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Retrofitting existing buildings to control indoor $PM_{2.5}$ concentration on smog days: Initial experience of residential buildings in China

Yiyi Chu, Peng Xu, Zhiwei Yang and Weilin Li

Abstract

Severe smog days in many parts of developing countries, such as China and India, have drawn worldwide attention. This study aims at integrating various building retrofitting methods of existing buildings to control indoor particulate matter 2.5 concentrations. Methods are such as airtightness improvement, room pressure control, recycling air filtration and combinations of the above. The study verifies the effectiveness of each control method to reduce the indoor particulate matter 2.5 concentration below 25 μg/m^3 under certain outdoor conditions in building. Measurements and modelling are conducted for different outdoor particle concentration scenarios under different control strategies at an apartment in Shanghai, China. Overall, the retrofitting methods depend on outdoor smog circumstances and building structures. Therefore, it would be wise to choose appropriate control method depending on outdoor particulate matter 2.5 concentrations. This is the first time that various existing residential building retrofitting strategies are integrated jointly and the combination of different control methods are tested to ensure indoor air quality under different outdoor conditions. To validate the generality of these control strategies, a simulation model is developed and calibrated against experimental data under different scenarios. The variation of the indoor particulate matter 2.5 concentration in an extremely bad day is simulated and the influencing factors including infiltration air change rate, air volume and filter efficiency are all analyzed according to the model. The results and conclusions of this study can be used in many parts of the worlds, when building occupants have to choose proper equipment or retrofitting methods to control their indoor air quality.

Practical application: The building retrofitting methods introduced in this article could be used in any residential building to control indoor particulate matter 2.5 concentrations continuously below 25 μg/m^3 under different outdoor conditions.

Keywords

Indoor particulate matter 2.5 control, residential building retrofit, control strategies integration, filtration model validation, influencing factors analysis

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Introduction

Epidemiologic evidence has shown a relationship between particle pollution exposure and adverse health effects, which has drawn increasing attention regarding methods for controlling particulate matter 2.5 ($PM_{2.5}$) pollutants indoors. Brook[1] provided evidence that PM is capable of acutely increasing blood pressure and that exposure to PM has tremendous public health implications. Hwang et al.[2] conducted a two-year study of 12-year-old Taiwanese children and concluded that long-term exposure to $PM_{2.5}$ may have a detrimental effect on the development of lung function in children. Loftus et al.[3] provided evidence that $PM_{2.5}$ contributes to elevated asthma morbidity in rural US communities. Choo et al.[4] showed through statistical analysis that exposures to poor indoor air quality (IAQ) might increase the risk of developing respiratory symptoms among preschoolers in Malaysia. Guo et al.[5] explored the association between $PM_{2.5}$ and the hospital emergency room visits in Beijing, China for cardiovascular diseases. There are also many other epidemiological studies on particular hazards reviewed in.[6]

Since people spend approximately 80–90% of their time indoors, indoor pollution becomes very important to human health,[7,8] and various studies from different academic fields on indoor air pollution, especially $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than approximately 2.5 μm), have attracted attention.

Many studies have been undertaken to discuss the sources, composition and characteristics of indoor $PM_{2.5}$,[9–13] indicating that indoor particles represent a combination of outdoor-originating particles, indoor-emitted particles and indoor secondary organic aerosol, among which particles coming from outside via ventilation systems or infiltration through door and window cracks contribute to large portions of indoor particles.[14] Although source control is the preferred method to solve the problem at the root, this option is not always available. Therefore, most researchers concentrate on indoor particle formation mechanisms in order to analyze the influencing factors of indoor $PM_{2.5}$ as well as seek solutions to control it by experimental measurements and numerical simulations.

Chen and Zhao[15] described the $PM_{2.5}$ concentration relationship between indoors and outdoors in detail using different concepts such as indoor/outdoor (I/O) ratio, infiltration factor and penetration factor. Studies also focused on the factors influencing indoor $PM_{2.5}$ concentration, such as meteorological parameters including wind speed, wind direction, temperature and relative humidity relating to outdoor $PM_{2.5}$ concentration;[16] indoor emission sources such as smoking, cooking and human disturbance;[10] penetration factor and deposition factor;[17–19] infiltration with different openings to the external environment (airtightness); filter efficiency of the makeup air and indoor recirculated air (air purifier)[20,21] and ventilation systems.[22–25]

Some building retrofit measures have been proposed by many researchers to reduce indoor $PM_{2.5}$ concentrations, on the basis of the study of the influential factors mentioned above. For example, Wang et al.[20] presented a statistical analysis of the available data of $PM_{2.5}$ in four residential dwellings with different building airtightness levels and Heating, Ventilation and Air Conditioning (HVAC)-filter combinations, which revealed that the enhanced airtightness and the improvement of filter efficiency for both makeup air and indoor recirculated air decrease indoor $PM_{2.5}$ concentration significantly. Zhou et al.[21] also proposed a method for controlling infiltration of $PM_{2.5}$ from outdoors and reducing indoor emissions, based on the experimental results of a typical residential building with different voids of windows and doors and different indoor emission sources. Waring et al.[26] performed a two-phase investigation to evaluate the removal and generation of indoor pollution for two high-efficiency particle arresting (HEPA) filters, one electrostatic precipitator with a fan, and two ion generators without fans, which showed that the pollutant removal benefits of ozone-generating air cleaners can be outweighed by the generation of indoor pollution, and portable HEPA filters were ultimately recommended.

And Howard-Reed[27] presented the fine and coarse particle decay rates associated with a central forced-air fan and in-duct air cleaners in an occupied home under several scenarios with the fan in both the on and off modes as well as different filter efficiencies, indicating that the decay rates of indoor particles increased greatly when fan was on or when filter efficiency was higher, thus indoor particle concentration largely decreased. Pyo et al.[28] introduced a novel concept to remove $PM_{2.5}$ without HEPA filters using the condensational growth of particles and developed a prototype of a filter-free particle filtration unit consisting of an air saturator, a condenser and a multi-nozzle-impactor assembly. The results showed that it was effective with an acceptable collection efficiency of approximately 81%. However, the present filter-free particle filtration unit has an applicability limitation, as is recommended for use in hot and humid circumstances such as combustion exhaust. There are also some other limitations such as the larger size relative to conventional residential air purifiers and the noise.

Although the above measures have been performed to control indoor $PM_{2.5}$ concentrations to some extent, these methods consider only certain factors and the indoor $PM_{2.5}$ concentration cannot be controlled under the standard healthy value of $25\,\mu g/m^3$ continuously,[29,30] especially when the outdoor concentration is higher than $200\,\mu g/m^3$. To help address this gap in knowledge and provide appropriate retrofitting strategies for existing residential buildings, we conducted thorough experiments in a residential building in Shanghai in China and intend to (1) integrate various indoor $PM_{2.5}$ concentration control methods and provide general criteria for each control method; (2) quantitatively measure indoor and outdoor particle concentrations and survey the variation of I/O ratio under different control methods and outdoor $PM_{2.5}$ concentration ranges in order to determine a successful retrofitting method that ensures the $PM_{2.5}$ concentration remains below $25\,\mu g/m^3$ under heavy outdoor pollution and (3) validate the mathematical model to further predict indoor $PM_{2.5}$ concentration and evaluate the important factors of different control methods which affect the indoor $PM_{2.5}$ concentration to carry out proper control strategy and select appropriate equipment.

Indoor $PM_{2.5}$ control methods

The significance of $PM_{2.5}$ is strongly related to airborne particle concentration, size distribution and chemical or biological composition, which depend on factors broadly classified as sources, transformation processes and removal mechanisms.[31] Accordingly, the indoor $PM_{2.5}$ control methods consist of three aspects including source control, outdoor/indoor transportation control and indoor active control. Some of these aspects are easy to control and others are uncontrollable, as shown in detail in Figure 1.

Airtightness improvement

Building airtightness, defined as the resistance to air leakage through unintentional openings in the building envelope, is a fundamental building property that impacts infiltration. Air leakage is an important factor we must consider at first due to its three principle effects on the building performance: (1) Significant increasing in space conditioning load; (2) Degradation of envelope assemblies due to interstitial condensation or air driven rain penetration; (3) Ingress of outdoor pollutant – dust, noise, particles, etc. In this article, we focus on the third point, where the airtightness improvement could maximally prevent outdoor particles itself.

