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The transmission characteristics of indoor particles under different ventilation conditions

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Abstract: In modern society, ventilation is an important method for removing indoor particles. This study applies the parameter of attenuation index to analyze the effect of the removal of indoor particles in the two typical ventilation strategies called ceiling exhaust and slit exhaust strategy. Experiment was conducted in a chamber and riboflavin particles were used as the indoor particles source, instantaneous microbial detection (IMD) used to measure the particulate concentration. Conclusions can be found that air exchange rate is an important factor affecting the indoor particle concentration distribution. In the process of indoor free settling(air exchange rate is 0 h^{-1}), the deposition rate were 0.086 h^{-1}, 0.122 h^{-1}, 0.173 h^{-1} for the particles of 0.5–1.0 μm, 1.0–3.0μm and 3.0–5.0 μm. When the air exchange rate increased to 2.5 h^{-1}, the differences in the attenuation index is significant. There was also a significant linear relationship between air exchange rate and attenuation index. Furthermore, the effect of the slit exhaust strategy on the removal of coarse particles is more remarkable as the increasing air exchange rate.

1 Introduction

As the worsening of atmosphere particle pollution, indoor particle pollution has become increasingly severe due to the building exterior infiltration and other reasons. In modern society, people spend 80% of the time indoors [1, 2], hence people has begun to realize the importance of indoor particulate pollution on human health. Epidemiological studies showed that short or long-term exposure to particles would lead to widespread adverse effects on human mortality and morbidity, even if the concentration was lower than the national control standards [3–9]. Researches showed that all-cause mortality, cardiovascular mortality and lung cancer mortality significantly increased with the annual average concentration of particulate matter [5].

There are many factors that influence the distribution of indoor particle concentration, such as different forms of air supply, air exchange rate and gravity deposition will cause the diffusion and transmission of indoor particle. Zhang and Chen studied particle transportation and distribution in ventilation chamber that found that different forms of ventilation had a great impact on indoor particle concentration distribution [10]. Munat investigated and analyzed influence that different airflow forms to particle resuspension, the results showed that displacement ventilation system had small resuspension harm [11].

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Zhao B compared the diffusion characteristics of indoor particulate matter in displacement ventilation and mixing ventilation using numerical simulation method [12].

Although a large number of studies have been conducted on the diffusion and deposition characteristics of indoor particles, there is no good method to evaluate the removal effect of indoor particle under different ventilation strategies. Therefore, the attenuation index is defined to express the decay rate of indoor particles in this paper. It has important scientific significance for solving the problem of indoor particulate pollution to take into account the characteristics of indoor particle transfer and sedimentary and the relationship between air exchange rate and the attenuation index of particles with different particle sizes in the slit exhaust and ceiling exhaust strategy.

2 METHOD

2.1 Materials and equipment

In the experimental study of indoor particulate matters, JIS-11 powder was used as experimental particles in Japan [13]. JIS-11 test powder is made of volcanic ash, soil, etc., belonging to non-biological particles. In this study, however, the riboflavin powder was used as experimental materials instead of indoor particle, considering the concentration of non-biological particles in the background value is higher and the impact on the health of laboratory personnel is not clear [14]. Riboflavin is a special kind of biological particles, emitting fluoresce when exposed to light sources with certain specific wavelength. Previous studies have shown that the riboflavin powder concentration is at a low level in the indoor air that does not affect the results basically [14].

Instantaneous Microbial Detection-Air (IMD-A 200-1, Bio Vigilant Systems) can distinguish between biological and non-biological particles in the air particles based on the optical sensor and fluorescence detection technology, which was used to indoor particle concentration detection in the room. In addition, the instrument can realize continuous detection, the measurement of the particle size range 0.5 μm ~ 1 μm, 1 μm ~ 3 μm, 3 μm ~ 5 μm, 5 μm ~ 7 μm, 7 μm ~ 10 μm, 10 μm ~ 15 μm.

2.2 Ventilation systems and experiment process

This study analyzes the transmission characteristics of indoor particles in the two typical ventilation strategies including ceiling exhaust and ground slit exhaust strategy (as illustrated in Fig. 1), which the ceiling exhaust strategy is a traditional ventilation way. Fig. 2 shows experimental chamber size (L × W × H = 5.37 m × 2.74 m × 2.25 m) and the distribution of measuring points and instruments. In this experimental chamber, the delivery outlet was located in the center of the ceiling; a ceiling exhaust port located in the corner of the ceiling and two slit exhaust port located in the junction of walls and floors. The delivery outlet of two ventilation system was the same that the size was 0.05 m × 0.10 m. The exhaust port size in ceiling exhaust system was 0.05m × 0.10m and the two exhaust port size of the slit exhaust system was 4.2 m × 0.005 m and 4.53 m × 0.005 m, respectively.

