Experimental and numerical analysis of indoor air quality affected by outdoor air particulate levels ($PM_{1.0}$, $PM_{2.5}$ and PM_{10}), room infiltration rate, and occupants' behaviour

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Abstract

This study conducted an experimental analysis of how Indoor Air Quality (IAQ) is influenced by the outdoor air pollutants levels, infiltration rate, and occupants' behaviours. The impacts of these factors on IAQ were analyzed using on-site measurements and numerical simulations. The results contribute to a better understanding of how to control the Indoor Particulate Level (IPL) for the specific conditions of the studied building. Results showed that occupant behaviour was the primary factor in determining the IPL, significantly changing the number of outdoor particles introduced to the building. Moreover, it was found that the IPL was exponentially correlated to the Outdoor Particulate Level (OPL). Based on numerical simulations, this study concluded that smaller particles do not always have more chance than larger particles of accessing the indoor environment through the building envelope. Meanwhile, a steady-state indoor particle concentration numerical model was established and verified using the 4-fold cross-validation method. Finally, simulation results identified that the room infiltration rate had a positive linear impact on IAQ if the OPL was under 30 μg/m^3. This is because the increased air exchange rate can help to dilute indoor air pollutants when the outdoor air is relatively clean.

Keywords: Outdoor air pollution, Indoor air quality, Infiltration, Occupant behaviour, Portable air purifier

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1 Introduction and background

The outbreak of COVID-19 poses a threat to public health worldwide. Better understating of the virus transmission could help reduce the spread of the disease. Recently, research has shown that airborne particles can carry numerous viruses on their surface, including the coronavirus, and can readily be deposited into human lungs and even the bloodstream (Bowe et al., 2021; Ehsanifar, 2021; Meo et al., 2020; Prinz & Richter, 2022; Stieb et al., 2020). Further, previous research also indicated that a higher Outdoor Particulate Level (OPL) was linked to higher morbidity and mortality (Garaga & Kota, 2018; Wu et al., 2020). Moreover, airborne particles in outdoor air pollution can enter the indoor environment through openings in building envelopes via infiltration and ventilation air, resulting in the Indoor Particulate Level (IPL) being several times higher than the OPL (Kim, 2022; Liu et al., 2020; Zong et al., 2022). Therefore, although people now spend much of their time indoors, due to the rapid urbanization and economic development in many countries, they might still suffer from the impact of outdoor origin air pollutants, which can result in increased respiratory and cardiovascular morbidity and mortality (Chen et al., 2017; EPA, 2019a; Hu et al., 2018; WHO, 2013; Yang et al., 2019; Zauli-Sajani et al., 2018). Consequently, it is essential to understand how to achieve and maintain good Indoor Air Quality (IAQ) within a healthy range in buildings.

There are two primary means of outdoor particles entering and influencing the indoor environment. Firstly, occupants' behaviour is the primary mechanism for changing the number of outdoor particles introduced into a building, which determines IAQ (Um et al., 2022). The human-building interactions, such as window opening behaviour, will significantly impact IAQ since it exposes the indoor environment directly to the outdoor physical environment. Tong et al. (2016) reported that the IPL could be around 20% higher in a naturally ventilated building than in a mechanically ventilated one. Moreover, several studies reported that occupants' ventilation behaviour showed a low correlation with the outdoor particle concentration but was, instead, mainly driven by indoor thermal comfort (Jeong et al., 2016; Langer et al., 2017; Ren et al., 2022). Therefore, it can be expected that IAQ will quickly degrade when the outdoor air deteriorates. Rotko et al. (Rotko et al., 2002) conducted a study and found that occupant has a lack of opportunity to assess the outdoor air quality. Under this circumstance, investigating to what extent human behaviours influence IAQ in homes can help to reduce residents' exposure to indoor particles. However, most of the previous studies have not focused on discussing the effect of this factor.