Hui-xing et al.[32] proposed retrofit methods including window replacement and using high-quality advanced window installations or adding sealing strips to reduce air penetrating through the cracks and channels. And Adetunji[33] presented a comprehensive strategy for achieving high airtightness for both new buildings and

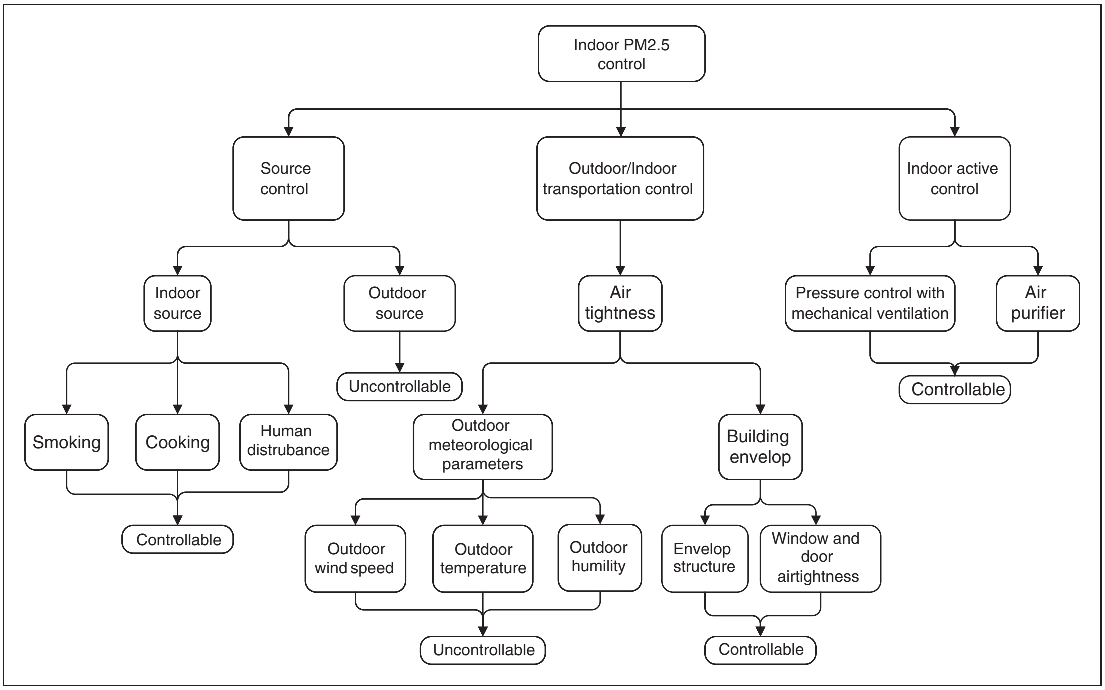

Figure 1. Indoor $PM_{2.5}$ concentration control methods.
PM: particulate matter.

refurbished buildings, consisting of a set of guidelines in the pre-design stage, design stage and construction stage. All of these could serve as references for us to improve airtightness.

Pressure control with mechanical ventilation

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) handbook[34] and ASHRAE standard 62.1,[35] maintaining a positive pressure indoors with a mechanical ventilation system, which follows the same goal of airtightness improvement, is a possible approach to prevent outdoor particles from penetrating into the indoor environment. This method has been widely used in specialized care environments such as hospitals.[36,37]

However, Chen et al.[38] suggested that the indoor positive pressure control strategy may not work all the time due to the two-way airflow effect, especially in winter when the temperature difference may reach up to 30°C. Under certain conditions with different temperature differences of indoor–outdoor and different effective opening areas, there is a threshold of superfluous airflow rate for total prevention of outdoor particles from entering indoor spaces supplied by mechanical ventilation. In light of this, with the consideration of energy saving, it should be recommended that the doors and windows be closed when implementing a positive pressure control strategy. Therefore, the pressure control method discussed in this article is based on the consideration that the door and window openings are both closed.

Chen et al. also researched the influencing factors affecting the satisfied superfluous airflow rate, and found that the two dominating factors are outdoor wind velocity and the effective air leakage area coefficient, which have positive relations with the satisfied superfluous airflow rate.[39] The cost of the two control methods consists of positive pressure control and indoor air purification. Considering the energy consumption of the fan, pressure control is more effective for maintaining the same I/O particle concentration (I/O ratio) under most outdoor conditions.

The current standard for suitable indoor pressurization value is intended for industrial facilities such as clean rooms. The relevant code for residential buildings is not available. We can take the low end of the clean room code as a reference in order to obtain a reasonable pressurization value of approximately 5 Pa for residential buildings.[40] The ventilated building will maintain positive pressure as long as the supply airflow rate is greater than the return airflow rate, and the wind pressure effect is minimized by enhancing the supply airflow rate, since the superfluous airflow rate must exit the space through air leakages or other openings to outdoors.

Air filter

Historically, standards for evaluating the results of the reference filter test have been developed in response to the needs of the times. ANSI/ASHRAE Standard 52.2 provides filter minimum efficiency reporting value (MERV) rating recommendations to evaluate the performance of air cleaners.[41] ASHRAE Standard 62.1 also specifies the minimum requirements for HVAC particle filtration efficiency that requires a minimum of MERV 8 on the mixed airstream for commercial buildings.[35] ASHRAE Standard 62.2 also requires a minimum of MERV 6 on the recirculating airstream for low-rise residential buildings.[42] However, none of these standards are designed for heavy outdoor pollution, and the current concerns are indoor $PM_{2.5}$ control.

Stephens et al.[43] provided MERV rating recommendations for 100 of the world's most popular cities, including 20 of China's main metropolises, in order to achieve minimum outdoor air quality standards for the incoming outdoor ventilation air of both commercial and residential buildings. They found that the standard cannot always address the need for acceptable indoor air quality in highly populated environments. For instance, in China, where the outdoor $PM_{2.5}$ concentration is extremely high, filters with a minimum of MERV 16 would need to be applied to bring $PM_{2.5}$ concentrations in indoor ventilation air down to Environmental Protection Agency-recommended maximums (12 µg/m^3 for annual average $PM_{2.5}$, 35 µg/m^3 daily).[44]

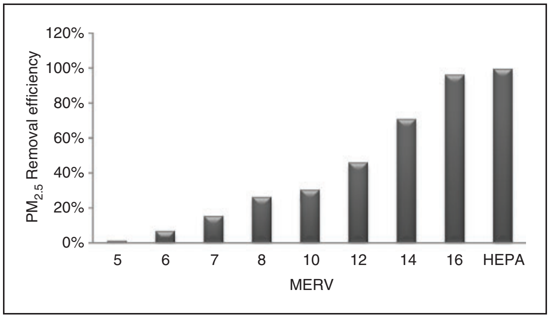

Figure 2. Estimates of $PM_{2.5}$ removal efficiency of outdoor origin for filters tested according to ASHRAE 52.2-2012.[45]
ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers; PM: particulate matter; ANSI: American National Standards Institute.

However, there is no explicit reference to $PM_{2.5}$ mass concentration removal efficiency in various standards. Azimi et al.[45] used nearly 200 outdoor particle size distributions from literature to estimate $PM_{2.5}$ removal efficiencies of a wide range of MERV-rated single-pass HVAC filters. The average removal efficiency values are shown in Figure 2, which can serve as the reference for designers to choose appropriate filter efficiency in improving IAQ in residential buildings.

Case study

Sampling site – building description

An apartment on the sixth floor in Shanghai was selected to be retrofitted according to the methods mentioned above. The apartment measures 110 m^2 of gross floor and 2.6 m clear height from floor to ceiling. This is a typical apartment building in many China cities. Figure 3 shows the floor plan of the apartment. The experiment

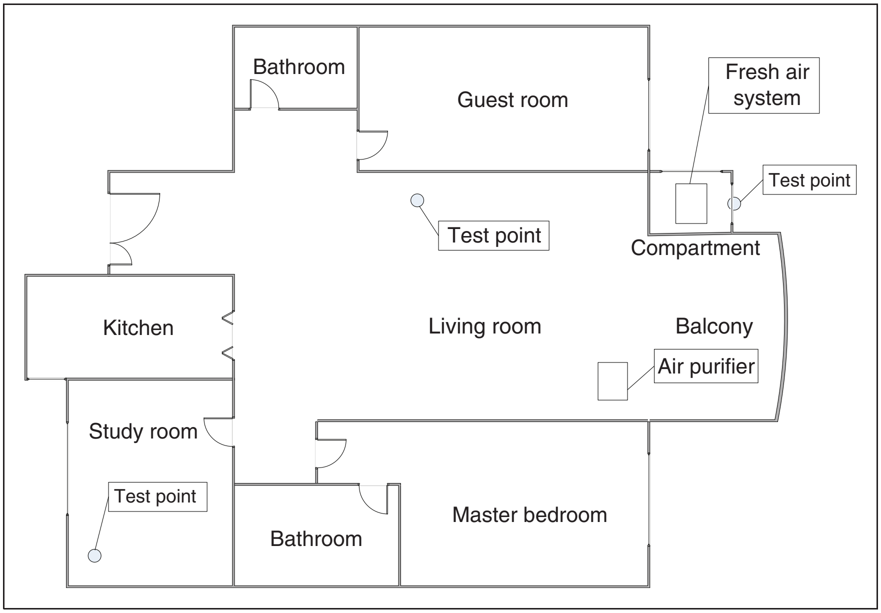

Figure 3. Floor plan of the apartment.

was conducted during the winter season from November 2016 to February 2017.

Instruments and measured parameters

Plantower particle measuring systems (PMS) 5003 was used to measure indoor and outdoor $PM_{2.5}$ concentrations with an averaging interval of 60 s in the above apartment. The PMS sensor operates based on light scattering technique where the amount of scattered light is proportional to the volume concentration of the aerosol, of which the collected data in this study were corrected against a DustTrak DRX aerosol monitor (TSI 8534). During the experiment, one sensor was placed right outside of the window next to the balcony to collect outdoor $PM_{2.5}$ concentration. The window was opened and the door between the compartment and balcony closed. The other two indoor air sampling sites were in the living room and the study room, respectively, at a height of approximately 1.2 m. Their locations were carefully considered to avoid the direct influence of nearby occupants and air outlets, which can be seen in Figure 3. Meanwhile, a Model 3 blower door system with DG-700 was used to measure the airtightness of the apartment by blower door test method. And a BM-80-CO_2 and a hot bulb anemoscope ZRQF-D30J were used to measure CO_2 concentration at an interval of 10 s to test the airtightness by CO_2 concentration attenuation method and air velocity to calculate air flow. All instruments were tested and calibrated in the laboratory before being used for field measurements. Comparative quality assurance tests for the three particle instruments were also conducted with all instruments co-located and sampling indoor air before test.

