Journal of Hazardous Materials 186 (2011) 1290–1299

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Impact of two-way air flow due to temperature difference on preventing the entry of outdoor particles using indoor positive pressure control method

Chun Chen, Bin Zhao*, Xudong Yang

Department of Building Science, School of Architecture, Tsinghua University, Beijing, China

ARTICLE INFO

Article history:
Received 7 July 2010
Received in revised form 9 October 2010
Accepted 1 December 2010
Available online 9 December 2010

Keywords:
Indoor air quality
Outdoor
Particle
Mechanical ventilation
Positive pressure
Two-way air flow

ABSTRACT

Maintaining positive pressure indoors using mechanical ventilation system is a popular control method for preventing the entry of outdoor airborne particles. The idea is, as long as the supply air flow rate is larger than return air flow rate, the pressure inside the ventilated room should be positive since the superfluous air flow must exfiltrate from air leakages or other openings of the room to the outdoors. Based on experimental and theoretical analyses this paper aims to show the impact of two-way air flow due to indoor/outdoor temperature difference on preventing the entry of outdoor particles using positive pressure control method. The indoor positive pressure control method is effective only when the size of the opening area is restricted to a certain level, opening degree less than 30° in this study, due to the two-way air flow effect induced by differential temperature. The theoretical model was validated using the experimental data. The impacts of two-way air flow due to temperature difference and the supply air flow rate were also analyzed using the theoretical model as well as experimental data. For real houses, it seems that the idea about the positive pressure control method for preventing the entry of outdoor particles has a blind side.

1. Introduction

Epidemiologic evidence have shown strong association between exposure to outdoor airborne particles and adverse health effects [1–3]. In many buildings, large concentrations of ambient particles penetrate into the indoor environment [4], where people spend roughly 90% of their time. Consequently, individuals receive a considerable fraction of their exposure to ambient-generated particles while they are indoors. Therefore, preventing outdoor airborne particles from entering indoor environments is an important issue of indoor environment design and control. ASHRAE Handbook [5] states that the correct internal air flow for a building is toward the contaminated side, and air flow direction is maintained by controlling pressure differentials between spaces. Therefore, one possible control method is maintaining absolute positive pressure indoors using a mechanical ventilation system to prevent outdoor particles from entering the indoor environment. ASHRAE Standard 62.1 [6] also suggests a slightly positive pressurization of buildings. This method has been widely used in protective environments in hospitals [7]. Sapkota et al. [8] highlighted the especially protective nature of tollbooths equipped with positive pressure control ventilation systems. It has been also used in normal indoor environments such as residences and offices. In some countries such as Korea, it is required by the (mandatory) standard that residences must equip with a mechanical ventilation system to maintain positive pressure indoors. The effectiveness of positive pressure control used in protective hospital environments has been well studied [9–11]. However, there were few studies focusing on the effectiveness of this control method used in normal indoor environments.

Maintaining positive pressure indoors using mechanical ventilation system necessitates the use of outdoor fresh air flow that may contain airborne particles so it is possible that outdoor airborne particles can still enter the indoor environment. However, as long as the filter efficiency in the ventilation system is high enough and there are no external forces to push outdoor airborne particles into the indoor environment through gaps in the building envelope, the concentration of indoor particles should be much lower than outdoors. In real situation, the influencing factors on the effectiveness of positive pressure control are complicated. For instance, when the outdoor wind speed is relatively large, outdoor particles may penetrate through one of the air leakages in building envelopes where outdoor pressure is higher than indoor due to wind pressure effect. Therefore, when designing positive pressure control system, the effect of wind pressure is always considered carefully [12].

As long as the supply air flow rate is larger than return air flow rate and the issue of wind pressure effect is avoided by enhancing supply air flow rate, the ventilated room would maintain positive pressure since the superfluous air flow must exfiltrate from air leakages or other openings of the room to the outdoor envi-

---

* Corresponding author. Tel.: +86 10 62779995; fax: +86 10 62773461.
E-mail address: binzhao@tsinghua.edu.cn (B. Zhao).

0304-3894/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2010.12.003

ronment. This approach makes sense for ventilation engineers since mass balance is always the first concern. The question is if this approach always works, or is there any other influencing factor that can affect the effectiveness of positive pressure control of the entry of outdoor airborne particles? Can the two-way air flow due to indoor/outdoor temperature difference become a major influencing factor? To our knowledge, these questions have not been well answered. This paper aims to evaluate the impact of two-way air flow due to temperature difference on preventing the entry of outdoor airborne particles using indoor positive pressure control method, based on experimental and theoretical analyses.

2. Method

2.1. Experimental setup

The experimental configuration is illustrated schematically in Fig. 1. The indoor chamber which is 2 m × 2 m × 2 m and made from stainless steel simulates the indoor environment, while the surrounding chamber (6 m × 3.6 m × 4 m, Length × Width × Height) simulates the outdoor environment. The door simulates an opening in the building envelope that connects the indoor environment with the outdoor environment. A mechanical ventilation system with a variable speed fan was installed to control the air parameters inside the indoor chamber. The ventilation pattern was set as supply-only pattern, which means indoor air flow can only exit from the door. This design ensures indoor positive pressure which is what expected with the designed ventilation. The dimensions of the inlet are 250 mm × 250 mm, while the dimensions of the door are 0.6 m × 1.6 m (Width (*W*) × Height (*H*)). The frequency of the fan can vary from 0 to 50 Hz. The surrounding chamber was relatively tight-sealed from "real" outside. As shown in Fig. 1, the supply air was taken out from the outdoor chamber to the indoor chamber by the fan. Therefore, there was no extra driven force caused by tight sealed condition to make the air move from outdoor to indoor chamber.