To date, a considerable number of existing buildings are not equipped with mechanical ventilation systems, which results in natural ventilation being the only way to supply fresh air indoors. However, using unfiltered natural ventilation for areas with high outdoor pollution could increase the risks of people being exposed to air pollutants. For those buildings with no mechanical ventilation system, a portable air purifier (PAP) is an effective technology that can dilute indoor air pollutants and supply clean air to the indoor environment. In addition, most of the literature has studied the influence of air filters on particles, and all of them reported a varied capture rate of the same filter regarding particles of different sizes (Ben-David et al., 2018; Feng et al., 2020; Fu et al., 2021b; Ruan & Rim, 2019; Stephens, 2018). Moreover, previous studies also explored that the PAP could substantially reduce the indoor $PM_{2.5}$ level (Cooper et al., 2021; Shao et al., 2017). However, how people use the PAP and the extent to which the PAP can influence the indoor particle level have not been well studied. Pei et al. (2019) conducted a study within 43 residential buildings in China and found that the majority of occupants will not use the PAP even if it is provided. Further, only around 19% of the family will use the PAP, but they were only operating for 1 to 4 hours each day, and they reported that this pattern of using the PAP could not maintain a healthy indoor $PM_{2.5}$ level. Cooper et al. (2021) concluded that the PAP could sufficiently maintain the indoor $PM_{2.5}$ level in a residential building, which can reduce around 45% average after 90 mins operated. However, there is little to explain how a commercial PAP could influence indoor particle concentration in a naturally ventilated office building under different outdoor conditions.

Secondly, outdoor particles can enter a building through envelope cracks or ventilation system leakages with infiltrating air. As one of the critical impact factors, infiltrating air can significantly degrade IAQ by bringing outdoor air pollutants indoors if the outdoor air is contaminated (Fu et al., 2021a; Hu et al., 2020; Li et al., 2019; Liang et al., 2021; Nazaroff, 2021). Previous research has shown that fine and ultra-fine particles are more likely to enter the indoor environment through the building envelope with the infiltrating air than coarse particles, due to their smaller size (Li et al., 2017; Liu & Nazaroff, 2003; Wang, 2013). This is because the particle size substantially impacts the penetration factor, which presents the fraction of particles in the infiltration air that passes through the building envelope. Due to the impact of the particle size, the passing rate of particles through the windows and doors is varied. Furthermore, the deposition rate as one of the loss mechanisms for the indoor particles also affects the IPL, and its value is highly correlated to the particle size (Ben-David & Waring, 2016; Chen et al., 2012; Li et al., 2017). Thus, the impact of outdoor particles on IAQ evidently corresponds to the particle size. However, little information is available for comparing the different sizes of particles' impact on IAQ in a building under different outdoor conditions.

It is under such circumstances that the studies in this paper were inspired. Hence, this study selected three sizes of particles as the target - $PM_{1.0}$ (particle size less than 1.0 μm), $PM_{2.5}$ (particle size less than 2.5 μm), and PM_{10} (particle size less than 10 μm). The purpose of this study was to investigate to what extent the outdoor air pollutant levels, room infiltration rates, and human-building interactions impacted on IAQ under natural conditions and to examine the significance of using a PAP in reducing residents' exposure to indoor particles. The results contribute to a better understanding of how the outdoor particles and occupants' behaviours impact IAQ in buildings. To this end, three research questions were defined:

(1) How does occupants' behaviour, such as opening doors and windows for natural ventilation and installing an air purifier, influence indoor air quality?
(2) How do air infiltration rates, outdoor air pollution levels, and particle sizes affect IAQ?
(3) By using comparative analysis between experimental and numerical investigations, how do outdoor air pollution levels and occupants' behaviour impact on IAQ for a real case study building in China?

2 Methodology

The methodologies for experimental and numerical analysis of indoor air quality are affected by outdoor air pollutant levels ($PM_{1.0}$, $PM_{2.5,}$ and PM_{10}), room infiltration, and occupants' behaviour can be divided into four steps: 1) Test the airtightness of the selected room by using a blower door; 2) Do on-site measurements of indoor and outdoor concentrations of PM with different specific conditions; 3) Develop numerical models based on collected data to assess the fluctuation of the IPL; 4) Validate the numerical model using the cross-validation method.

2.1 Descriptions of the measured building

A test room was created in the case study building that was located in Suzhou, Jiangsu Province, China. The building is naturally ventilated and is 12 stories, approximately 63 metres high, and the tested room was located on the 3rd floor of the building at a height above ground level of 10.4 m. The selected building is north-south oriented, and the tested room was in the north part of the building. Details of the test room and building are presented in Figure 1. The selected building is located on a relatively open site, surrounded by a pedestrianized area and a vehicular road.