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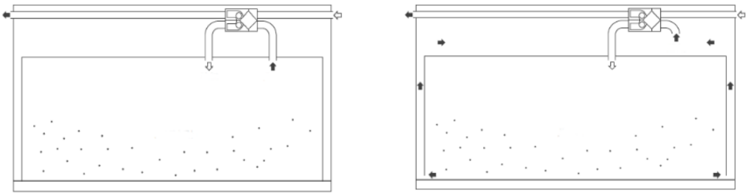


(a) Ceiling exhaust (b) Slit exhaust

Fig. 1. Two typical ventilation strategies.

As shown in Fig. 2, the indoor particles were put in a measuring flask that was fixed at the corner near the ceiling of the room. Nitrogen gas was blown into the measuring flask to disperse particles at a rate of 10 L/min. The airborne particulate matters were mixed by two electric fans in order to ensure the distribution of house dust particles as evenly as possible in the room. Taking into the account of the height of the child, the position of the monitoring point was set at 0.1m and 1.0 m height. During the experiment, the window was sheltered by aluminum foil corrugated board to prevent solar radiation, and the walls were insulated by expanded polystyrene board. The experimental chamber was closed and stable for 12 hours before the release of particles in order to ensure that the indoor background concentration was unchanging. Then the particles were released and the fans were turned on for an hour so that the indoor particles are evenly mixed. Stop particle released and turn off the fan, whereafter, the ventilation system was opened (the air change rate was 0.75 h^{-1} and 2.5 h^{-1}) after the free settlement is maintained for 8 hours until the indoor particle concentration was in a stable state.

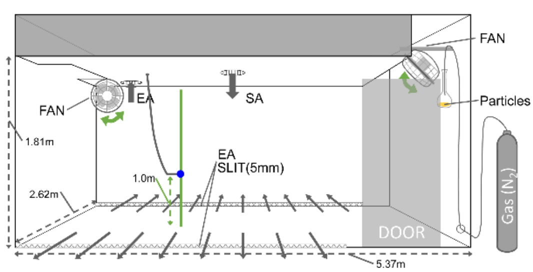
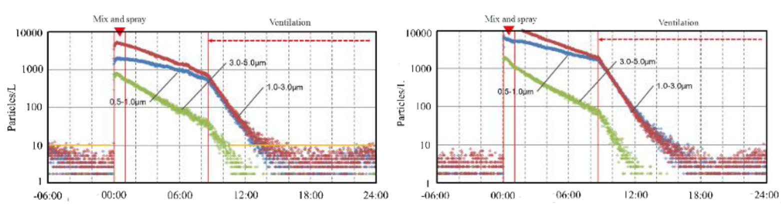


Fig. 2. The experimental chamber size and the distribution of measuring points.

3 Results and analysis

3.1 The effect of air exchange rate on particle distribution



(a) Ceiling exhaust (b) Slit exhaust

Fig. 3. The concentration changes characteristics of two ventilation modes (0.75 h^{-1})

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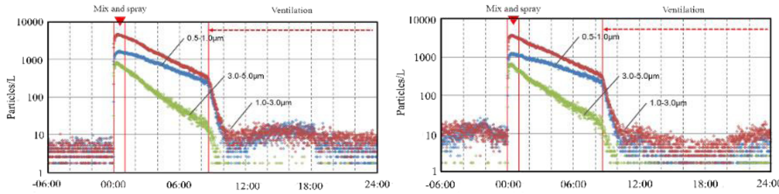

(a) Ceiling exhaust (b) Slit exhaust

Fig. 4. The concentration changes characteristics of two ventilation modes (2.5 h^{-1}).

In order to further study the influence factors of indoor particulate matter distribution, the concentration changes characteristics of two ventilation modes at different air changes rate were analyzed and compared. During the operation of the ventilation system, the attenuation rate of indoor particulate matter concentration is obviously accelerated, but there was no obvious difference in the time that indoor particles concentration of two ventilation modes achieve stability, as shown in Fig. 3 and Fig. 4. At the time of the air exchange rate is 0.75 h^{-1}, the stable time of fine particles is 7h, and the coarse particles is about 4h. When the air exchange rate is 2.5 h^{-1}, the time required for the concentration of indoor particles to stabilize is about 0.67 h. Therefore, air exchange rate is an important factor affecting the distribution of indoor particulate matter concentration. As the increasing of air exchange rate, the elimination rate of indoor pollutants can also greatly accelerate, but ventilation mode has little effect on the elimination time.