For investigating the effectiveness of maintaining positive pressure indoors using mechanical ventilation system under different supply air flow rates, four frequencies of the fan were chosen: 10, 20, 30 and 40 Hz. Before each experiment, the surfaces of indoor chamber were cleaned up to avoid the influence of particle resuspension. At the beginning of each experiment, the air in the indoor chamber was diluted by the ventilation system for half an hour to avoid the influence of initial particle concentration. Then the supply particle concentrations at inlet were measured. After the whole measurements, the supply particle concentrations at inlet were re-measured to ensure consistent results. To investigate the effectiveness of this method for openings with different resistance characteristics, five opening degrees of the door were chosen: 4.6°, 5.7°, 10°, 30° and 90° (totally open). Each experiment was carried out from opening degree of 4.6–90° (small opening to large opening), and the opening degrees were switched every 15 min. The particle concentrations indoors and outdoors, supply air velocity in the duct and pressure difference between indoor and outdoor were continuously measured during the whole period. The air flow directions under each supply air flow rate and each opening degree of the door were measured using visible smoke in repeated independent experiments. The outdoor chamber was a quiet environment without any activity or wind, which simulates a real situation when outdoor wind speed is near zero. The particle concentrations in the outdoor chamber were relatively steady as there were no particle sources, which match to our measurement results. Temperatures indoors and outdoors were also continuously measured during the whole period. There was no specific heat source in the chamber. The supply air temperature was higher than that in outdoor chamber. All the temperature differences were naturally formed. The temperatures in the chambers were relatively steady, which match to our measurement results. Since each experiment was carried out at different periods, the temperatures in indoor and outdoor chambers were different in each experiment. These variable temperature differences contain different cases for thermal pressure effect, which help to provide more useful experimental data for model validation.

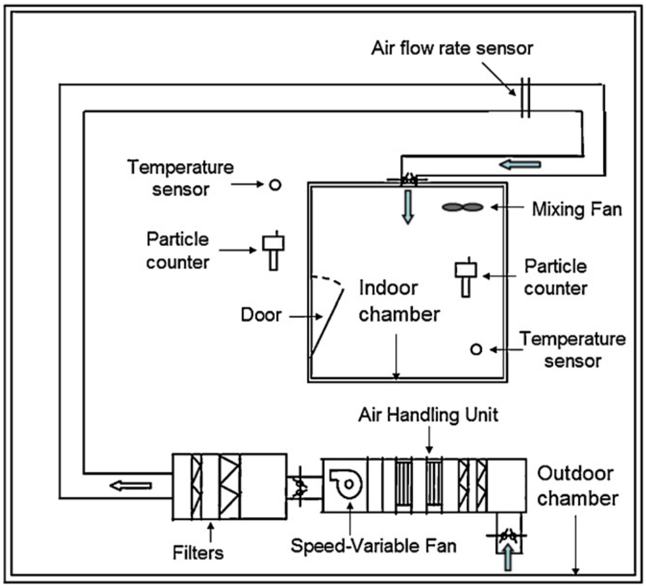

Fig. 1. Experimental schematic for measuring the effectiveness of mechanical ventilation system for preventing outdoor particles entering indoors through envelop.

An air velocity sensor with a precision of 0.01 m/s was installed near the inlet for measuring the supply air flow rate. Two FLUKE 983 optical particle counters (Fluke Inc.) were used to measure the particle concentrations. The Fluke 983 simultaneously measures and records six channels of particle sizes (0.3–0.5 μm, 0.5–1.0 μm, 1.0–2.0 μm, 2.0–5.0 μm, 5.0–10.0 μm and ≥10.0 μm). The counter has a coincidence loss of 5% when the particle concentration is 2,000,000 particles per cubic inch and a 100% counting efficiency when the measured particle diameter is larger than 0.45 μm [13]. The counters had been calibrated by the manufacturer and also calibrated prior to each measurement using a Zero Counter Filter. The particle concentration was measured in the same location using the two counters to check if they were consistent. The two Fluke 983 particle counters can also be used to measure the temperature with a precision of 0.1 °C. A KIMO PM200 differential pressure meter with a precision of 1 Pa was used to measure the pressure difference between indoor and outdoor environments.

2.2. Theoretical model

The theoretical model presented in this section is based on mass balance of air flow, particles, and the pressure relationship between each zone and opening. If the air flow at the door directs from indoor to outdoor, then the indoor particle concentration is equal to that at the supply inlet. If the mechanical ventilation system cannot maintain absolute positive pressure, two opposite directions shall exist at the door. In order to calculate the indoor particle concentration, the air flow rate from outdoor to indoor and from indoor to outdoor through the door should be calculated. The mass balance equation of air flow in the indoor chamber can be expressed as:

$$Q_{\mathrm{sup}} + Q_{\mathrm{out-in}} = Q_{\mathrm{in-out}}, \quad (1)$$

where Q_{sup} is the air flow rate at supply inlet, $Q_{\mathrm{out-in}}$ is the air flow rate from outdoor chamber to indoor chamber through the door, and $Q_{\mathrm{in-out}}$ is the air flow rate from indoor chamber to outdoor chamber through the door.

The elevation of $H/2 = 0.8$ m was assumed as the reference elevation of the door, $y = 0$. The pressure at y can be calculated by:

$$P_{\mathrm{in}}(y) = P_{\mathrm{in}}(0) - \rho_{\mathrm{in}} g y, \tag{2}$$

$$P_{\mathrm{out}}(y) = P_{\mathrm{out}}(0) - \rho_{\mathrm{out}} g y, \tag{3}$$

where g is gravitational acceleration. ρ_{in} and ρ_{out} are the indoor and outdoor air densities, respectively. The neutral height, y, is at the position where the air velocity is zero, which is equivalent to the following equation:

$$P_{\mathrm{in}}(Y) = P_{\mathrm{out}}(Y), \tag{4}$$

When $|Y| < H/2$, the relationship between air flow and pressure difference at the opening can be described as [14]:

$$Q_{\mathrm{in-out}} = \frac{2}{3}\mu W \sqrt{\frac{2g\Delta\rho}{\rho}}\left(\frac{H}{2} + Y\right)^{3/2}, \tag{5}$$

$$Q_{\mathrm{out-in}} = \frac{2}{3}\mu W \sqrt{\frac{2g\Delta\rho}{\rho}}\left(\frac{H}{2} - Y\right)^{3/2}, \tag{6}$$

where μ is discharge coefficient of the door. $\Delta\rho$ is the density difference between indoor and outdoor air. If $|Y| \geq H/2$, there is no two-way air flow existing at the door opening. In this case, slightly different formulae are needed [15].

According to Eqs (1)–(6), $Q_{\mathrm{out-in}}$ and $Q_{\mathrm{in-out}}$ can be calculated. The mass balance equation of particles can be described as:

$$Q_{\mathrm{sup}}C_{\mathrm{sup}} + Q_{\mathrm{out-in}}C_{out} = Q_{\mathrm{in-out}}C_{\mathrm{in}} + V_d A C_{\mathrm{in}}, \tag{7}$$

where C_{sup} is the particle concentration at supply inlet, C_{out} is the outdoor particle concentration. C_{in} is the indoor particle concentration, V_d is the averaged particle deposition velocity and A is the total area of surfaces of indoor chamber. Therefore, the indoor particle concentration can be calculated by:

$$C_{\mathrm{in}} = \frac{Q_{\mathrm{sup}}C_{\mathrm{sup}} + Q_{\mathrm{out-in}}C_{\mathrm{out}}}{Q_{\mathrm{in-out}} + V_d A}. \tag{8}$$

Table 1
Indoor and outdoor temperatures in each experiment.

