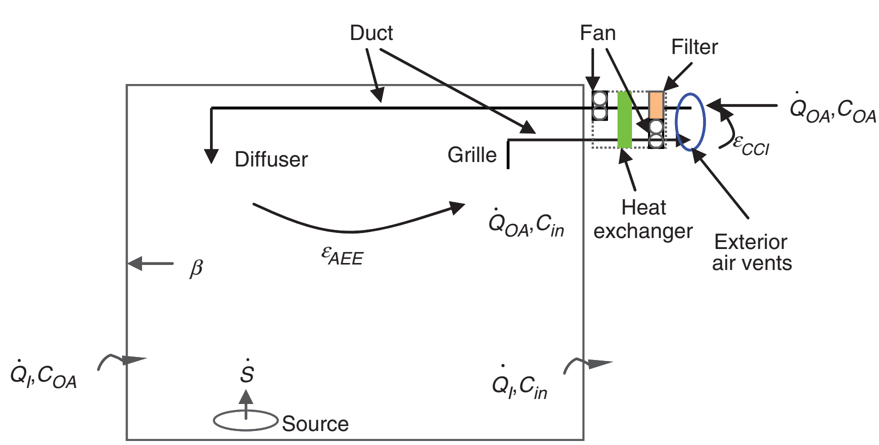

Fig. 1. Schematic of a mass balance model.

particles (numbers·m^{-3}), $\dot{Q}_{OA}$ is the outdoor airflow rate (m^3·h^{-1}), $\dot{Q}_I$ is the infiltration airflow rate (m^3·h^{-1}), ε_{CCI} is the cross-contamination index around the exterior air vent (–), ε_{AEE} is the air-exchange effectiveness (–), ε_f is the collection efficiency of the filter in the heat exchanger (–), V is the indoor volume (m^3), P is the penetration efficiency of particles through the air infiltration (–), $\dot{\beta}$ is the deposition rate of particles onto surfaces (h^{-1}) and $\dot{S}$ is the generation rate of particles (numbers·h^{-1}). Equation (2) shows the steady-state solution of the mass-balance equation:

$$\frac{C_{in}}{C_{OA}} = \frac{(1-\varepsilon_{CCI})[\varepsilon_{AEE}(1-\varepsilon_f)\cdot\frac{\dot{Q}_{OA}}{V}] + P\frac{\dot{Q}_I}{V} + \frac{\dot{S}}{V\cdot C_{OA}}}{\varepsilon_{AEE}\cdot\frac{\dot{Q}_{OA}}{V} + \frac{\dot{Q}_I}{V} + \dot{\beta} - \varepsilon_{CCI}[\varepsilon_{AEE}(1-\varepsilon_f)\cdot\frac{\dot{Q}_{OA}}{V}]} \quad (2)$$

The air-exchange effectiveness (ε_{AEE}), also termed the ventilation effectiveness, is a parameter that has been used to characterise indoor air and pollutant-flow patterns; this is determined by the locations of diffusers, grilles and obstacles in quantitative terms. Fisk and Faulkner reported that the typical values of the air-exchange effectiveness could be ranged from 0.8 to 1.2 [18]. The effect of pollutants that exit from the exhaust air-vent and re-enter the supply air-vent can be described by the cross-contamination index (ε_{CCI}). It is defined by the ratio between the relative concentrations of pollutants in the supply air and the relative concentrations of pollutants in the indoor air, as shown in the following equation:

$$\varepsilon_{CCI} = \frac{C_{SA} - C_{OA}}{C_{in} - C_{OA}} = \frac{(C_{OA} + x) - C_{OA}}{C_{in} - C_{OA}} \quad (3)$$

where x represents the various concentrations of pollutants that have been discharged from the exhaust air-vent; but re-supplying the heat exchanger. The values of the cross-contamination index could be ranged from 0.0 to 0.5, when the distance between the supply and exhaust air-vents was about 1 m and the outdoor air velocity varied from 0.0 to 10.0 m·s^{-1} [19].