Application of control strategies and results

As mentioned in section ‘Indoor $PM_{2.5}$ control methods’, the three $PM_{2.5}$ control strategies are airtightness improvement, pressure control with fresh air system and air purifier. We tested each method individually and then combined two or three methods in the experimental apartment to verify their effect. These tests provide valuable information for individuals to select proper retrofit methods to always ensure indoor $PM_{2.5}$ concentrations below 25 μg/m^3 under different outdoor conditions.

Airtightness improvement. According to section 'Pressure control with mechanical ventilation', good airtightness ensures less infiltration. It is necessary to improve the airtightness of the apartment at first to reduce the source of $PM_{2.5}$. The single entrance door has been replaced with a double door, and the single glazing windows were replaced with high-quality double glazing windows. Some of the remaining windows were well sealed. To evaluate the effect of the airtightness improvement, the blower door test was used to measure the airtightness of the building envelope.[46]

A basic blower door system includes three components: a calibrated fan, a door panel system and a pressure measurement device. The blower door fan is temporarily mounted on the exterior doorway using the door panel system to blow air into or out of the building, creating either a positive or negative pressure differential between inside and outside. The multi-point blower door test procedure results in a series of known values of infiltration air flow Q and the indoor–outdoor pressure difference Δp in order to establish the power low relationship between Q and Δp. And n_{50}, the air change per hour rate when the house is under 50 Pa pressure, is measured by the test.

Because there is no related standard about the airtightness of residential buildings in China, we can only borrow the foreign standards to evaluate the airtightness performance, which is summarized by Chen et al.[47] The n_{50} value before and after the airtightness improvement are 9.5 and 6.4, respectively, indicating that the airtightness improvement can decrease the air change rate significantly to effectively prevent the ingress of outdoor particles.

To examine the airtightness improvement behaviour of indoor $PM_{2.5}$ concentration when the door and windows were well sealed, the C_i before and after the airtightness improvement were measured under two weather conditions with different outdoor $PM_{2.5}$ concentrations, which can be seen in Figure 4(a) to (d).

Figure 4(a) and (b) illustrates the changes of C_i and C_o with the I/O ratio fluctuated with a mean value of 0.66. After retrofitting, the average I/O ratio was 0.53 shown in Figure 4(c) and (d), indicating the decrease of outdoor particle invasion. From Figure 4(d), we observed that indoor $PM_{2.5}$ concentration could be kept lower than 25 μg/m^3 when outdoor $PM_{2.5}$ concentration was in a relatively low level (lower than 40 μg/m^3) after airtightness improvement. However, when outdoor $PM_{2.5}$ concentration grew higher, indoor $PM_{2.5}$ concentration could not be controlled in a healthy range as shown in Figure 4(c), then other measures must be taken to decrease the indoor $PM_{2.5}$ concentration.

Pressure control with mechanical ventilation

According to section 'Pressure control with mechanical ventilation', a fresh air system with a high-efficiency $PM_{2.5}$ removal filter was chosen to be installed on the balcony of the apartment to achieve micro-positive pressure control, as described in section 'Instruments and measured parameters'. The fan has two grades, high air volume with 216.8 m^3/h and low air volume with 170.3 m^3/h. And the positive pressure values under the two air volumes were 2 and 1 Pa, respectively, by calculation due to the relationship between indoor–outdoor pressure difference and infiltration air flow obtained by the blower door test. The $PM_{2.5}$ removal efficiency for the filter was 84.1%, reported by the manufacturer which lies between MERV 14 and MERV 16, depending on the outdoor conditions in Shanghai.

Figure 5(a) shows that indoor $PM_{2.5}$ concentration decreased gradually from 70 to 9 μg/m^3 with the I/O ratio from 0.75 to 0.09 with an average value of 0.28 when using fan with low air flow rate. As Figure 5(b) illustrates, C_i is very low at the beginning though the outdoor $PM_{2.5}$ concentration was at approximately 140 μg/m^3, because the air cleaning was on before the experiment. Similarly, the I/O ratio fluctuated

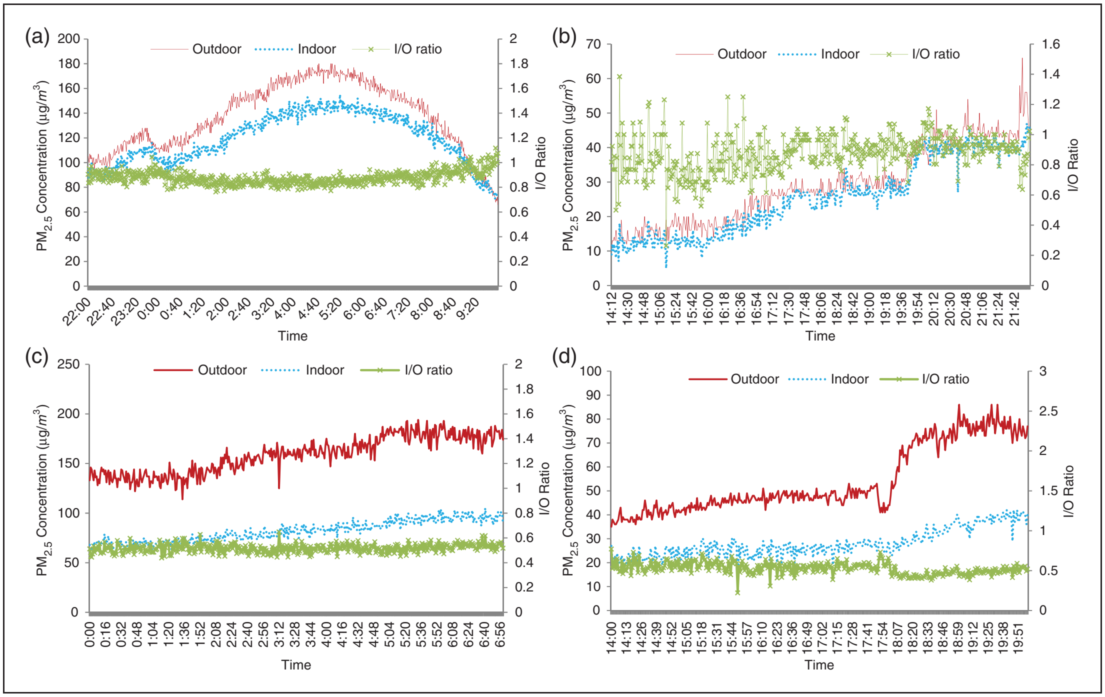

Figure 4. Indoor PM$_{2.5}$ concentrations with airtightness improvement. (a) Average C_o of 137 μg/m^3 before airtightness improvement. (b) Average C_o of 29 μg/m^3 before airtightness improvement. (c) Average C_o of 172 μg/m^3 after airtightness improvement. (d) Average C_o of 54 μg/m^3 after airtightness improvement.
PM: particulate matter.

with an average value of 0.25. It is worth noting that low air flow could maintain indoor PM$_{2.5}$ concentration below 25 μg/m^3 while C_o was under 120 μg/m^3.

Considering that the fresh air system with a small airflow rate could not control indoor PM$_{2.5}$ concentration when C_o was not under 120 μg/m^3, a large unit was used as Figure 5(c) shows. The I/O ratio dropped from 0.46 to 0.07 with a mean value of 0.16. From Figure 5(c), we observed that that high air volume fresh air unit can keep indoor PM$_{2.5}$ concentration in a healthy level while C_o remained under 160 μg/m^3.

Air purifier. Except for indoor pressure control, which introduces outdoor air that must be cleaned by a filter before entering indoors, an air purifier, circulating indoor air repeatedly through filters to clean indoor air, is another active way to control indoor air quality. Therefore, an air purifier with PM$_{2.5}$ removal efficiency of 99%, reported by the manufacturer, was chosen to be installed in the living room of the apartment, which can be seen in Figure 3. Similarly, the air purifier also has two grades with high recirculating air volume of 350.24 m^3/h and low recirculating air volume of 158.98 m^3/h.

Figure 6(a) shows the variations of C_i and C_o with the I/O ratio fluctuated between 0.15 and 0.59 with an average of 0.33, indicating that an air purifier with low circulated air volume could not keep indoor PM$_{2.5}$ concentration under 25 μg/m^3 when outdoor PM$_{2.5}$ concentration was over 80 μg/m^3. Figure 6(b) and (c) shows the results when an air purifier with high circulated air volume was used. Figure 6(b) illustrates that C_i continually decreased while C_o increased within a certain range with the I/O ratio from 0.71 to 0.07 with an average of 0.13.