Fan frequency (Hz)	Indoor temperature (°C)	Outdoor temperature (°C)	Temperature difference (°C)
10	16.0	13.2	2.8
20	20.8	16.0	4.8
30	26.9	21.9	5.0
40	25.0	19.0	6.0

3. Results

3.1. Experimental data analysis

Tables 1 and 2 show the measurement results of indoor and outdoor temperatures, supply air flow rate, pressure difference and directions of air flow at the door. Obviously, smaller opening degree of the door would cause higher pressure difference. However, when the opening degree is large enough, the pressure difference is too small to be measured which is shown as zero in the differential pressure meter. The air flow direction tests show that when the opening degree of the door is larger than 30°, the two-way air flow exists except for the 40 Hz case. Fig. 2 shows the size-dependent indoor and outdoor particle concentrations under fan frequency of 20 Hz. The trends of particle concentrations in other three cases are similar to the 20 Hz case. All the experimental data are summarized in Tables 3 and 4. The results of indoor particle concentrations match well with the air flow direction tests, which also show the existence of two-way air flow. All the air flow directs from outdoor to indoor exist at the lower area of the door and the indoor temperature is higher than outdoor temperature in each experiment. Since there was no wind in the outdoor chamber, the experimental results indicate that the two-way air flow due to indoor/outdoor temperature difference affects the transport of outdoor airborne particles to some extent. The mechanical ventilation system was supposed to maintain absolute positive pressure indoors to prevent outdoor particles entering indoors. Nevertheless, it was too weak to prevent the influence of two-way air flow due to temperature difference with relatively large opening. It seems that the idea about the positive pressure control method for preventing the entry of outdoor particles has a blind side.

Figs. 3 and 4 show the ratios of indoor and outdoor particle concentrations (I/O ratio) and the ratios of supply and outdoor

Table 2
Supply air flow rate, pressure difference and air flow direction at the door in each experiment.

Fan frequency (Hz)	Opening degree (°)	Supply air flow rate (m^3/h)	Pressure difference (Pa)	Air flow direction[a]
10	4.6	196	2	In–out
	5.7	198	0	In–out
	10	200	0	In–out
	30	205	0	In–out while out–in
	90	205	0	In–out while out–in
20	4.6	450	10	In–out
	5.7	468	5	In–out
	10	482	0	In–out
	30	491	0	In–out while out–in
	90	491	0	In–out while out–in
30	4.6	745	27	In–out
	5.7	770	12	In–out
	10	788	1	In–out
	30	788	0	In–out while out–in
	90	788	0	In–out while out–in
40	4.6	963	50	In–out
	5.7	1028	27	In–out
	10	1053	2	In–out
	30	1055	0	In–out
	90	1055	0	In–out while out–in

[a] In–out means air flow directs from indoor to outdoor at the door; out–in means air flow directs from outdoor to indoor; in–out while out–in means two opposite air flow directions exist, and out–in all exist at lower area of the door.

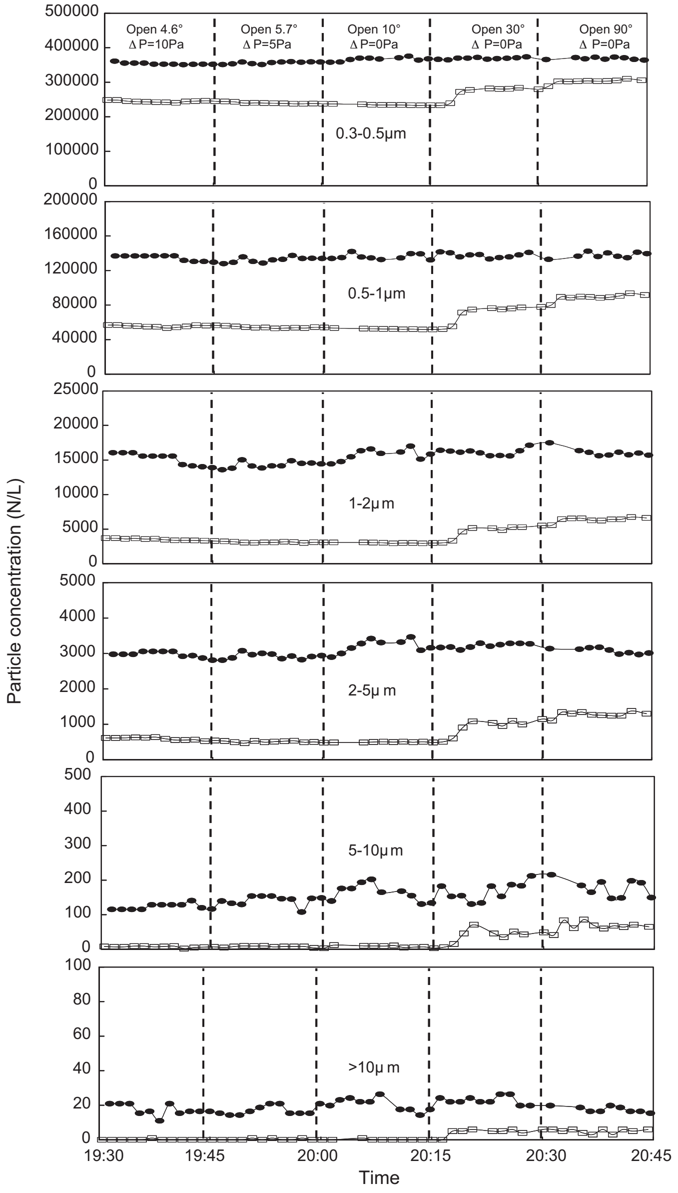

Fig. 2. Indoor and outdoor particle concentrations under 20 Hz. Black points represent outdoor particle concentrations, Blank points represent indoor particle concentrations.