The collection efficiency values as provided by the manufacturer were used for four types of filter (Table 1). These were rated according to the ASHRAE minimum efficiency reporting value (MERV). Three different-sized particles of 0.1, 1.0 and 10 µm were selected to represent ultra-fine, fine and coarse particles, respectively.

According to Abt et al. [20], most of the indoor 0.1 µm particles were from outdoor sources, a half of the 1.0 µm particles were also from outdoor sources, but most of the 10 µm particles were generated from indoor sources. The diffusion mechanism would be mainly predominant with 0.1 µm particles and the impaction mechanism is predominant with both 1.0 and 10 µm particles [16,21]. Therefore, the collection efficiencies of a filter for 0.1, 1.0 and 10 µm-sized particles could be expressed as:

$$\varepsilon_{f,0.1\,\mu m} = 1 - \exp\left[-k_{0.1\,\mu m}\cdot\left(\frac{1}{\dot{Q}_{OA}}\right)^{2/3}\right] \quad (4)$$

$$\varepsilon_{f,1.0\mu m} = 1 - \exp[-k_{1.0\mu m}\cdot\dot{Q}_{OA}], \varepsilon_{f,10\mu m} = 1 - \exp[-k_{10\mu m}\cdot\dot{Q}_{OA}] \quad (5)$$

In Equations (4) and (5), k would be the characteristic coefficient of collection, and this would depend on the solidity, fibre diameter, filter thickness, filter media area and particle size [21]. The values of the characteristic coefficient of collection are given in Table 2.

The indoor volumes (V) were assumed to be 150–300 m^3 and the outdoor airflow rates ($\dot{Q}_{OA}$) were assumed to be in the range of 100–300 m^3·h^{-1} [22]. The penetration efficiencies (P) were assumed to be 0.86, 0.72 and 0.14 for 0.1, 1.0 and 10 µm, respectively [23]. The deposition rates of particles ($\dot{\beta}$) were assumed to be 0.036, 0.18 and 7.2·h^{-1} when the particle sizes were 0.1, 1.0 and 10 µm, respectively [13]. The infiltration rate ($\dot{Q}_I/V$) was assumed to be 0.25·h^{-1} for all the calculations [12]. The percentage contributions of indoor sources to the normalised indoor particle concentration (C_{in}/C_{OA}) were 14%, 48.5% and 88% for 0.1, 1.0 and 10 µm, respectively [20].

Fan Power Consumption

This study focused on the fan power consumption that resulted from the energy generated to move air through

Table 1. Collection efficiencies for the four kinds of filters considered in this study

Filter	Collection efficiency (%)		
	At 0.1 µm	At 1.0 µm	At 10 µm
A (MERV07)	2	30	55
B (MERV11)	46	78	98
C (MERV13)	59	88	100
D (MERV14)	75	98	100

Table 2. Characteristic coefficients of collection

Particle size (µm)	Characteristic coefficient of collection			
	Filter A	Filter B	Filter C	Filter D
0.1	1.1	33.5	48.5	75.4
1.0	0.0009	0.0038	0.0053	0.0075
10	0.002	0.0098	0.04	0.05

Unit: (m^3·h^{-1})$^{2/3}$ for 0.1 µm; (m^3·h^{-1})$^{-1}$ for 1.0 or 10 µm.

the duct, the heat exchanger and the filter. The fan power consumed was as described by Equation (6):

$$\text{Fan power} = \frac{(\text{Airflow rate}) \times (\text{Total pressure drop})}{(\text{Overall fan efficiency})} \quad (6)$$

where the total pressure drop is the sum of the pressure drops in the duct, heat exchanger and filter. The pressure drop in the duct system can be characterised by Equation (7) as follows [24]:

$$\Delta P_{duct} = K_S \cdot \dot{Q}_{OA}^2 \quad (7)$$

In Equation (7), K_S is the characteristic of the duct section. This would depend on the flow, size, length and fittings. Assuming that both the supply and exhaust ducts were installed, a value of 0.0016 [Pa/(m^3·h^{-1})^2] was used for K_S that was obtained from the experimental work reported by Choi and Yee [22] for an indoor volume of about 200 m^3. When indoor volumes were 150, 250 and 300 m^3, K_S values of 0.0012, 0.0020 and 0.0024 were used, respectively.