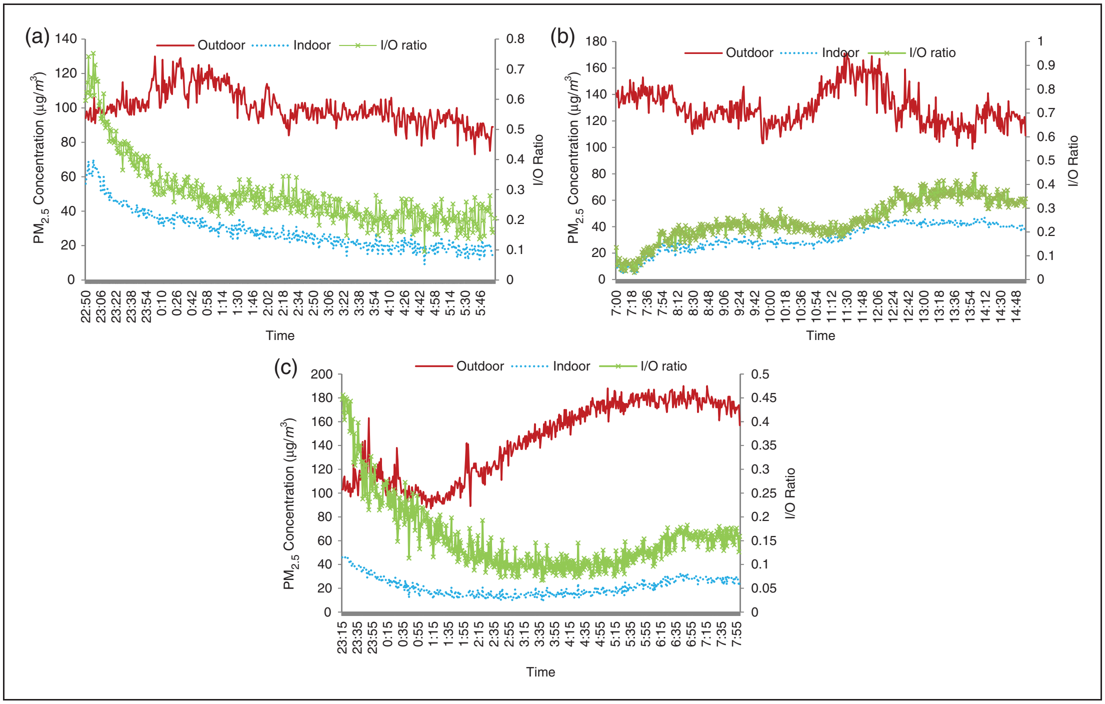

Figure 5. Indoor $PM_{2.5}$ concentrations with positive pressure control. (a) Indoor $PM_{2.5}$ concentrations with low air volume (starting at 11:00). (b) Indoor $PM_{2.5}$ concentrations with low air volume (starting at 7:39). (c) Indoor $PM_{2.5}$ concentrations with high air volume (starting at 23:21).
PM: particulate matter.

Nevertheless, as illustrated in Figure 6(c), indoor $PM_{2.5}$ concentration increased along with the sudden growth of C_o before it decreased to a healthy level. The I/O ratio fluctuated between 0.25 and 0.79 (Mean = 0.41).

Combination control. From the above data analysis, the three measures – airtightness improvement, pressure control with mechanical ventilation and air purifier – were not effective if used alone when outdoor pollution was high. Therefore, integrated application of the three measures has been considered and tested.

Figure 7 combines airtightness improvement, pressure control with low air volume and an air purifier with high circulation air volume, in order to control indoor $PM_{2.5}$. Under the combination control mode, C_i declined rapidly from 66 to 10 $\mu g/m^3$ with higher outdoor $PM_{2.5}$ concentration and kept steady decline even C_o showed a modest increase at approximately 4:00 p.m. The I/O ratio declined from 0.41 to 0.01 with an average value of 0.05, which is much lower than that of the isolated operation mode of the earlier scenario, indicating that only the combined operation is effective when outdoor $PM_{2.5}$ is high.

The results of different control methods were summarized in Table 1. Due to the experimental results of different control strategies, we could conclude that selecting a reasonable control method under different outdoor $PM_{2.5}$ concentrations is sufficient for indoor $PM_{2.5}$ concentration control in Shanghai. The valid range summarized in Table 1 indicates the top limit value of outdoor $PM_{2.5}$ concentration that the indoor $PM_{2.5}$ concentration could be decreased to equal or less than 25 $\mu g/m^3$ when the specific control strategy is used. This information provides a reference for selection of appropriate

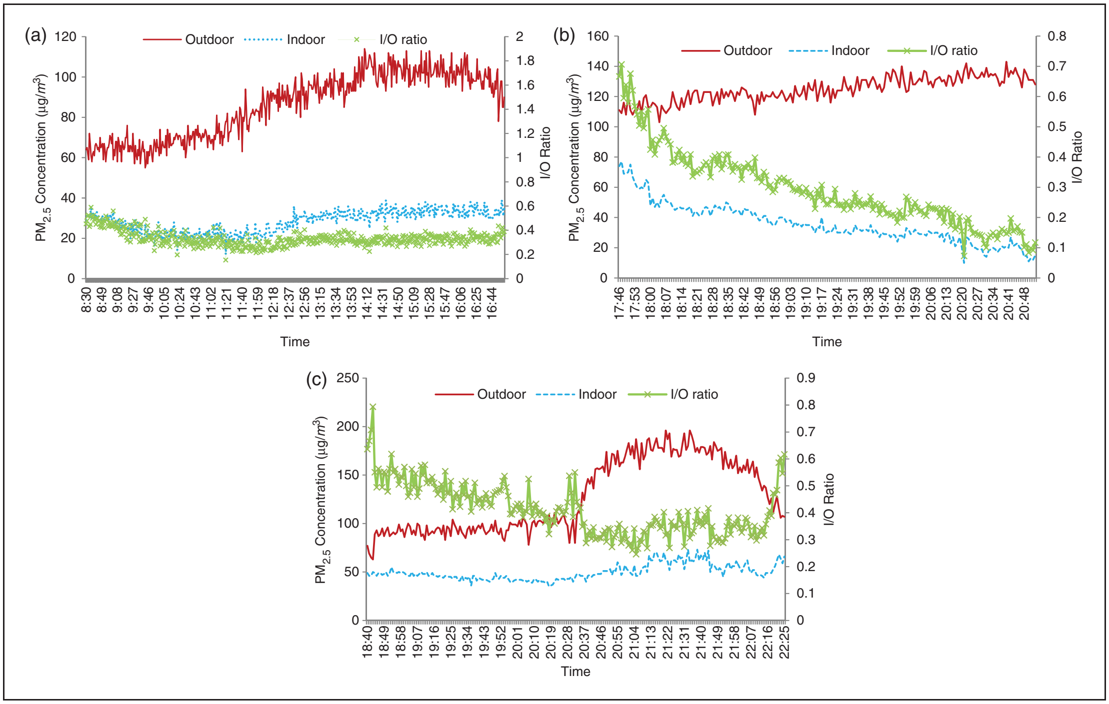

Figure 6. Indoor PM$_{2.5}$ concentrations with air purifier. (a) Indoor PM$_{2.5}$ concentrations with low circulated air volume (starting at 8:59). (b) Indoor PM$_{2.5}$ concentrations with high circulated air volume (starting at 17:46). (c) Indoor PM$_{2.5}$ concentrations with high circulated air volume (starting at 18:57).
PM: particulate matter.

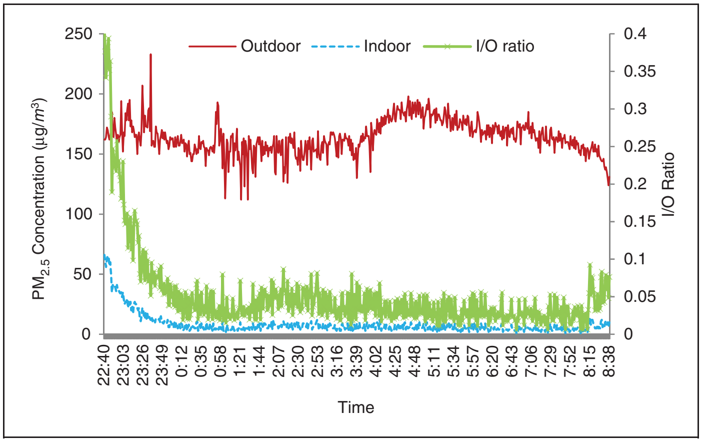

Figure 7. Indoor PM$_{2.5}$ concentrations with combination control (starting at 22:46).
PM: particulate matter.

Table 1. Summary of the above control methods.

$PM_{2.5}$ concentration control method	Grade	Figures	Valid range ($\mu g/m^3$)	Average I/O ratio	n (h^{-1})	Initial indoor $PM_{2.5}$ concentration ($\mu g/m^3$)	Average indoor $PM_{2.5}$ concentration ($\mu g/m^3$)
Airtightness improvement	/	Figure 4(c)	<=40	0.53	6.4 (n_{50})	61	82
	/	Figure 4(d)	<=40	0.52	6.4 (n_{50})	27	42
Pressure control	Low	Figure 5(a)	<=120	0.28	0.74	56	28
	Low	Figure 5(b)	<=120	0.25	0.74	19	32
	High	Figure 5(c)	<=160	0.16	0.94	46	21
Air purifier	Low	Figure 6(a)	<=80	0.33	0.69	29	28
	High	Figure 6(b)	/	0.29	1.52	74	36
	High	Figure 6(c)	/	0.41	1.52	49	50
Combination control	/	Figure 7	/	0.05	/	66	8

PM: particulate matter.

methods according to the outdoor environment. However, because a severe outdoor environment (outdoor $PM_{2.5}$ concentration is over 200 $\mu g/m^3$) rarely appears (3–5 days per year on average), the limited value for the combination control method has not been attained due to the absence of the corresponding experimental data.