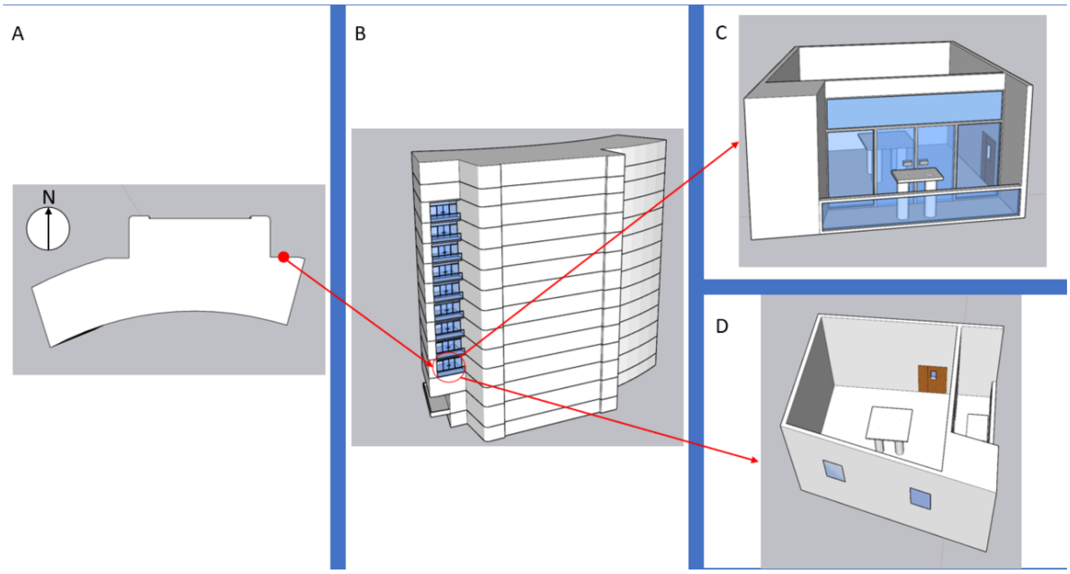

Figure 1 : The test room and selected building

2.2 Blower door test

In this study, the blower door test method was used to access the airtightness measurements of the building envelope. The airtightness measurements for the selected room were performed in strict accordance with the standard EN 13829 (CEN, 2001). The Retrotec 5000 test system was utilized in this test method, as shown in Figure 2. The adopted test system consisted of three parts: a cloth panel for sealing the opening and setting up the instruments, the Model 5000 fan, which is capable of moving air into or out of the zone at required airflow rates (the flow accuracy is ± 5%), and a 32-DM digital manometer control device for setting the fan.

Ten airtightness measurements for the selected room have been done to minimize the error, and all of the tests show high agreement. The results are presented in Table 1. According to the ASHRAE Handbook (ASHRAE, 2017), the air infiltration rate is calculated based on the pressure differential method and can be described as:

$$\lambda_i = \frac{3600}{V} \times c \times (\Delta p)^n \tag{1}$$

where λ_i is the air change rate attributed to the infiltration rate in h^{-1}, and V is the volume of the tested room in m^3. Then, the average value was calculated for the exponent n and the airflow coefficient, c, in $m^3/(s \cdot Pa^n)$. The equation was shown in Equation (2):

$$\lambda_i = 0.146 \times (\Delta p)^{0.5966} \tag{2}$$

Figure 3 shows the relationship between the tested room air infiltration rate and the pressure differential. Because the wind direction and wind speed in the outdoor environment are changing rapidly, the wind-effect induced pressure differential is hard to measure. Thus, this study aimed to investigate how significant the impact of the wind-induced pressure differential was on estimating the IPL. Hence, the stack-effect induced pressure differential and the total pressure differential were considered separately.