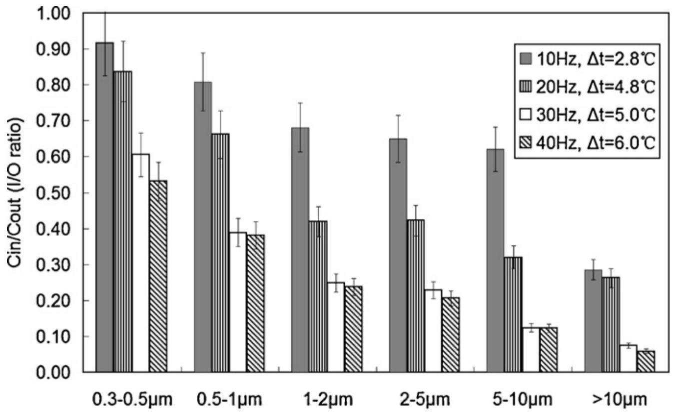

Fig. 3. The ratios of indoor and outdoor particle concentrations (*I*/*O* ratio) when the door is totally open.

Table 3
Size-dependent outdoor and supply particle concentrations.

Fan frequency (Hz)	Particle size (μm)	Mean outdoor particle concentration (N/L)	Mean supply particle concentration (N/L)
10	0.3–0.5	3.96E+05	2.61E+05
	0.5–1	1.88E+05	7.37E+04
	1–2	2.54E+04	4.93E+03
	2–5	5.05E+03	8.00E+02
	5–10	2.48E+02	1.4E+01
	>10	3.5E+01	1E+00
20	0.3–0.5	3.63E+05	2.40E+05
	0.5–1	1.36E+05	5.40E+04
	1–2	1.54E+04	3.20E+03
	2–5	3.08E+03	5.30E+02
	5–10	1.53E+02	8.0E+00
	>10	1.9E+01	0E+00
30	0.3–0.5	3.27E+05	1.80E+05
	0.5–1	1.06E+05	3.50E+04
	1–2	9.98E+03	1.95E+03
	2–5	2.10E+03	3.20E+02
	5–10	1.37E+02	5E+00
	>10	2.7E+01	0E+00
40	0.3–0.5	2.41E+05	9.99E+04
	0.5–1	7.16E+04	2.00E+04
	1–2	7.15E+03	1.24E+03
	2–5	1.50E+03	2.36E+02
	5–10	5.7E+01	4E+00
	>10	1.7E+01	0E+00

particle concentration (*S*/*O* ratio) of each experiment when the door is totally open, respectively. Under each fan frequency, the *I*/*O* ratios are strongly size-dependent. The *I*/*O* ratio decreases with the increase of particle size for two reasons. First, for the particle size range from 0.3 to 10 μm, the particle loss due to gravitational deposition indoors for large particles is much more than that for small ones. Second, as shown in Fig. 4, the particle loss due to the removal effect of the ventilation system with filter for large particles is also much more than that for small ones. Therefore, the *I*/*O* ratio is larger for smaller particles in each experiment.

As shown in Fig. 3, the *I*/*O* ratio decreases with the increase of fan frequency. When the fan frequency increased, the supply air flow also increased, which makes the mechanical ventilation stronger to prevent the influence of two-way air flow due to temperature difference and the entry of outdoor particles. Thus, the *I*/*O* ratio for higher fan frequency case is lower. However, as shown in Table 1, the temperature difference is larger for the higher fan frequency case, which may cause larger two-way air flow effect. But in these experiments, the differences of two-way air flow effect among these four experiments are not big enough to change the trend of *I*/*O* ratios with fan frequency. Detailed analysis for two-way air flow effect is performed in the next section.

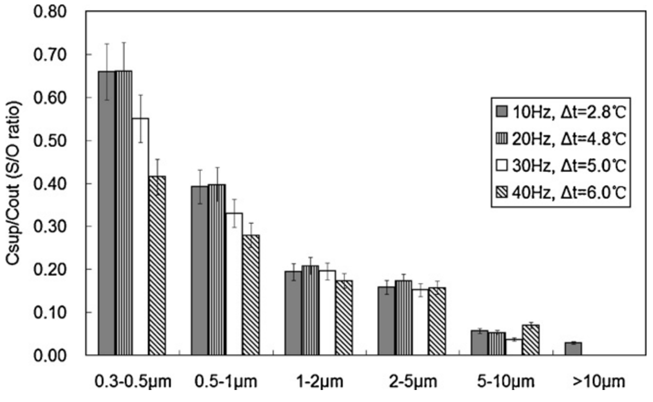

Fig. 4. The ratios of supply and outdoor particle concentrations (*S*/*O* ratio).

Table 4a
Indoor particle concentrations for particles with diameter in the range of 0.3–0.5 μm.

Fan frequency (Hz)	Opening degree of the door (°)	Mean indoor particle concentration (N/L)	Fan Frequency (Hz)	Opening degree (°)	Mean indoor particle concentration (N/L)
10	4.6	2.61E+05	30	4.6	1.80E+05
	5.7	2.61E+05		5.7	1.80E+05
	10	2.61E+05		10	1.80E+05
	30	3.63E+05		30	1.79E+05
	90	3.63E+05		90	1.98E+05
20	4.6	2.40E+05	40	4.6	9.99E+04
	5.7	2.40E+05		5.7	9.99E+04
	10	2.40E+05		10	9.99E+04
	30	2.79E+05		30	9.99E+04
	90	3.04E+05		90	1.28E+05

When comparing these experiments with the situation in real houses, some implications can be obtained. The experimental supply air flow simulates the superfluous air flow of mechanical ventilation in real houses. The selected supply air flow rates are larger than 200 m^3/h for a small room with volume of 8 m^3 i.e. the superfluous air exchange rates are larger than 25ACH which is quite huge in real houses with a mechanical ventilation system. Thus, in real houses, the superfluous air exchange rates by mechanical ventilation should be lower, which results in the weaker effectiveness of maintaining positive pressure for preventing the entry of outdoor particles when the opening area is relatively large. Furthermore, the temperature differences in the experiments were in the range of 2.8–6.0 °C, while in real situation, especially in winter or summer, the indoor/outdoor temperature difference may be up to 30 °C, which can result in much more stronger two-way air flow effect on the positive pressure control of the entry of outdoor particles. Therefore, in real houses, this positive pressure control method may not work all the time.

3.2. Validation of the theoretical model

Experimental data were used to validate the theoretical model presented in this study. Since the concentrations of particles with diameter larger than 5 μm are quite low, only the concentration data of particles with diameter in the range of 0.3–5 μm were selected for validation. Two key parameters of the model; supply air flow rate and temperature difference between indoor and outdoor,

Table 4b
Indoor particle concentrations for particles with diameter in the range of 0.5–1 μm.