Indoor $PM_{2.5}$ concentration prediction model

Due to the lack of heavy smog days in Shanghai, a theoretical model was established and validated by experimental data to further analyze the general application of these control strategies.

Model establishment

Buildings are typically ventilated with three mechanisms: mechanical ventilation, natural ventilation and infiltration. Mechanical ventilation introduces fresh air, which includes outdoor-originated particles that cannot be removed entirely by filters. Natural ventilation occurs by moving wind and buoyant-induced flow through open doors and windows. Infiltration goes through cracks and leaks of the building envelopes. All of these can result in outdoor particles entering into the indoor environment, as shown in Figure 8.

A box model of a single house was developed here, with the consideration of the building physical factors, HVAC-filter systems, air purifier application, indoor particles generation and deposition. The indoor $PM_{2.5}$ concentration model was developed mathematically by equation (1) based on the mass balance principle

$$\mathrm{V}\left(\frac{dC_i}{dt}\right) = \mathrm{p}\lambda_v VC_o + Q_nC_o - \lambda_v VC_i + Q_fC_o(1-\eta_f) - Q_rC_i\eta_r - Q_{ex}C_i + G - kC_i - Q_{ap}C_i\eta_{ap} \tag{1}$$

where V is the building volume, m^3. C_i and C_o are indoor and outdoor $PM_{2.5}$ concentration, respectively, $\mu g/m^3$. t is time, s. p is the penetration factor. λ_v is the infiltration air change rate, h^{-1}. Q_n is the airflow through natural ventilation, m^3/h. Q_f is the makeup airflow, m^3/h. η_f is the filter efficiency of the fresh air. Q_r is the recirculated airflow, m^3/h. η_r is the filter efficiency of the recirculated air. Q_{ex} is the

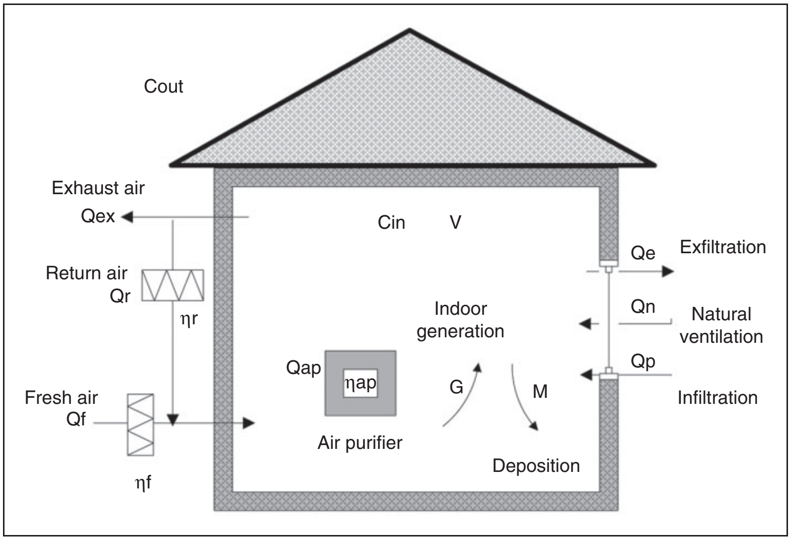

Figure 8. Transport of particles within a building.

exhausted airflow due to mechanical ventilation, m^3/h. G is the indoor particle generation rate, $\mu g/s$. k is the particle deposition loss rate coefficient, h^{-1}. Q_{ap} is the indoor recirculated air volume of the air purifier, m^3/h. η_{ap} is the filter efficiency of the air purifier.

The tested apartment is equipped with unitary air conditioners; therefore, no primary return air system has been installed. The split system was also closed during the experiment, all the windows and doors were closed, and there were no main indoor emission sources such as cigarette smoking or cooking existing during the experiment period, so $Q_n \approx 0$, $G \approx 0$. Then this equation could be reduced to equation (2)

$$\mathrm{V}\left(\frac{dC_i}{dt}\right) = \mathrm{p}\lambda_v V C_o + Q_f C_o\left(1 - \eta_f\right) - \lambda_v V C_i - kC_i - Q_{ap} C_i \eta_{ap} - Q_f C_i \tag{2}$$

In these experiments, the time step used was 1 min, corresponding to the measurement interval. Therefore, indoor $PM_{2.5}$ concentration could be calculated at each time step, taking C_i and C_o at previous time as the input parameters, which can be seen in equation (3)

$$C_i(\mathrm{t}_2) = \frac{\left\{\begin{array}{l} C_i(\mathrm{t}_1)\mathrm{V} + \mathrm{p}\lambda_v V C_o(\mathrm{t}_1) + Q_f C_o\left(1 - \eta_f\right) \\ -\lambda_v V C_i(\mathrm{t}_1) - kC_i(\mathrm{t}_1) - Q_{ap}\eta_{ap} C_i(\mathrm{t}_1) - Q_f C_i \end{array}\right\}}{\mathrm{V}} \tag{3}$$

In this equation, the infiltrate air change rate λ_v is determined on the basis of airtightness test results of the apartment introduced in section 'Airtightness improvement', which is assumed to be constant throughout the experiment, supposing that the wind and temperature differences during the experimental period are sufficiently mild. The deposition rate coefficient k is supposed to 0.09 h^{-1},[48,49] and the penetration factor p will be attained through the training of the model.

Model validation

To validate the indoor $PM_{2.5}$ concentration variation of the prediction model comprehensively, several scenarios under different control

Table 2. Descriptions of different scenarios for model validation.

Scenarios	Control method	Q_f (m^3/h)	η_f	Q_{ap} (m^3/h)	η_{ap}
1	Airtightness improvement	0	/	0	/
2	Fresh air system with high air volume	216.8	84.10%	0	/
3	Air purifier with high air circulation volume	0	/	350.24	99%
4	Fresh air system with low air volume and air purifier with high air circulation volume	170.3	84.10%	350.24	99%

methods were chosen, as shown in Table 2. The experiments of different scenarios are divided into two groups, i.e. a training group and a validating group. Scenario 1 is used to verify the indoor $PM_{2.5}$ concentration model with airtightness improvement. In the training group, the input is the outdoor and indoor $PM_{2.5}$ concentration at previous time. The output is indoor $PM_{2.5}$ concentration at the moment and the adjustable property is the penetration factor. The purpose of the model introduced in this article is to accurately describe the indoor $PM_{2.5}$ concentration variation, so that it can monitor the indoor $PM_{2.5}$ concentration exceeding the healthy value and take measures to control the concentration.

Next, the input condition changes to the outdoor $PM_{2.5}$ concentration of the verification group. The trained model is accurate if the outputs of the verification group, i.e. the indoor $PM_{2.5}$ concentration, are also consistent with the experimental data. Scenarios 2 and 3 are the pressure control and air purifier method on the premise of airtightness improvement. The training and verification process is similar to that of scenario 1. During the pressure control period, the inside air pressure usually remained positive; therefore, in this case, the infiltration portion was considered negligible compared to ventilated outdoor air, namely, the infiltration factor λ_v may be thought to be zero, which means the discussion of the penetration factor is meaningless considering the infiltration term $p\lambda_v VC_o$ in the mass balance equation. When the air purifier operates, the infiltration air change rate is assumed to be constant, and the penetration factor is adjusted to make the theoretical prediction value comparable to the actual measurement. The specific parameters are summarized in Table 2. Scenario 4 is a combination of scenarios 1–3; therefore, there was no need to train the model.

The validation results of the indoor $PM_{2.5}$ prediction model under the several scenarios are shown in Figure 9(a) to (g). Through training and validation, the variation trend of indoor $PM_{2.5}$ concentration of the prediction model of each scenario is consistent with the trend of the test results. To assess the effectiveness of the model, the calculated results of the model were evaluated using the mean error (ME) and root mean square error (RMS) indexes, which are defined in equations (4) and (5). The ME and RMS values of each scenario are summarized in Table 3, indicating that the indoor $PM_{2.5}$ concentration model is reasonable

$$\mathrm{ME} = \frac{\sum_{i=1}^{n}(C_{model,i} - C_{test,i})}{n} \tag{4}$$

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(C_{model,i} - C_{test,i})^2}{n}} \tag{5}$$

Discussion

The above results showed that the indoor $PM_{2.5}$ concentration can be maintained below 25 $\mu g/m^3$ continuously by choosing appropriate control methods. To select optimal devices and better employ these measures, the influencing factors