Figure 2: The blower door test system

Table 1：Airtightness test results

Air flow coefficient ($m^3/(h*Pa^n)$)	Air change rate at 50 Pa (h^{-1})	ELA at 50Pa (cm^2)	ELA per envelope area at 50Pa (cm^2/m^2)	Slope, n
24.83	8.30	25.28	2.14	0.5966

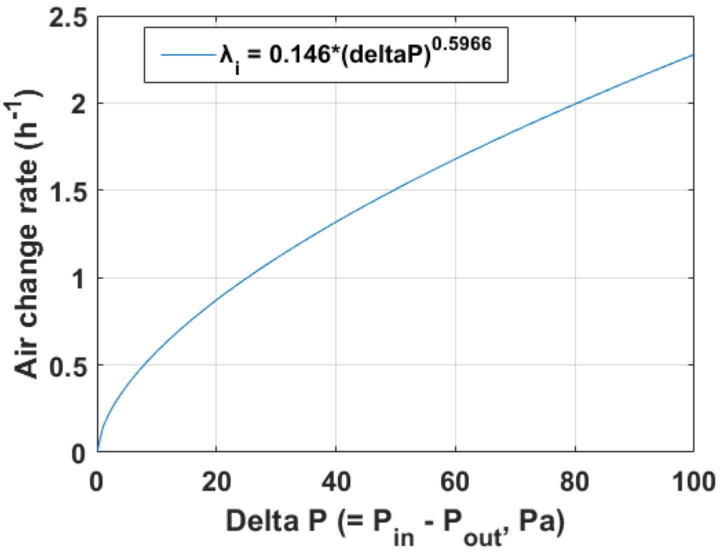

Figure 3: Measured air infiltration rate of the tested room

2.3 Experiment design

The experiments were conducted between 15th January and 21st January 2022. The test room is trapezoidal and is controlled by a centralized ventilation system. During the experiment, the doors and ventilation system were kept closed, and a heating system was used to control the indoor air temperature, which aimed to simulate different temperature differences between indoors and outdoors. In addition, five different scenarios were set for experimental analysis to achieve the purpose of the study, as shown below list, and Table 2 summarizes all the experiments.

(1) Experiment 1: All room openings were kept closed during the experiment, including an inner door, outer door, and two windows. A manometer was used to measure the pressure differential in the experiment, as shown in Figure 4 (E). The tube connected between the outdoor environment and the manometer was perpendicular to the window.

(2) Experiment 2: The inner door was opened during the experiment, while the other two openings were kept closed. An anemometer was used to measure the air velocity through the opening. The anemometer was set at the middle point of the opening and is perpendicular to it, as shown in Figure 4 (B).

(3) Experiment 3: One of the windows was opened during the experiment, while the other two openings were kept closed. The anemometer was used to measure the air velocity through the opening, and the setting up method is the same as experiment 2, as shown in Figure 4 (D).

(4) Experiment 4: The outer door was opened during the experiment, while the other two openings were kept closed. The anemometer was used to measure the air velocity through the opening, and the setting up method is the same as experiment 2, as shown in Figure 4 (C).

(5) Experiment 5: An air purifier was set in the middle of the room to dilute indoor air pollutants. During the experiment, a PAP was set at the maximum power, gave a Clean Air Delivery Rate (CADR) of 230 m^3/h. Further, the PAP was equipped with a HEPA13 filter, which has a 99.9% removal efficiency for $PM_{1.0}$, $PM_{2.5}$, and PM_{10}.

The purpose of Experiment 1 was to explore the impact of outdoor air pollution levels on IAQ under natural conditions. The results of this experiment can be used as the benchmark for the follow-up comparative study and also answer research question 2 listed above. Experiments 2, 3, 4, and 5 aimed to investigate the effect of the inner door, windows, outer door, and PAP on IAQ. Comparing Experiment 2 with Experiment 4, the influence of different outdoor conditions on IAQ could be determined. Moreover, the results, based on comparing Experiments 3 with 4, indicated the impact of the conducted area between indoors and outdoors on IAQ. The Experiment 5 results illustrated how IAQ is affected by the PAP. The results of Experiments 2, 3, 4, and 5 could answer research question 1.

For all experiments, samples were collected indoors and outdoors simultaneously. Then, each experiment was conducted for 90 minutes. Each instrument will be calibrated before every experiment. Then, the calibrated instruments were placed on the middle table, as shown in Figure 4 (A), which is around 0.9 m above the floor level. The instruments were set to collect data every 10 s, and the record data were the mean values of every minute.