For the calculations of the pressure loss in the heat exchanger and filters, the curve-fitting equations that were based on data provided by the manufacturers were used. The equations were assumed to be second-order polynomial forms [25,26] as shown in Equation (8):

$$\Delta P_{\text{heat exchanger or filter}} = a \cdot \dot{Q}_{OA}^2 + b \cdot \dot{Q}_{OA} \quad (8)$$

In Equation (8), a and b are the parameters as given in Table 3.

Table 3. Parameters in Equation (7)

Device	a [Pa/(m^3·h^{-1})^2]	b [Pa/(m^3·h^{-1})]
Heat exchanger	2.50×10^{-4}	0.35230
Filter A	4.86×10^{-4}	0.15720
Filter B	7.59×10^{-4}	0.17513
Filter C	8.79×10^{-4}	0.24186
Filter D	1.11×10^{-3}	0.35415

Results

The Effect of Filter Performance on Indoor Particle Concentration

Figure 2 shows the effect of a filter on the normalised particle concentration in a residential housing unit of 200 m^3, as a function of the ventilation rate.

The model assumed that there were no indoor sources of the particulate pollution, the air-exchange effectiveness was unity and the cross-contamination index was zero. The outdoor particle concentration was assumed to be constant. The concentrations of indoor particles varied with the performance of the filter and the particle size. The penetration efficiency would decrease and the particle deposition rate would increase with the particle size. Therefore, the overall particulate concentration decreased, when the larger particle size predominated the indoor air. For any given particle size, the indoor concentration would decrease as the collection efficiency of the filter increased. When the filter of MERV07 was used, the particles concentrations gradually increased as the ventilation rate was increased, regardless of the particle size. On the other hand, the use of filters of MERV11 through to MERV14 would always reduce the concentration of 0.1 μm particles with enhanced ventilation. The use of the filters of MERV11, MERV13 and MERV14 for 1.0 μm particles would require the minimum ventilation rates of 1.14, 0.82 and 0.58·h^{-1}, respectively, to reduce the concentrations below those levels that were obtained without ventilation.

The concentration of 10 μm particles was much lower than those of 0.1 and 1.0 μm, since the deposition rate of these coarse particles was much higher than those of the fine and ultra-fine particles, and the infiltration rate of coarse particles was lower than those of the fine and ultra-fine particles. The concentration of 10 μm particles will therefore not be discussed hereafter.

Figure 3 displays the results when there were indoor particle sources. Ventilation and the use of a filter caused the indoor particles concentrations to be lower than the outdoor particles concentrations.

Figure 3 shows the concentration of 1.0 μm particles increased about twice as much as the level that was obtained by the model without indoor sources (Figure 2), while the concentrations of 0.1 μm particles were slightly higher than those levels that were obtained without indoor sources. To keep the concentration lower than that without ventilation for any of the particle sizes, ventilation rates that were higher than 0.27, 0.20 and 0.14·h^{-1} were needed for MERV11, MERV13 and MERV14, respectively.

The Effect of the Size of the Residential Housing Unit

Figure 4 illustrates the effect of ventilation on the particles concentrations for various sizes of residential housing units that have a MERV11 ventilation filter.