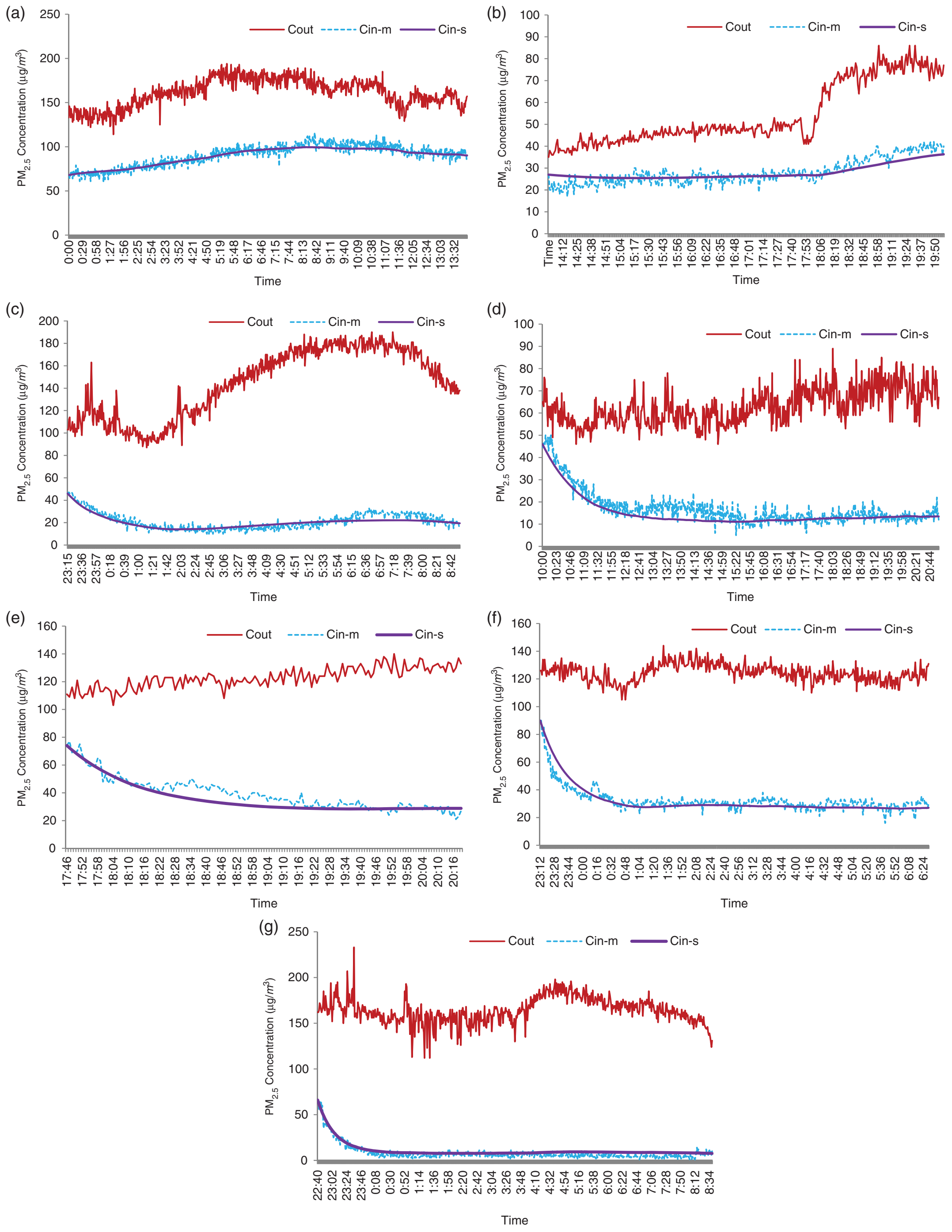

Figure 9. Typical days of the training and verification groups under different scenarios. (a) Training day of scenario 1. (b) Verification day of scenario 1. (c) Training day of scenario 2. (d) Verification day of scenario 2. (e) Training day of scenario 3. (f) Verification day of scenario 3. (g) Verification day of scenario 4.

Table 3. Accuracy of the $PM_{2.5}$ prediction model and related coefficients.

	Mean error ($\mu g/m^3$)		RMS (Root mean square error) ($\mu g/m^3$)		
Scenarios	Training group	Verification group	Training group	Verification group	*P*
1	–0.01	–0.33	4.72	3.33	0.71
2	2.00	–2.06	4.11	3.72	/
3	–0.50	–1.19	5.54	5.16	1
4	/	2.42	/	3.66	/

PM: particulate matter.

– infiltration air change rate λ_v, air volume of the fresh air Q_f and circulated air Q_{ap}, and filter efficiency of the fresh air system η_f and air purifier η_{ap} – were further analyzed depending on the indoor $PM_{2.5}$ concentration prediction model.

Infiltration air change rate λ_v

Although the infiltration air change rate λ_v would not be considered when the fresh air system operates because indoor air is pressurized relative to outdoor air, it is closely related to the required air volume of the fresh air fan to maintain a positive pressure value at approximately 5 Pa. The leakier the building is, the more airflow is necessary to induce a specific I/O pressure difference. Therefore, lower λ_v ensures lower required airflow of the pressurization fan as well as reduced energy consumption of the fan and costs.

In addition, a low infiltration factor indicates lower I/O ratio, which prevents more particles intruding indoors compared with a higher λ_v value under the same outdoor condition, so that there is no need to take active control as pressure control and air purifier when outdoor $PM_{2.5}$ concentration is relatively low.

Air volume Q

The air volume factor discussed here consists of the fresh air flow and the circulated air volume. Several scenarios for different sets of fresh air rate and recirculating air rate were chosen in order to understand their influence on indoor $PM_{2.5}$ concentration control. One data set with outdoor $PM_{2.5}$ concentration varying from 112 to 233 $\mu g/m^3$ was taken as the input to simulate indoor $PM_{2.5}$ concentration variation, as shown in Figure 10. Scenario 1 is the baseline. Scenarios 1–3 indicate the effect of different fresh air volumes while the circulation air rate is constant, and scenarios 1, 4 and 5 denote the reverse. Figure 10(a) shows the variation trends for the indoor $PM_{2.5}$ concentrations are the same in the five scenarios, and different air volumes, regardless of the fresh air system or of the air purifier, only affects the descending rate with slight discrepancy. The stable value of indoor $PM_{2.5}$ concentration is decreased by only 2 $\mu g/m^3$ although the circulation air flow increases from 350.24 to 576 m^3/h. Similarly, the influence of fresh air volume increase on the stable indoor $PM_{2.5}$ concentration is also negligible, but with a growth trend for indoor $PM_{2.5}$ concentration, which is contrary to the circulated air.

To further verify the influence of the air volume factor, an extremely severe day assuming outdoor $PM_{2.5}$ concentration is constant at 450 was chosen, as shown in Figure 10(b). Table 4 shows that the circulation air flow increasing could still maintain the indoor $PM_{2.5}$ concentration under a healthy value, and it has little influence on indoor $PM_{2.5}$ concentration, so low circulation air volume could be used to save money. However, the growth of fresh air rate put the growth of indoor $PM_{2.5}$ concentration above 25 $\mu g/m^3$. This is because some of the outdoor particles are introduced indoors when the fresh air system operates, and the more fresh air

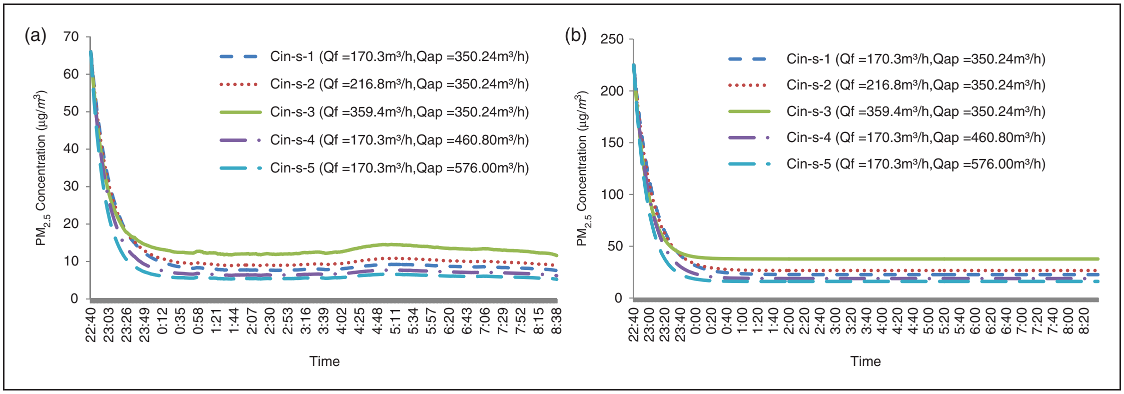

Figure 10. Indoor $PM_{2.5}$ control of different air volume groups. (a) Indoor $PM_{2.5}$ control with outdoor $PM_{2.5}$ varying from 112 to 233 μg/m^3. (b) Indoor $PM_{2.5}$ control with outdoor $PM_{2.5}$ stable at 450 μg/m^3.
PM: particulate matter.

Table 4. Specific parameters of the five scenarios with different air volumes.

							Stable value of C_i (μg/m^3)	
Scenarios	Q_f (m^3/h)	Positive pressure (Pa)	η_f	Q_{ap} (m^3/h)	Circulated n (h^{-1})	η_{ap}	C_o (112 –233)	C_o (constant at 450)
1	170.3	1	84.1%	350.24	1.52	99.0%	7.55	22.66
2	216.8	2	84.1%	350.24	1.52	99.0%	8.80	26.55
3	359.4	4	84.1%	350.24	1.52	99.0%	11.59	37.78
4	170.3	1	84.1%	460.8	2.0	99.0%	6.21	18.83
5	170.3	1	84.1%	576.0	2.5	99.0%	5.23	16.01

volume increases, the more outdoor particles are introduced. Therefore, a relatively small fresh air flow should be selected on the condition of satisfying the requirement for positive pressure control, otherwise, the higher filter efficiency (more than 84.1%) or greater circulation air volume should be chosen under adverse conditions, as either of them will increase the expenses.