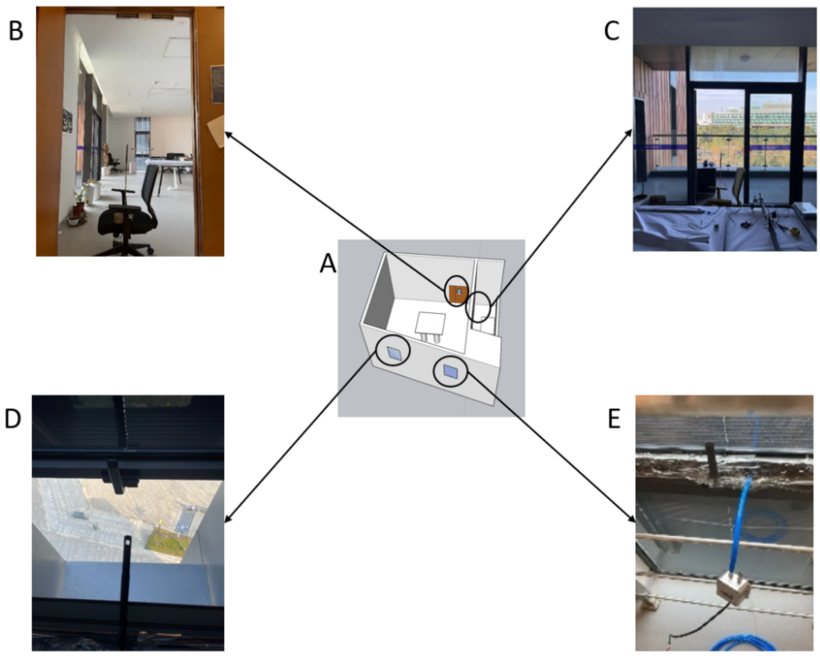

Figure 4: The detailed information regarding the setup of experiments. Picture A shows the layout of the tested room. Pictures B, C, D, and E present the status of each opening during different scenarios.

Table 2: The setup of the experiments

Exp.	Inner door	Outer door	Windows	Air purifier
1	-	-	-	-
2	+	-	-	-
3	-	-	+	-
4	-	+	-	-
5	-	-	-	+

1. '-' means the component was kept closed during the experiment
2. '+' means the component was kept open during the experiment

2.4 Instrumentation

The TSI Model 8534 DustTrak Aerosol Monitor (TSI incorporated USA) was used to measure $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations. It is a handheld instrument that uses the 90° light scattering technique, in which the amount of scattered light is proportional to the volume concentration of an aerosol. This instrument has been used to measure atmospheric particles in several widely accepted papers (Liu et al., 2018; Wu et al., 2002). Moreover, the instrument was calibrated for Arizona Test Dust by the manufacturer and recalibrated before the on-site measurement. The TSI Model 7575 Q-Trak Indoor Air Quality Monitor (TSI incorporated USA) measures CO_2 concentrations. This handheld instrument has been used successfully in a recent outdoor CO_2 concentration measurement (Kim & Choi, 2019). Table 3 presents detailed information on the manufacturer-reported detection range, accuracy, and resolution for the testing instruments used in this study.

Table 3: Manufacturer-reported detection range, accuracy, and resolution for testing instruments in this study

Parameter	Instrument	Range	Accuracy	Resolution
CO_2	TSI Model 7575 Q-Trak Indoor	0 to 5000 ppm	±3% of reading	1 ppm
$PM_{1.0}$	TSI Model 8534 DustTrak	-	1 μg/m^3 or ±0.1% of the reading	0.1 to 15 μm
$PM_{2.5}$				
PM_{10}				
Air temperature	Testo 635-2	-60 – 400 ℃	0.1 ℃ or ±0.3 ℃ of reading	0.1 ℃
Air velocity	Testo 440	0 – 30 m/s	0.03 m/s ± 4% observed value	0.01 m/s
Pressure differential	Vadias QDF70A-VD-S	± 100 Pa	0.5% FS	0.1 Pa

2.5 Mass balance model of indoor particles

Over time, the change in indoor PM concentration levels can be modelled as a function that mainly depends on source terms (S_i) and loss terms (L_i) and can be represented by Equation(3) (Ben-David & Waring, 2016; Fu et al., 2021a, 2021b; Kim & Choi, 2019; Liu et al., 2021; Serfozo et al., 2014).

$$\frac{dC_i}{dt} = S_i - L_i \times C_i \tag{3}$$

where C_i is the indoor pollutant concentration in μg/m^3. As the tested room is an office room, thus this study assumed that there were no indoor particle emission sources (EPA, 2019b), and the particle concentration in the room was uniform (Huang et al., 2017). Equation (4) represents the dynamic solution of the mass balance equation that describes the indoor particle concentration (Diapouli et al., 2013; Quang et al., 2013; Ruan & Rim, 2019; Yu et al., 2014).