Fan frequency (Hz)	Opening degree of the door (°)	Mean indoor particle concentration (N/L)	Fan frequency (Hz)	Opening degree (°)	Mean indoor particle concentration (N/L)
10	4.6	7.37E+04	30	4.6	3.50E+04
	5.7	7.37E+04		5.7	3.50E+04
	10	7.37E+04		10	3.50E+04
	30	1.52E+05		30	3.50E+04
	90	1.52E+05		90	4.12E+04
20	4.6	5.40E+04	40	4.6	2.00E+04
	5.7	5.40E+04		5.7	2.00E+04
	10	5.40E+04		10	2.00E+04
	30	7.54E+04		30	2.00E+04
	90	9.00E+04		90	2.73E+04

Table 4c
Indoor particle concentrations for particles with diameter in the range of 1–2 μm.

Fan frequency (Hz)	Opening degree of the door (°)	Mean indoor particle concentration (N/L)	Fan frequency (Hz)	Opening degree (°)	Mean indoor particle concentration (N/L)
10	4.6	4.93E+03	30	4.6	1.95E+03
	5.7	4.93E+03		5.7	1.95E+03
	10	4.93E+03		10	1.95E+03
	30	1.73E+04		30	2.48E+03
	90	1.73E+04		90	2.48E+03
20	4.6	3.20E+03	40	4.6	1.24E+03
	5.7	3.20E+03		5.7	1.24E+03
	10	3.20E+03		10	1.24E+03
	30	5.11E+03		30	1.24E+03
	90	6.46E+03		90	1.70E+03

Table 4d
Indoor particle concentrations for particles with diameter in the range of 2–5 μm.

Fan frequency (Hz)	Opening degree of the door (°)	Mean indoor particle concentration (N/L)	Fan frequency (Hz)	Opening degree (°)	Mean indoor particle concentration (N/L)
10	4.6	8.00E+02	30	4.6	3.20E+02
	5.7	8.00E+02		5.7	3.20E+02
	10	8.00E+02		10	3.20E+02
	30	3.28E+03		30	4.80E+02
	90	3.28E+03		90	4.80E+02
20	4.6	5.30E+02	40	4.6	2.36E+02
	5.7	5.30E+02		5.7	2.36E+02
	10	5.30E+02		10	2.36E+02
	30	1.00E+03		30	2.36E+02
	90	1.30E+03		90	3.10E+02

Table 4e
Indoor particle concentrations for particles with diameter in the range of 5–10 μm.

Fan frequency (Hz)	Opening degree of the door (°)	Mean indoor particle concentration (N/L)	Fan frequency (Hz)	Opening degree (°)	Mean indoor particle concentration (N/L)
10	4.6	1.4E+01	30	4.6	5E+00
	5.7	1.4E+01		5.7	5E+00
	10	1.4E+01		10	5E+00
	30	1.54E+02		30	1.7E+01
	90	1.54E+02		90	1.7E+01
20	4.6	8.0E+00	40	4.6	4E+00
	5.7	8.0E+00		5.7	4E+00
	10	8.0E+00		10	4E+00
	30	4.9E+01		30	4E+00
	90	4.9E+01		90	7E+00

Table 4f
Indoor particle concentrations for particles with diameter larger than 10 μm.

Fan frequency (Hz)	Opening degree of the door (°)	Mean indoor particle concentration (N/L)	Fan frequency (Hz)	Opening degree (°)	Mean indoor particle concentration (N/L)
10	4.6	1E+00	30	4.6	0E+00
	5.7	1E+00		5.7	0E+00
	10	1E+00		10	0E+00
	30	1.0E+01		30	2E+00
	90	1.0E+01		90	2E+00
20	4.6	0E+00	40	4.6	0E+00
	5.7	0E+00		5.7	0E+00
	10	0E+00		10	0E+00
	30	5E+00		30	0E+00
	90	5E+00		90	1E+00

were variables from the experiments, which make the validation more reliable. The discharge coefficient is another key parameter of the model since it represents the resistance characteristics of the opening, which is usually obtained by experiments. For totally open doors, the discharge coefficient can be set at 0.78, since experiments by Weber and Kearney [16] have shown that this value works well for most applications. Therefore, the experimental data of totally open cases were used for validation. The deposition velocity has been well reviewed by Lai [17]. Since the air exchange rate is quite large in the experiments, the deposition velocities were chosen in the summary by Lai [17] for large air exchange rate: 1.5E−04 m/s for 0.3–0.5 μm, 2.0E−04 m/s for 0.5–1 μm, 5.0E−04 m/s for 1–2 μm and 6.0E−04 m/s for 2–5 μm. The comparison of experimental data and calculated data of indoor particle concentrations is summarized in Table 5. The mean (S.D.) relative error between analysis model and experimental data is 10.0 ± 5.2%. Therefore, the model was well validated.

3.3. *Determining the discharge coefficient with the theoretical model*

Combined with the measured particle concentrations and supply air flow rate, the theoretical model can be used to determine the discharge coefficient for the door under different opening degrees, which is one of the key parameters for further analysis. Through modeling the cases using different discharge coefficients for 30° cases, we found that when the discharge coefficient was 0.65, the mean (S.D.) relative error between the experimental data and calculated data was 11.2% (9.4%). The detailed information is summarized in Table 6. The discharge coefficient for 4.6°, 5.7°and 10° openings of the chamber door cannot be obtained using this method since the two-way air flow effects due to temperature difference under these opening degrees are not strong enough to force the outdoor particles to enter the indoor chamber.

Table 5
Comparison of experimental data and calculated data of indoor particle concentrations when the door is totally open.

Fan frequency (Hz)	Particle size (μm)	Experimental data (N/L)	Calculated data (N/L)	Error[a]
10	0.3–0.5	3.63E+05	3.28E+05	9.7%
	0.5–1	1.52E+05	1.33E+05	12.5%
	1–2	1.73E+04	1.51E+04	13.0%
	2–5	3.28E+03	2.87E+03	12.4%
20	0.3–0.5	3.04E+05	2.84E+05	6.7%
	0.5–1	9.00E+04	8.45E+04	6.1%
	1–2	6.46E+03	7.59E+03	17.5%
	2–5	1.30E+03	1.44E+03	10.7%
30	0.3–0.5	1.98E+05	1.97E+05	0.6%
	0.5–1	4.12E+04	4.37E+04	6.0%
	1–2	2.48E+03	2.89E+03	16.4%
	2–5	4.80E+02	5.28E+02	10.0%
40	0.3–0.5	1.28E+05	1.08E+05	15.4%
	0.5–1	2.73E+04	2.32E+04	15.1%
	1–2	1.70E+03	1.58E+03	6.8%
	2–5	3.10E+02	3.08E+02	0.5%
Total: mean (S.D.)				10.0 ± 5.2%

[a] Error (%) = $\frac{|C_{\text{in,exp}} - C_{\text{in,cal}}|}{C_{\text{in,exp}}} \times 100$ $C_{\text{in,exp}}$ is experimental data of indoor particle concentration; $C_{\text{in,cal}}$ is calculated data of indoor particle concentration.