Filter efficiency η

Likewise, the filter efficiency η is also composed of the filter efficiency of the fresh air system η_f and of the air purifier η_{ap}. Several scenarios with different filtration efficiency groups were selected to assess their influence on indoor $PM_{2.5}$ concentration. The two data sets of outdoor $PM_{2.5}$ concentration are taken as the inputs and are the same as the simulation in the Air volume Q section where one varies from 112 to 233 μg/m^3, and the other remains constant at 450 μg/m^3, as shown in Figure 10. Scenario 1 is the baseline. Scenarios 1–3 indicate the effect of different η_f while the filter efficiency of the air purifier is constant, and scenarios 1, 4 and 5 denote the reverse. Figure 11(a) and (b) shows that the decay trend of the five scenarios are the same, only the rate of decay shows a difference. The three curves for different η_{ap} nearly coincide, indicating that the air purifier filter efficiency has little or no impact on final indoor $PM_{2.5}$ concentration, with only a little increase along with the η_{ap} decreasing. Nevertheless, the curves for scenarios 1–3 with different η_f denote

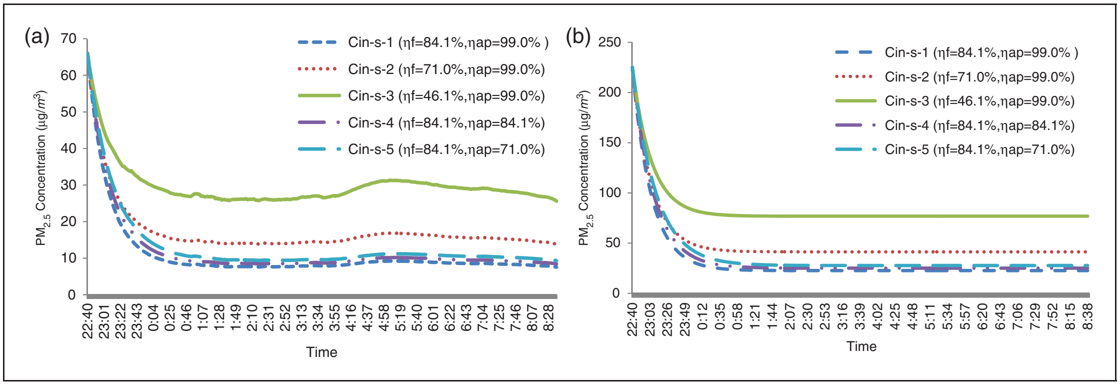

Figure 11. Indoor PM$_{2.5}$ control of different filter efficiencies. (a) Indoor PM$_{2.5}$ control with outdoor PM$_{2.5}$ varying from 112 to 233 μg/m^3. (b) Indoor PM$_{2.5}$ control with outdoor PM$_{2.5}$ stable at 450 μg/m^3.
PM: particulate matter.

Table 5. Specific parameters of the five scenarios with different filter efficiencies.

							Stable value of C_i (μg/m^3)	
Scenarios	Q_f (m^3/h)	η_f	Filter type	Q_{ap} (m^3/h)	η_{ap}	Filter type	C_o (112–233)	C_o (constant at 450)
1	170.3	84.1%	F9	350.24	99.0%	HEPA	7.55	22.66
2	170.3	71.0%	MERV14	350.24	99.0%	HEPA	13.77	41.33
3	170.3	46.1%	MERV12	350.24	99.0%	HEPA	25.59	76.81
4	170.3	84.1%	F9	350.24	84.1%	F9	8.41	25.09
5	170.3	84.1%	F9	350.24	71.0%	MERV14	9.34	27.71

HEPA: high-efficiency particle arresting; MERV: minimum efficiency reporting value.

greater differences between every two lines when the indoor PM$_{2.5}$ concentration tends to be stable, which shows that the indoor PM$_{2.5}$ concentration increases significantly with a decrease in the filter efficiency of the fresh air system. Table 5 summarizes the stable value of indoor PM$_{2.5}$ concentration under two outdoor conditions, which indicates that a high η_f should be chosen with a minimum of 71% when outdoor PM$_{2.5}$ concentration varies from 112 to 233 μg/m^3, and a minimum combination of 84.1% η_f and 99.0% η_{ap} when outdoor PM$_{2.5}$ concentration is constant at 450 μg/m^3. Obviously, if a higher η_f (larger than the minimum) is selected, the air purifier efficiency can be properly reduced.

Conclusions

The air pollution problem will continue to be a problem in many parts of developing countries. It will take a long time to improve outdoor environment governance, for example, in London and Los Angeles, where the smog problem has lasted for more than 30 years. In the near future, the primary task is to improve the indoor air quality and protect people from suffering caused by poor quality air. In this article, we investigated the influence of different indoor PM$_{2.5}$ control strategies – airtightness improvement, indoor positive pressure control with a fresh air system and an air purifier, on indoor particle concentrations within a residential building in Shanghai in China. Based on the results of both experimental measurements and modelling, we draw the following conclusions, and their implications are summarized below.

1. *Airtightness*. The infiltration air change rates of the experiment building before and after the airtightness improvement were 0.56 and 0.38, respectively. The correspondent average I/O ratio was reduced from 0.88 to 0.53, indicating the effective obstruction against outdoor particles of the airtightness improvement method. Experimental results show that the indoor $PM_{2.5}$ concentration could be kept below $25\,\mu g/m^3$ when outdoor $PM_{2.5}$ concentration was no more than $40\,\mu g/m^3$ without other measures to remove indoor particles.
2. *Positive pressure*. A small fresh air fan with two speeds (170.3 and 216.8 m^3/h) can maintain indoor air pressurization value at 1 and 2 Pa, respectively. The F9 filter with the $PM_{2.5}$ removal efficiency of 84.1%, which falls in between MERV 14 and MERV 16, was selected to clean the outdoor air before entering into indoors. The mean values of the I/O ratio of low air volume and high air flow were 0.26 and 0.16, respectively, under different outdoor conditions. The indoor $PM_{2.5}$ concentration can be retained at a healthy value with low air volume control when the outdoor $PM_{2.5}$ concentration was under $120\,\mu g/m^3$ and with high air volume control when the outdoor $PM_{2.5}$ concentration was less than $160\,\mu g/m^3$.
3. *Air purification*. Similarly, an air purifier with two different circulated air volumes (158.98 and 350.24 m^3/h) was selected to control indoor $PM_{2.5}$ concentration. The type of filter in the air cleaner was a HEPA. The average I/O ratio for the two different circulation air volumes was 0.33 and 0.35, under different outdoor conditions and the corresponding outdoor $PM_{2.5}$ limitation of the low air flow was $80\,\mu g/m^3$. Air purification alone cannot solve the indoor air $PM_{2.5}$ problem and maintain $PM_{2.5}$ under $25\,\mu g/m^3$ when outdoor pollutant levels are high.
4. Each of these control strategies alone cannot control the indoor $PM_{2.5}$ concentration below the healthy value. A combination of these control methods was investigated. The mean I/O ratio of the combination operation was 0.05, which was low enough to control indoor $PM_{2.5}$ concentration under all kinds of outdoor $PM_{2.5}$ concentrations.
5. To further verify the effectiveness of these control methods when the outdoor environment is extremely bad, a model for indoor particle concentration was developed, trained and validated to assess the influence of control strategy on indoor particle levels. The results of the modelling for the apartment indicated that the model generally performed well under most scenarios, which could be used to predict indoor $PM_{2.5}$ concentration variation under certain control policy in order to take appropriate measures to decrease indoor particles according to different outdoor conditions.
6. The influencing factors – infiltration air change rate, air volume of the fresh air and circulated air and filter efficiency of the fresh air system η_f and air purifier η_{ap} – were analyzed depending on the indoor $PM_{2.5}$ concentration prediction model. The airtightness improvement is the precondition ensuring lower air infiltration and required air volume for positive pressure control. The air volume and filter efficiency factors were evaluated under real outdoor environment that outdoor $PM_{2.5}$ concentration varying from 112 to $233\,\mu g/m^3$, and a hypothetical condition that outdoor $PM_{2.5}$ concentration remains constant at $450\,\mu g/m^3$ (which occurs in Beijing and New Delhi). The results showed that the variation of circulation air volume and fresh air flow both had little impact on indoor $PM_{2.5}$ control. However, the increase in fresh air volume could increase indoor $PM_{2.5}$ concentrations. Therefore, it is recommended that the lower fresh air rate be selected under the premise of ensuring indoor air pressurized relative to the outdoors to prevent more outdoor particles from entering

indoors. The results also indicated that the filter efficiency of the fresh air system had a great influence on indoor particle control. A minimum of 71% should be chosen when outdoor $PM_{2.5}$ concentration varies from 112 to 233 μg/m^3, and a minimum combination of 84.1% η_f and 99.0% η_{ap} when outdoor $PM_{2.5}$ concentration is constant at 450 μg/m^3. If a higher η_f (larger than the minimum) is selected, the air purifier efficiency can be properly reduced.