3.2 Indoor particle concentration prediction model

The indoor airborne particles are affected by air resistance, Magnus force, Basset force, slip shear lift force, pressure gradient force, electrophoretic force, Brown diffusion force and virtual mass force [15], and temperature and humidity, ventilation frequency and ventilation mode are also crucial factors to determine the power of the force, which have an effect on the diffusion and deposition process of particulate matter. Murakami et al. simulated the particle trajectories in the two regions of ventilation considering only the effects of gravity, buoyancy and flow resistance, who pointed out that indoor airflow pat, ventilation condition and particle properties had a great influence on the distribution and movement of indoor particles [16]. The air velocity affects the distribution and deposition of indoor particles under different ventilation modes, and the smaller the air velocity is, the higher the particle deposition rate is. As the increase of the air velocity, the particles are not only difficult to deposit, but also cause the resuspension of particles in virtue of indoor turbulent flow. When the air velocity is very large, the indoor particle concentration approaches to the outdoor concentration continuously [17]. In this paper, the attenuation index is defined to better represent the removal effect of indoor particulate matter under different conditions, considering the influence of sedimentation, resuspension, air exchange rate and other parameters.

In the course of our experiment, the temperature and humidity changed little, the chemical reaction of the particles was slow, the condensation and phase change could be ignored, and the distribution of aerosol particle size was also quite stable. Therefore, the prediction model of indoor particles concentration can be established according to the mass balance or quantity balance equation:

$$\frac{dC}{dt} = aC_1 - aC - kC + rC \tag{1}$$

where, C – the indoor particle concentration; C_1 – the outdoor particle concentration; r – the particle resuspension and other effects; k – the indoor deposition rate.

In this paper, the biological particles used in the experiment are very low in outdoor air, which can be ignored. The above equation can be simplified as:

$$C(t)=C_0e^{-\lambda t} \tag{2}$$

where, C_0 – the initial concentration of indoor particles, λ – the attenuation index of particles, which indicates the decay rate of indoor particles,

$\lambda=a+k-r$.

In the process of free settlement, the air exchange rate is zero, the indoor air disturbance is little and the resuspension process can also be ignored. The attenuation index is equal to the deposition rate of indoor particles, therefore, the Equation 2 can be expressed as:

$$C(t)=C_0e^{-kt} \tag{3}$$

3.3 The particle attenuation index of different air exchange rate

The indoor particles attenuation index of different air exchange rate (0 h^{-1}, 0.75 h^{-1}, 2.5 h^{-1}) under slit exhaust and ceiling exhaust strategies is indicated in Fig. 5. It can be found that the attenuation index of indoor particles is increasing with air exchange rate, which has been discussed in the previous paper. When the air exchange rate is 0 that is the free settling process of the particles in the room, the attenuation index is equal to the deposition rate of indoor particles. Thus, the deposition rate of three kinds of particle sizes in the free settling process can be obtained, as shown in the Fig. 5. For the particle size of 0.5–1.0 μm, 1.0–3.0 μm and 3.0–5.0 μm, indoor deposition rates are 0.086 h^{-1}, 0.122 h^{-1} and 0.173 h^{-1} respectively and the settlement rate is increasing with particle size. A number of studies have found that particles deposition is the main reason for indoor particles concentration decreased in the process of free settling without the effect of static electricity and high air temperature difference, and particle diffusion and gravity are the most important mechanisms for particle deposition. The attenuation rate of particle concentration in different particle size ranges varies widely. Brown diffusion dominates for the small particle, which results in the distribution of indoor particles uniform, and the deposition rate low. Large size particles are not evenly distributed in the interior due to obviously affected by gravity, hence the distribution in the lower part of the room is more and the deposition rate is higher [15, 17, 18].

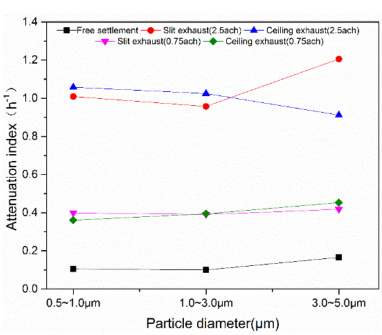

Fig. 5. The particle attenuation index of different air exchange rate under two ventilation modes.