3.4. Analysis of two-way air flow due to temperature difference with the theoretical model

The studied temperature differences were set in the range of 0–10 °C. The indoor chamber temperature was set at 20 °C. All the inputs were the experimental data including supply air flow rate, geometry of the chamber rooms and the supply and outdoor particle concentrations. Fig. 5 shows the ratios of indoor and outdoor particle concentrations under different temperature differences. When the temperature difference is relatively low, the *I*/*O* ratio equates to the *S*/*O* ratio due to the strong effectiveness of the mechanical ventilation system. When the temperature difference is relatively high, the *I*/*O* ratio would increase with the increase of temperature difference. Therefore, due to the effect of two-way air flow there is a threshold that mechanical ventilation system can preserve by maintaining absolute positive pressure to prevent outdoor particles from entering indoor spaces. For particles with diameter in the range from 0.5 to 1 μm under the conditions of total opening, the thresholds for each situation are: 0.1 °C for 10 Hz, 0.5 °C for 20 Hz, 1.7 °C for 30 Hz and 3.0 °C for 40 Hz. For 30° opening, the thresholds for each situation are: 0.1 °C for 10 Hz, 0.7 °C for 20 Hz, 2.2 °C for 30 Hz and 4.0 °C for 40 Hz. When the temperature differences are higher than the thresholds, the positive pressure control method cannot prevent outdoor particles entering to indoor environment. In real situation, tiny indoor/outdoor temperature difference such as 0.1 °C is impossible to be avoided. Therefore, if the opening area is relatively large, it is difficult to avoid two-way air flow in real situation even when the supply air flow rate is quite large (e.g. the supply air flow rate in the experiments).

3.5. Analysis of the satisfied supply air flow rate with the theoretical model

In the experiments if the supply air flow rate is large enough when the opening degree of the door is larger than 30°, the effectiveness of positive pressure control method can be satisfied. Using the validated model and the experimental inputs, the relationship between *I*/*O* ratio and supply air flow rate can be analyzed. Supply air flow rate varies from 0 to 2400 m^3/h. All the other inputs were the experimental data including temperature differences, geometry of the chamber rooms and the supply and outdoor particle concentrations. Fig. 6 shows the ratios of indoor and outdoor particle concentrations under different supply air flow rates. The larger supply air flow rate causes lower *I*/*O* ratio for all the cases until supply air flow reaches the satisfied value. The satisfied supply air flow rate means the threshold supply air flow value that can totally prevent outdoor particles from entering indoor spaces through the door. When the supply air flow rate is equal or larger than the sat-

Table 6
Comparison of experimental data and calculated data of indoor particle concentrations when the opening degree of the door is 30°.

Fan frequency (Hz)	Particle size (μm)	Experimental data (N/L)	Calculated data (N/L)	Error[a]
10	0.3–0.5	3.63E+05	3.18E+05	12.3%
	0.5–1	1.52E+05	1.25E+05	17.5%
	1–2	1.73E+04	1.37E+04	20.7%
	2–5	3.28E+03	2.60E+03	20.8%
20	0.3–0.5	2.79E+05	2.74E+05	1.7%
	0.5–1	7.54E+04	7.85E+04	4.1%
	1–2	5.11E+03	6.71E+03	31.2%
	2–5	1.00E+03	1.26E+03	25.6%
30	0.3–0.5	1.79E+05	1.87E+05	4.7%
	0.5–1	3.50E+04	3.92E+04	11.9%
	1–2	2.48E+03	2.39E+03	3.5%
	2–5	4.80E+02	4.19E+02	12.6%
40	0.3–0.5	9.99E+04	1.01E+05	1.3%
	0.5–1	2.00E+04	2.06E+04	3.0%
	1–2	1.24E+03	1.29E+03	4.4%
	2–5	2.36E+02	2.47E+02	4.6%
Total: mean (S.D.)				11.2 ± 9.4%

[a] Error (%) = $\frac{|C_{\text{in,exp}} - C_{\text{in,cal}}|}{C_{\text{in,exp}}} \times 100$ $C_{\text{in,exp}}$ is experimental data of indoor particle concentration; $C_{\text{in,cal}}$ is calculated data of indoor particle concentration.