In Figure 4, the air-exchange effectiveness was assumed to be unity, the cross-contamination index was zero and there were indoor particle sources. According to Equations (4) and (5), the increase in the airflow rate would reduce the removal efficiency for 0.1 μm particles but increase the efficiency for 1.0 μm particles. Since the

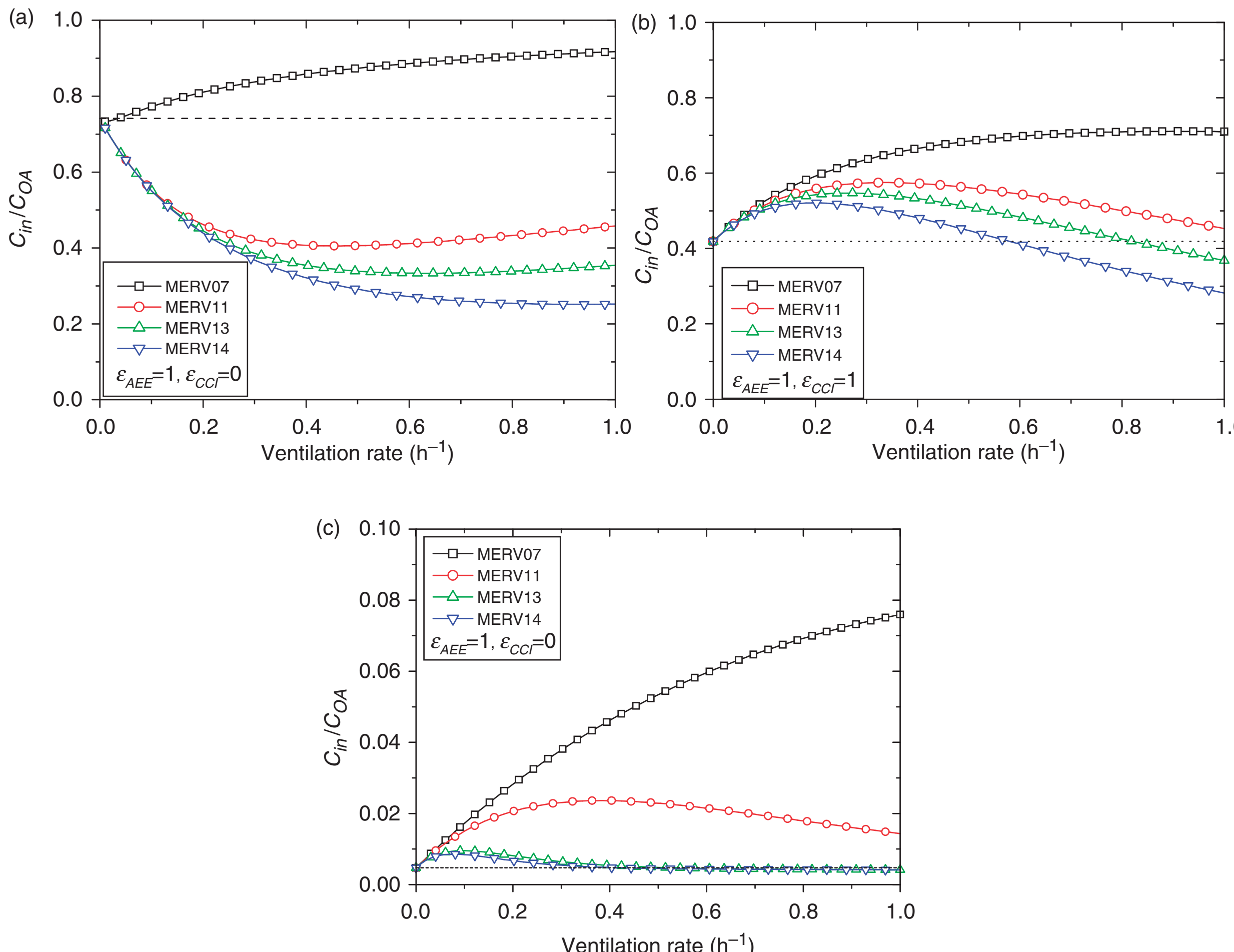

Fig. 2. Normalised concentrations in a residential housing unit of 200 m^3 without indoor sources: (a) 0.1 μm, (b) 1.0 μm, (c) 10 μm.

airflow rate is proportional to the size of the housing unit for the same ventilation rate, the concentration of 0.1 μm particles would be increased but the concentration of 1.0 μm particles decreased with the size of the housing unit. To keep all the concentrations below the values that prevail in the absence of ventilation for all particle sizes, ventilation rates that exceeded 0.36, 0.27, 0.21 and 0.18·h^{-1} would be needed when the sizes of residential housing units were: 150, 200, 250 and 300 m^3, respectively.