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At the time of the air exchange rate is 0.75 h^{-1}, indoor air velocity is also small and the main influence factors is still gravity for ceiling exhaust and slit exhaust strategies, so the difference of indoor three particle size range attenuation index is not obvious. When the air exchange rate increased to 2.5 h^{-1}, there are significant differences in the attenuation index of the two ventilation strategies, especially for coarse particles in the range of 3.0–5.0 µm. Fine particles are mainly controlled by the Brown diffusion effect, less affected by flow organization. The effect of gravity on coarse particles is more significant. As for the slit exhaust, the direction of the air flow is the same as that of gravity, which accelerates the deposition and removal of the particles, resulting in the increase of the coarse particles attenuation index. For the ceiling exhaust, the direction of gravity and airflow is in the opposite direction. The effect of gravity will hinder the particle removal and air lift will also impede the particle deposition process, which leads to the decrease of the coarse particles attenuation index.

3.4 The relationship between air exchange rate and particle attenuation index

The relationship between air exchange rate and particle attenuation index is compared as shown in Fig. 6, which can be found that the linear correlation between them is very significant (the correlation coefficient R^2 is above 0.99). With the increase of ventilation rate increases, therefore, the particle concentration will be lower and the particle propagation distance is shorter resulting in better indoor environment [19]. As for the fine particles with smaller diameters (0.5–1.0µm, 1.0–3.0µm), there was no significant difference in the correlation between air exchange rate and particle attenuation index (the correlation coefficient is about 0.36), the correlation coefficient of the ceiling exhaust is slightly higher than that of the slit exhaust. For the coarse particles of 3.0–5.0 µm, the correlation coefficient of slit exhaust is 0.4232 which significantly higher than 0.2879 that of the ceiling exhaust, indicating that the removal efficiency of coarse particles is better as the increase of ventilation rate under the condition of slit exhaust strategy, and this effect is mainly due to the gravity and particle flow superposition effect.

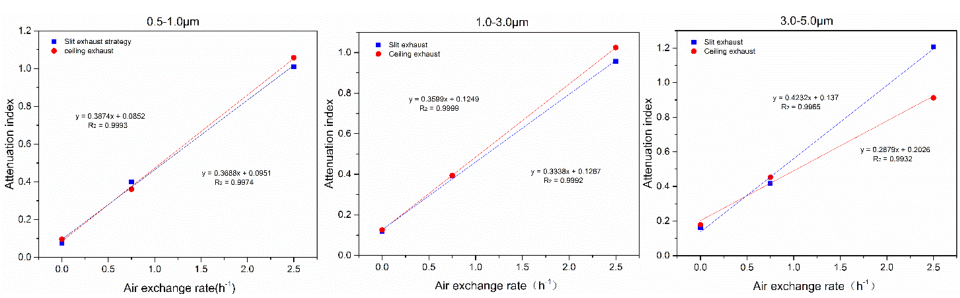

Fig. 6. The relationship between air exchange rate and different particle attenuation index under two ventilation modes.

4 Conclusion

This paper studies the variation characteristics of indoor particulate matter concentration under two ventilation strategies named the slit exhaust and the ceiling exhaust for the sake of eliminating the indoor particulate pollutants quickly. Specific conclusions are as follows:

Air exchange rate is an important factor affecting the indoor particle concentration distribution. In the process of free settlement (air exchange rate is 0 h^{-1}), the deposition rate is 0.086 h^{-1}, 0.122 h^{-1} and 0.173 h^{-1} respectively for 0.5–1.0 µm, 1.0–3.0 µm, 3.0–5.0 µm particles, which is increasing with particle size. When the air exchange rate is 0.75 h^{-1}, the difference of the particle attenuation index between the slit exhaust and the ceiling exhaust strategy is not obvious. However, there a significant differences when the air exchange rate increased to 2.5 h^{-1}, especially for the coarse particles in the range of 3.0–5.0 μm.

There is a significant linear relationship between air exchange rate and the attenuation index of particles. The fine particles of 0.5–1.0 μm and 1.0–3.0 μm has little significant difference under the two ventilation strategies, the correlation index of around 0.36. For the coarse particles of 3.0–5.0 μm, the correlation of slit exhaust (0.4232) is significantly higher than that of the ceiling exhaust (0.2879), indicating that the elimination effect slit exhaust strategy on the coarse particles is better significantly under the condition of increasing air exchange rate.

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