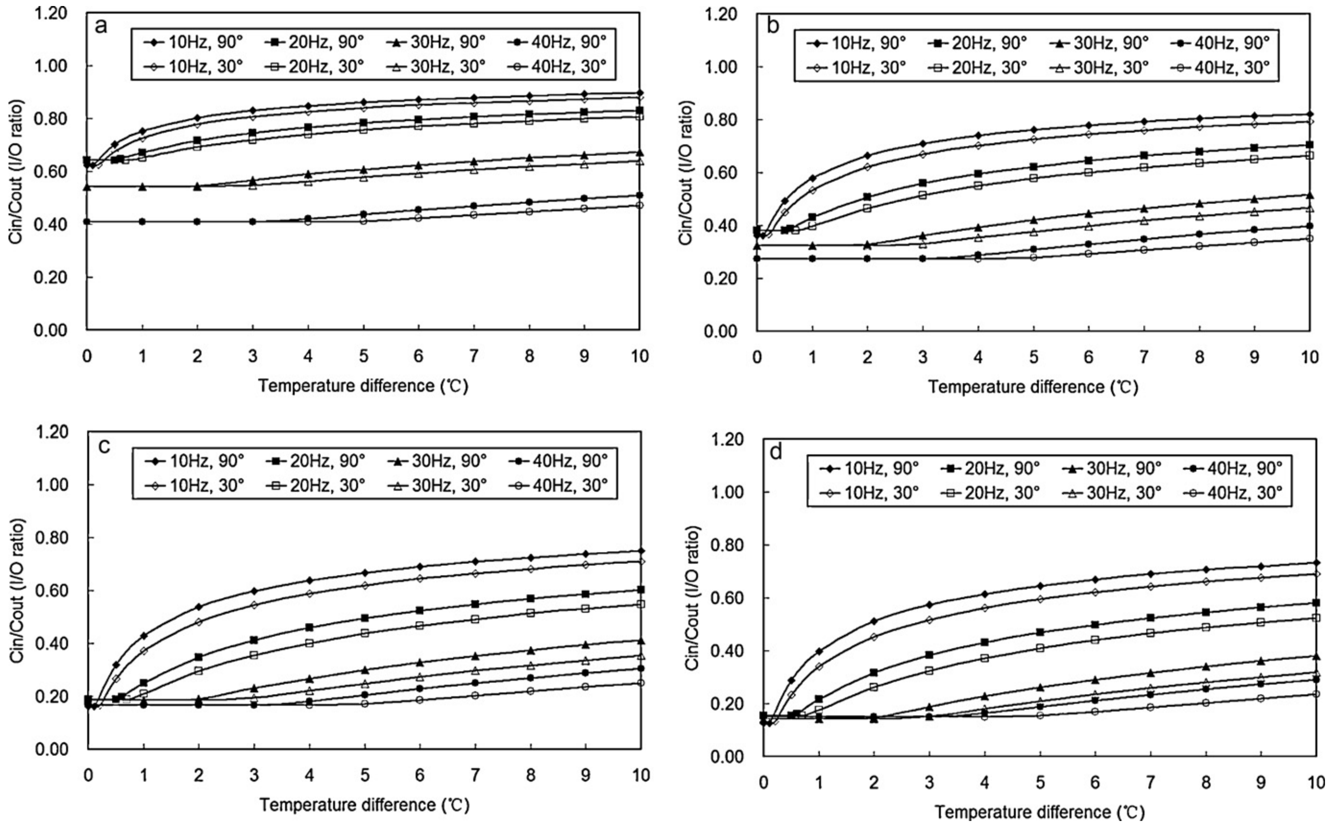

Fig. 5. The ratios of indoor and outdoor particle concentrations under different temperature differences: (a) 0.3–0.5 μm; (b) 0.5–1 μm; 1–2 μm; (d) 2–5 μm.

isfied value, the I/O ratio equates to the S/O ratio. For particles with diameter in the range from 0.5 to 1 μm, the satisfied supply air flow rates for total opening cases are: 1000 m^3/h for $\Delta t = 2.8\,^\circ C$, 1300 m^3/h for $\Delta t = 4.8\,^\circ C$, 1300 m^3/h for $\Delta t = 5.0\,^\circ C$ and 1400 m^3/h for $\Delta t = 6.0\,^\circ C$. For 30° opening, the satisfied values are: 800 m^3/h for $\Delta t = 2.8^\circ C$, 1000 m^3/h for $\Delta t = 4.8\,^\circ C$, 1000 m^3/h for $\Delta t = 5.0\,^\circ C$ and 1100 m^3/h for $\Delta t = 6.0\,^\circ C$.

4. Discussion

Although the experimental data presented in this study prove the weak effectiveness of the positive pressure control method for keeping away outdoor particles, real situations are more complicated than the experiment. The geometry and position of openings or cracks in building envelopes, the outdoor wind pressure and the temperature difference between indoor and outdoor environments can affect the effectiveness of this control method. Fortunately, the theoretical model has been well validated using experimental data, which can be used to do further analysis other influencing factors for this control method in real houses. Moreover, since mechanical ventilation consumes fan energy compared with the simple natural ventilation method by opening windows, it is very important to understand whether this control method really works in reality, and evaluate whether it is cost effective since the energy problem is quite important now. The effectiveness as well as the cost of outdoor particle control methods should be further analyzed through comparison with each other.

The particle concentration data in this study were collected by using a relatively large door size in a relatively smaller chamber compared to most residential and office spaces. In typical indoor/outdoor particle measurement experiments, as long as the filtered air contains fewer amounts of particles, it has been observed that positive pressure helps reduce the particle levels indoors. When air is passively exchanged by opening windows or doors, the indoor particle concentration was obviously increased. However, the level of increment by opening windows with positive pressure ventilation was lower than that observed without mechanical ventilation. Therefore, the actual effectiveness of the positive pressure control method may be underestimated from this point of view.

Indoor positive pressure control method has been recommended and used in some normal indoor environments such as residences and offices (in some cases the main goal is for controlling indoor air temperature and humidity). Although the occupants are recommended to close the windows or doors, some still open them for other purposes, because they were convinced that as long as the supply air flow rate is larger than return air flow rate, the ventilated room would maintain positive pressure since the superfluous air flow must exfiltrate to outdoors. This idea makes sense for most people even the ventilation engineers since mass balance is always the first concern. However, they did not realize the two-way air flow due to temperature difference may “break” the positive pressure indoors. Thus, this impact should be analyzed for enhancing the understanding of indoor positive pressure control method. Additionally, it should be noticed that recommendation of closing windows or doors is for energy saving, however, occupants like to open windows because they want more fresh air and better indoor air quality. Therefore, the strategy of achieving the balance between energy saving and indoor air quality deserves further study.

Additionally, this method can result in indoor pressurization, which is generally unacceptable in very cold climates because the exfiltrating air can cause condensation in the building envelope [18]. The condensation may cause additional air pollution in indoor environments, which needs to be considered carefully.