The Effect of the Air-Exchange Effectiveness and the Cross-contamination Index

Figure 5 shows the variation of the concentrations with the air-exchange effectiveness inside a residential housing unit of 200 m^3.

The modelled results shown in Figure 5, assumed that the cross-contamination was zero and that there were particle sources in the housing unit. When the air-exchange effectiveness increased; the concentrations, for particles of all sizes, reduced.

Figure 6 displays the variation of the particles concentrations with the cross-contamination index, around the exterior air vent. The modelled results assumed that the air-exchange effectiveness was unity, there were indoor particle sources in the housing unit and the size of the housing unit was 200 m^3.

When the cross-contamination index increased, the concentrations of particles of all sizes decreased since the outdoor air with a relatively high concentration of particles was diluted by the exhaust air with a low concentration of indoor particles. When the MERV11 and MERV14 filters were used, the minimum ventilation rates were reduced by about 0.04 and 0.02·h^{-1}, respectively, as the cross-contamination index increased by 0.2.

Fan Power Consumption

Figure 7 shows the effect of the use of a filter on fan power, as a function of the ventilation airflow rate. The overall fan power efficiency was assumed to be 0.15. The filter performance would gradually affect the fan power as

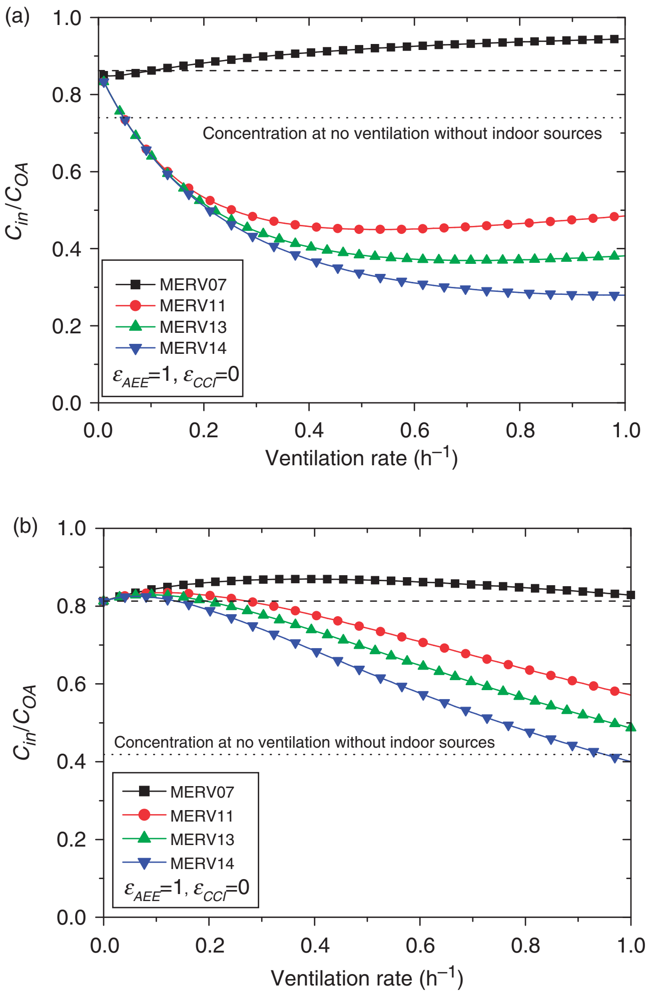

Fig. 3. Normalised concentrations in a residential housing unit of 200 m^3 with indoor sources: (a) 0.1 µm, (b) 1.0 µm.