In general, the experimental results showed that the indoor $PM_{2.5}$ concentration can be maintained below 25 μg/m^3 continuously under different outdoor $PM_{2.5}$ concentrations by choosing appropriate control methods. The airtightness improvement is the premise for control, since it will reduce the source and the load. The two control strategies of pressure control and air purification can be used alone when outdoor $PM_{2.5}$ concentrations are not high. However, each of them has their own limitations. When outdoor $PM_{2.5}$ concentration is relatively high (usually over 200 μg/m^3), the combination control method must be used instead of the single control method to control indoor air quality. A relatively small fresh air volume should be chosen to make sure that the indoor air is kept pressurized. It is advisable that a high-efficiency filter (larger than 84.1%) for the fresh air system be selected when the outdoor $PM_{2.5}$ is higher than 100 μg/m^3. In regard to other areas with more severe pollution, a higher efficiency filter for the fresh air system should be considered.

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References

1. Brook R. You are what you breathe: evidence linking air pollution and blood pressure. *Curr Hypertens Rep* 2005; 7: 427–434.
2. Hwang BF, Chen YH, Lin YT, et al. Relationship between exposure to fine particulates and ozone and reduced lung function in children. *Environ Res* 2015; 137: 382–390.
3. Loftus C, Yost M, Sampson P, et al. Regional $PM_{2.5}$ and asthma morbidity in an agricultural community: a panel study. *Environ Res* 2015; 136: 505–512.
4. Choo C, Jalaludin J, Hamedon T, et al. Preschools' indoor air quality and respiratory health symptoms among preschoolers in Selangor. *Procedia Environ Sci* 2015; 30: 303–308.
5. Guo Y, Jia Y, Pan X, et al. The association between fine particulate air pollution and hospital emergency room visits for cardiovascular diseases in Beijing, China. *Sci Total Environ* 2009; 407: 4826–4830.
6. Li Z, Wen Q and Zhang R. Sources, health effects and control strategies of indoor fine particulate matter (PM 2.5): a review. *Sci Total Environ* 2017; 586: 610–622.
7. Jenkins P, Phillips T, Mulberg E, et al. Activity patterns of Californians: use of and proximity to indoor pollutant sources. *Atmos Environ Gen Top* 1992; 26: 2141–2148.
8. Klepeis N, Nelson W, Ott W, et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Anal Environ Epidemiol* 2001; 11: 231–252.
9. Sajani ZS, Ricciardelli I, Trentini A, et al. Spatial and indoor/outdoor gradients in urban concentrations of ultrafine particles and $PM_{2.5}$ mass and chemical components. *Atmos Environ* 2015; 103: 307–320.
10. Chatoutsidou SE, Ondráček J, Tesar O, et al. Indoor/outdoor particulate matter number and mass concentration in modern offices. *Build Environ* 2015; 92: 462–474.
11. Massey D, Masih J, Kulshrestha A, et al. Indoor/outdoor relationship of fine particles less than 2.5 μm ($PM_{2.5}$) in residential homes locations in central Indian region. *Build Environ* 2009; 44: 2037–2045.
12. Elbayoumi M, Ramli NA and Md Yusof NFF. Spatial and temporal variations in particulate matter concentrations in twelve schools environment in urban and overpopulated camps landscape. *Build Environ* 2015; 90: 157–167.
13. Cheng KC, Zheng D, Tetteh AO, et al. Personal exposure to airborne particulate matter due to residential dryer lint cleaning. *Build Environ* 2016; 98: 145–149.
14. Ji W and Zhao B. Contribution of outdoor-originating particles, indoor-emitted particles and indoor secondary organic aerosol (SOA) to residential indoor $PM_{2.5}$ concentration: a model-based estimation. *Build Environ* 2015; 90: 196–205.

15. Chen C and Zhao B. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. *Atmos Environ* 2011; 45: 275–288.
16. Zhao L, Chen C, Wang P, et al. Influence of atmospheric fine particulate matter ($PM_{2.5}$) pollution on indoor environment during winter in Beijing. *Build Environ* 2015; 87: 283–291.
17. Tung T. A methodology to investigate the particulate penetration coefficient through building shell. *Atmos Environ* 1999; 33: 881–893.
18. Chen C, Zhao B, Zhou W, et al. A methodology for predicting particle penetration factor through cracks of windows and doors for actual engineering application. *Build Environ* 2012; 47: 339–348.
19. Chao C. Penetration coefficient and deposition rate as a function of particle size in non-smoking naturally ventilated residences. *Atmos Environ* 2003; 37: 4233–4241.
20. Wang F, Meng D, Li X, et al. Indoor-outdoor relationships of $PM_{2.5}$ in four residential dwellings in winter in the Yangtze River Delta, China. *Environ Pollut* 2016; 215: 280–289.
21. Zhou Z, Liu Y, Yuan J, et al. Indoor $PM_{2.5}$ concentrations in residential buildings during a severely polluted winter: a case study in Tianjin, China. *Renew Sustain Energ Rev* 2016; 64: 372–381.
22. Li Y. A balance-point method for assessing the effect of natural ventilation on indoor particle concentrations. *Atmosp Environ* 2003; 37: 4277–4285.
23. Quang TN, He C, Morawska L, et al. Influence of ventilation and filtration on indoor particle concentrations in urban office buildings. *Atmos Environ* 2013; 79: 41–52.
24. Yu CKH, Li M, Chan V, et al. Influence of mechanical ventilation system on indoor carbon dioxide and particulate matter concentration. *Build Environ* 2014; 76: 73–80.
25. Paul T, Sree D and Aglan H. Effect of mechanically induced ventilation on the indoor air quality of building envelopes. *Energ Build* 2010; 42: 326–332.
26. Waring MS, Siegel JA and Corsi RL. Ultrafine particle removal and generation by portable air cleaners. *Atmos Environ* 2008; 42: 5003–5014.
27. Howard-Reed C. Effect of ventilation systems and air filters on decay rates of particles produced by indoor sources in an occupied townhouse. *Atmos Environ* 2003; 37: 5295–5306.
28. Pyo J, Ock Y, Jeong D, et al. Development of filter-free particle filtration unit utilizing condensational growth: with special emphasis on high-concentration of ultrafine particles. *Build Environ* 2017; 112: 200–208.
29. World Health Organization. Ambient (Outdoor) Air Quality and Health [Internet]. *World Health Organization*, http://who.int/mediacentre/factsheets/fs313/en/ (2013, accessed 15 November 2013).
30. European Union. Air Quality Standards [Internet]. *European Union*, http://ec.europa.eu/environment/air/quality/standards.htm (2013, accessed 15 November 2013).
31. Nazaroff W. Indoor particle dynamics. *Indoor Air* 2004; 14: 175–183.
32. Hui-xing L, Ran Z, Guo-hui F, et al. The test and analysis of air tightness for zero energy building in cold region. *Procedia Eng* 2016; 146: 239–243.
33. Adetunji I. Strategy for achieving low airtightness. Report, Corus Research, Development & Technology (Corus), UK, June.
34. ASHRAE. *ASHRAE handbook fundamentals: Ventilation and infiltration*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2009.
35. ASHRAE. *Ventilation for acceptable indoor air quality*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2013.
36. Sehulster L, Chinn RYW, Arduino MJ, et al. Guidelines for environmental infection control in health-care facilities. *Morbidity and Mortality Weekly Report Recommendations and Reports RR* 2003; 52: 1–42.
37. Leung M and Chan AHS. Control and management of hospital indoor air quality. *Med Sci Mon* 2006; 12: SR17–SR23.
38. Chen C, Zhao B and Yang X. Impact of two-way air flow due to temperature difference on preventing the entry of outdoor particles using indoor positive pressure control method. *J Hazard Mater* 2011; 186: 1290–1299.
39. Chen C, Zhao B and Yang X. Preventing the entry of outdoor particles with the indoor positive pressure control method: analysis of influencing factors and cost. *Build Environ* 2011; 46: 1167–1173.
40. Ministry of Environmental Protection of the China's Republic of China. *Code for design of clean room*. Beijing: Ministry of Environmental Protection of the China's Republic of China, 2013.
41. ASHRAE. *Method of testing general ventilation air-cleaning devices for removal efficiency by particle size*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2007.
42. ASHRAE. *Ventilation and acceptable indoor air quality in low-rise residential buildings*. Atlanta, GA: ASHRAE, 2016.
43. Stephens B, Brennan T and Harriman L. Selecting ventilation air filters to reduce pm2. 5 of outdoor origin response. *ASHRAE J* 2016; 58: 10.
44. United States Environmental Protection Agency. National Ambient Air Quality Standards for particulate matter [Internet]. *United States Environmental Protection Agency*, http://gpo.gov/fdsys/pkg/FR-2013-01-15/pdf/2012-30946.pdf (2013, accessed 15 January 2013).

45. Azimi P, Zhao D and Stephens B. Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin. *Atmos Environ* 2014; 98: 337–346.
46. Alfano FRd A, Dell'Isola M, Ficco G, et al. Experimental analysis of air tightness in Mediterranean buildings using the fan pressurization method. *Build Environ* 2012; 53: 16–25.
47. Chen S, Levine MD, Li H, et al. Measured air tightness performance of residential buildings in North China and its influence on district space heating energy use. *Energ Build* 2012; 51: 157–164.
48. Riley W, McKone T, Lai A, et al. Indoor particulate matter of outdoor origin: importance of size-dependent removal mechanisms. *Environ Sci Tech* 2002; 36: 200–207.
49. Liu DL and Nazaroff WW. Modeling pollutant penetration across building envelopes. *Atmos Environ* 2001; 35: 4451–4462.