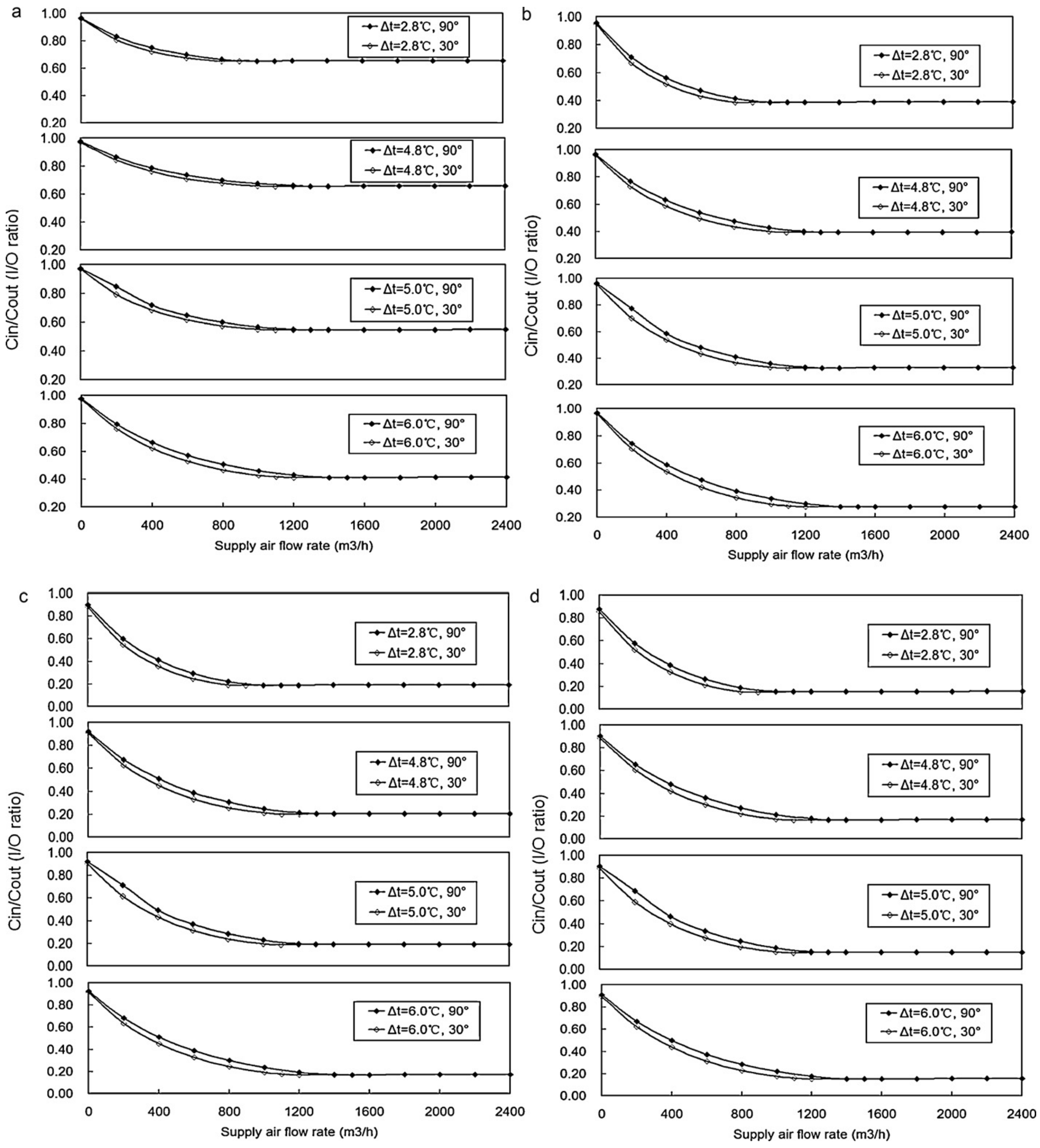

Fig. 6. (a) The ratios of indoor and outdoor particle concentrations under different supply air flow rates: (a) 0.3–0.5 μm; (b) 0.5–1 μm; 1–2 μm; (d) 2–5 μm.

5. Conclusions

This study presents experimental data and theoretical model to analyze the impact of two-way air flow due to indoor/outdoor temperature difference on preventing outdoor particles from entering indoor environments using indoor positive pressure control method. Within the scope of this research, the following conclusions can be made:

(1) The indoor positive pressure control method is effective only when the size of the opening area is restricted to a certain level, opening degree less than 30° in this study, due to the two-way air flow effect induced by differential temperature.

(2) In real houses, the superfluous air exchange rates by mechanical ventilation should be lower than that in experiments, and the indoor/outdoor temperature difference may be up to 30 °C (much larger than that in experiments), which can result in

much more stronger two-way air flow effect on the positive pressure control of the entry of outdoor particles. Therefore, in real houses, this positive pressure control method may not work all the time.

Acknowledgements

This study was sponsored by the National Natural Science Foundation of China (Grant No. 51078216) and supported by Tsinghua University Initiative Scientific Research Program. We thank Mike Grinshpon for carefully checking the English writing of the manuscript.

References

[1] D.W. Dockery, C.A. Pope, S.P. Xu, J.D. Spengler, J.H. Ware, M.E. Fay, B.G. Ferris, F.E. Speizer, An association between air pollution and mortality in six United States cities, New Engl. J. Med. 329 (1993) 1753–1759.
[2] J.M. Samet, F. Dominici, F.C. Curriero, I. Coursac, S.L. Zeger, Fine particulate air pollution and mortality in 20 U.S. cities, 1987–1994, New Engl. J. Med. 343 (2000) 1742–1749.
[3] C.A. Pope 3rd, R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, G.D. Thurston, Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, JAMA 287 (2002) 1132–1141.
[4] C. Chen, B. Zhao, Review of relationship between indoor and outdoor particles: *I*/*O* ratio, infiltration factor and penetration factor, Atmos. Environ. 45 (2011) 275–288.
[5] ASHRAE Handbook Fundamentals Chapter 16, Atlanta, GA, 2001.
[6] ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality, Atlanta, GA, 2007.
[7] CDC, Guidelines for Environmental Infection Control in Health-care Facilities, US Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, Atlanta, GA, 2003.
[8] A. Sapkota, D. Williams, T.J. Buckley, Tollbooth Workers and mobile source-related hazardous air pollutants: how protective is the indoor environment? Environ. Sci. Technol. 39 (2005) 2936–2943.
[9] Y. Li, W.H. Ching, H. Qian, P.L. Yuen, W.H. Seto, J.K. Kwan, J.K.C. Leung, M. Leung, S.C.T. Yu, An evaluation of the ventilation performance of new SARS isolation wards in nine hospitals in Hong Kong, Indoor Built Environ. 16 (2007) 400–410.
[10] H. Humphreys, Positive-pressure isolation and the prevention of invasive aspergillosis. What is the evidence? J. Hosp. Infect. 56 (2004) 93–100.
[11] N. Rice, A. Streifel, D. Vesley, An evaluation of hospital special-ventilation-room pressures, Infect. Control Hosp. Epidemiol. 22 (2001) 19–23.
[12] ASHRAE, HVAC Design Manual of Hospitals and Clinics, Atlanta, GA, 2003.
[13] Fluke Inc., Manual for Fluke 983 Optical Particle Counter, Fluke Inc., Everett, WA, 2005.
[14] CONTAMW, CONTAMW User's Manual, National Institute of Standards and Technology (NIST), Gaithersburg, MD, 2002.
[15] Y. Li, A. Delsante, J. Symons, Prediction of natural ventilation in buildings with large openings, Build. Environ. 35 (2000) 191–206.
[16] D.D. Weber, R.J. Kearney, Natural convective heat transfer through an aperture in passive solar heated buildings, in: 5th National Passive Solar Conference, 1980, pp. 1037–1041.
[17] A.C.K. Lai, Particle deposition indoors: a review, Indoor Air 12 (2002) 211–214.
[18] ASHRAE Handbook Fundamentals Chapter 26, Atlanta, GA, 2001.