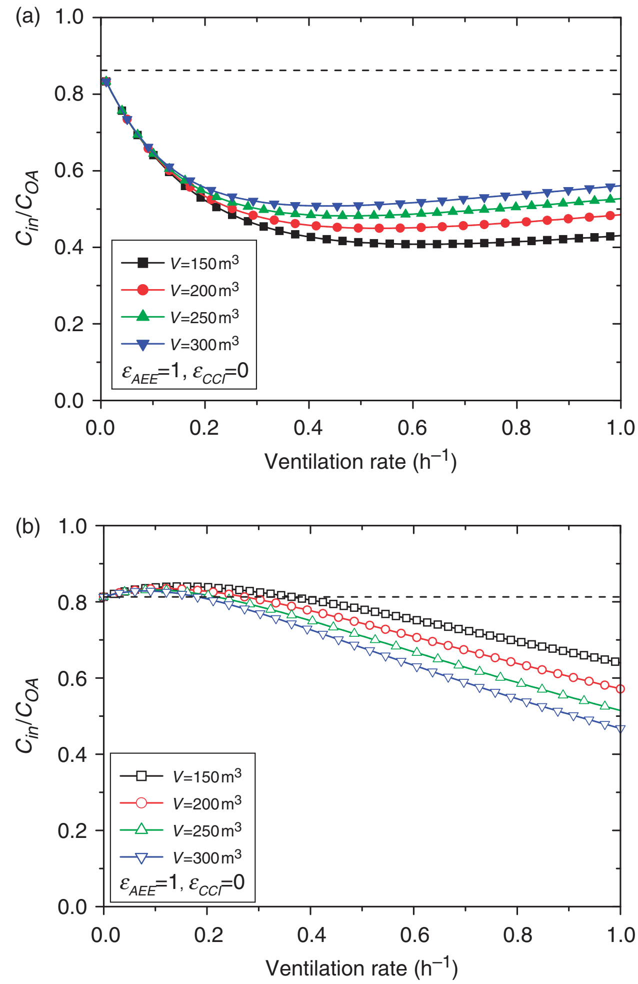

Fig. 4. Normalised particles concentrations for the various residential unit sizes (MERV11 filter in use and with indoor particle sources): (a) 0.1 µm, (b) 1.0 µm.

the ventilation airflow rate increases. When the airflow rate was 150 m^3·h^{-1}, the fan powers were 35.7, 38, 42 and 47.1 W for MERV07, MERV11, MERV13 and MERV14, respectively. When the airflow rate was 300 m^3·h^{-1}, the fan powers were 200, 217, 235 and 265 W for MERV07, MERV11, MERV13 and MERV14, respectively.

For a low rate of ventilation airflow, the filter performance did not much affect the fan power consumption since the increase in the pressure loss due to the use of a filter was relatively small in comparison to the losses that were caused by the ducts and the heat exchanger at the low rate of ventilation airflow.

Discussion

For all of the particle sizes, when using MERV07, the indoor particle concentration increased as the ventilation rate was increased. This result suggested that filters with a performance that was lower than MERV07 were insufficient to reduce the concentration of contaminant particles that came through the ventilation filter. Also, a higher ventilation rate would reduce the indoor air quality with the use of a low-performance filter leading to more unfiltered particles being delivered indoors. On the other hand, the use of filters of higher performance than MERV11 with enhanced ventilation would reduce the concentration of ultra-fine particles. When filters of higher performance than MERV11 were used, minimum ventilation rates would be required to reduce the concentrations of fine particles below the levels that were achieved without ventilation. The results showed that the lower ventilation rate would be needed if the filter performance was better. Therefore, the selection of an appropriate ventilation rate for a ventilation filter is very important to reduce the concentration of contaminants particles below

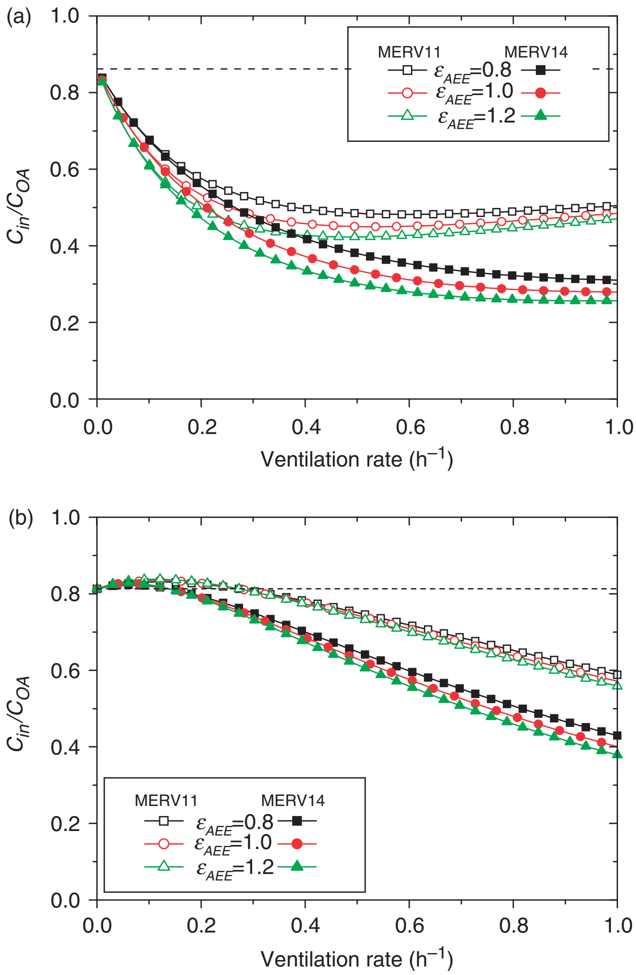

Fig. 5. Normalised particles concentrations with variation of air exchange effectiveness: (a) 0.1 μm, (b) 1.0 μm.

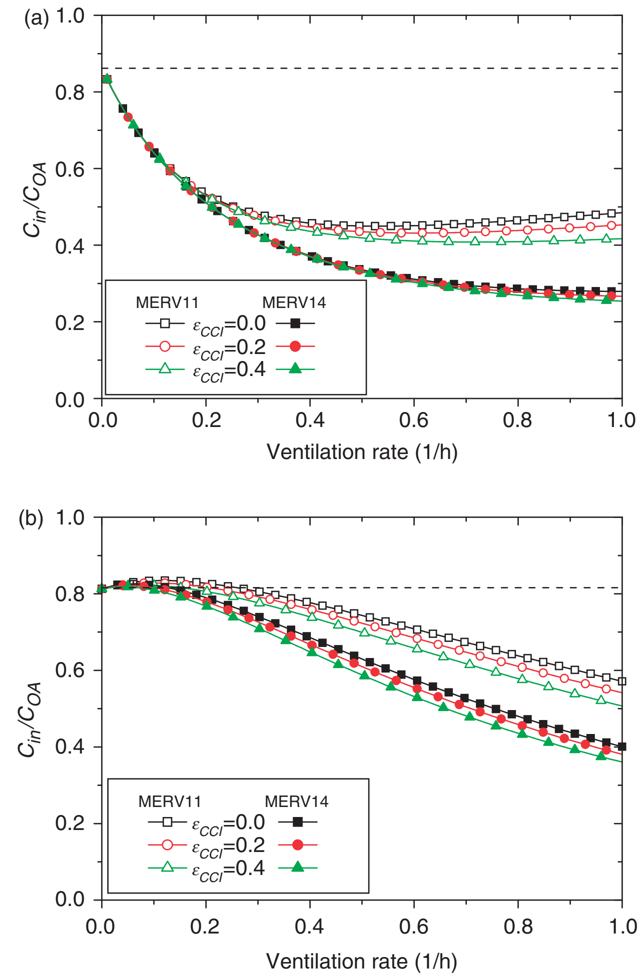

Fig. 6. Normalised particles concentrations with a variation of cross contamination index: (a) 0.1 μm, (b) 1.0 μm.

the levels that would be obtained without ventilation and this would save energy.

A higher ventilation rate was needed for a given amount of particle sources for a smaller size residential housing unit in comparison the larger units. This result was qualitatively similar to the suggestion of a previous report [27], which pointed out that the ventilation requirements should vary with the size of the house and that a higher ventilation rate would be needed for a given amount of indoor sources when the size of the housing unit was small.

The air-exchange effectiveness affected the concentration of 0.1 μm particles more than that of 1.0 μm particles. However, for the use of any filter, the air-exchange effectiveness did not affect the minimum ventilation rate that was required to keep the particle concentration lower than the value that would be obtained in the absence of ventilation. The minimum ventilation rate was less

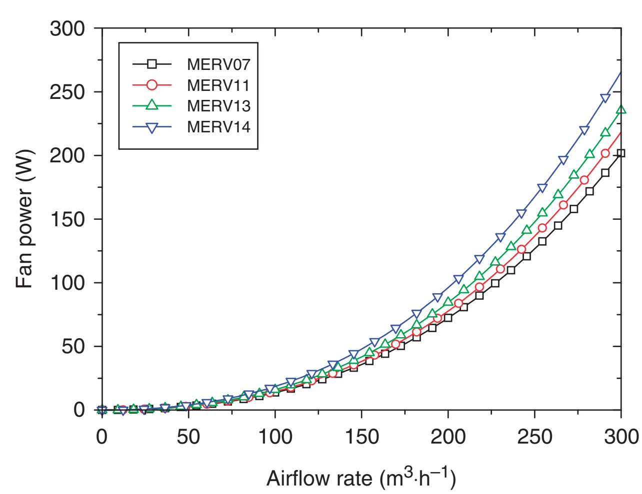

Fig. 7. Fan powers as a function of ventilation airflow rate.

sensitive to the variation in the cross-contamination index as the filter performance increases, since an increase in the removal efficiency of the filter would lead to a decrease in the effect of the cross-contamination. However, if the pollutant concentration is higher in the indoor spaces than in the outdoor areas, as with volatile organic compounds, formaldehyde and CO_2, the indoor concentration will increase as the cross-contamination index increases. Therefore, the concentrations of both gaseous and particulate pollutants must be considered when the cross-contamination index greatly increases.

To satisfy the minimum ventilation requirement of 0.35–0.5·h^{-1} for gaseous pollutants [28] and to keep the particle concentrations below the values in the absence of ventilation, filters with a performance that exceeds MERV11 should be used. The fan power consumption would not increase much with the increment grade in the filter performance. Therefore, the use of a higher grade filter than MERV11 is desirable when the size of the residential housing unit is in the range of 150–300 m^3.

Conclusions

A proper ventilation filter in a residential housing unit must be selected to satisfy the guidelines for concentrations of particulates pollutants to minimise the associated energy cost. In this study, the variation of particle concentrations, with the fan power for different filters used and with different ventilation rates, were investigated. The following conclusions were established by the study for mechanically ventilated housing units where the recirculation of indoor air was not considered in the ventilation system.

When using a MERV07 filter and with a ventilation rate that was lower than 1.0·h^{-1}, the indoor particles concentrations for any of the particle sizes were always higher than the corresponding values under no ventilation. Therefore, filters with performance that was lower than MERV07 would be insufficient for the purpose of reducing indoor concentrations.

The change in the size of the residential housing unit could lead to a variation in the minimum ventilation rate. A higher rate of ventilation would be needed for a given amount of indoor particle sources, in a smaller housing unit as compared to the larger units.

The minimum ventilation rate would not be sensitive to the variation in the air-exchange effectiveness inside a residential housing unit and to the cross-contamination index around the exterior air vents. To satisfy the ventilation requirement for gaseous pollutants and keep the particle concentrations below the corresponding values under no ventilation, filters with a performance that exceeds MERV11 should be used when the residential housing unit is in the range of 150–300 m^3.

Acknowledgements

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