$$\mathrm{PM}_{in,t_k} = PM_{in,t_{k-1}} \times e^{-L(t_k - t_{k-1})} + (\frac{S}{L} - \frac{S}{L} \times e^{-L(t_k - t_{k-1})}) \tag{4}$$

where, PM_{in,t_k} is the concentration of the indoor PM concentration at time k in μg/m^3, S is the source term, L is the loss term, and t_k is the ventilation system's operation time. For the source term, the origin of $PM_{2.5}$ in the indoor environment is the outdoor air coming through the ventilation system or penetrating through building cracks and wall cavities in a mechanically ventilated building (Liu & Nazaroff, 2001; Morawska et al., 2017; Shi & Li, 2018b). However, there was no ventilation system in the tested building, and all openings were kept closed during the experiment, which means the particles penetrated the building with the infiltrating air was the only source of the indoor particles. Moreover, compared to the deposition rate, the particle resuspension rate induced by indoor human activities was weak enough to be neglected (Shi & Li, 2018a), so the source term can be expressed as Equation (5). In addition, if there is an air purifier, the source term of indoor particles can be rewritten as Equation (6).

$$\mathrm{S} = C_{out} \times p \times \lambda_i \tag{5}$$

$$\mathrm{S} = C_{out} \times p \times \lambda_i + C_{in} \times \frac{CADR}{V} \tag{6}$$

where C_{in} and C_{out} are the indoor and outdoor particle concentrations in μg/m^3, p is the penetration rate of particles, with values set to 0.95, 0.85, 0.76 for $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, respectively (Chen et al., 2012; Liu & Nazaroff, 2001), λ_i is the air change rates attributed to the air infiltration rate, the Clean Air Delivery Rate (CADR) is in m^3/h, and V is the volume of the tested room in m^3. Furthermore, the loss terms contain the air pollutant removal mechanisms by ventilation and deposition onto indoor surfaces, while only the room infiltration was considered. Hence, the loss term can be expressed as Equation (7), and the equation can be rewritten as Equation (8) if considering the air purifier.

$$\mathrm{L} = \lambda_i + \beta \tag{7}$$

$$\mathrm{L} = \lambda_i + \beta + \frac{CADR}{V} \tag{8}$$

Where β is the deposition rate, which is 0.1, 0.17, 0.29 h^{-1} for $PM_{1.0}$, $PM_{2.5}$, PM_{10}, respectively (Chen et al., 2012; He et al., 2005).

3 Results and discussion

3.1 The impact of occupants' behaviour on the indoor particle level

Based on the data analysis, the results indicated that human behaviour impacted notably on the IPL, as presented in Figure 5, Figure 6, and Figure 7. The results showed high agreement with recent studies (Ahmed et al., 2021; Cooper et al., 2021; Luo et al., 2019; Um et al., 2022). It can be seen that the number of outdoor particles introduced into the building rapidly increases if unfiltered natural ventilation is used.

From Figures 5 to 7, it can be seen that opening the outer door could create a substantially degraded indoor environment, followed by opening the inner door and window. This indicates that the outdoor pollution rate and the contact area between the indoors and outdoors are directly proportional to the concentration of the indoor particles. The human-building interaction had the most significant influence on indoor PM_{10} levels, followed by $PM_{2.5}$ and $PM_{1.0}$. Accordingly, the larger particle finds it easier to enter indoors with the airflow through the openings of the building, and this is why the Indoor/Outdoor (I/O) concentration ratio of coarse particles always rises over one during the experiment.

Moreover, experiment 5 illustrated that PAP used indoors could effectively reduce the risk of occupants' exposure to indoor particles. The present study showed that $PM_{1.0}$, $PM_{2.5}$, and PM_{10} levels were reduced by a mean of 86%, 81%, and 70%, respectively, over 90 minutes with PAP use. Based on the results, the air purifier's particle removal efficiency decreases as the particle size increases. Hence, human-building interactions, such as opening the outer door, could efficiently degrade IAQ, regardless of how high the OPL (Um et al., 2022). In addition, it is highly recommended to use PAP properly indoors if outdoor air is contaminated (Cooper et al., 2021; Shi & Li, 2018a).

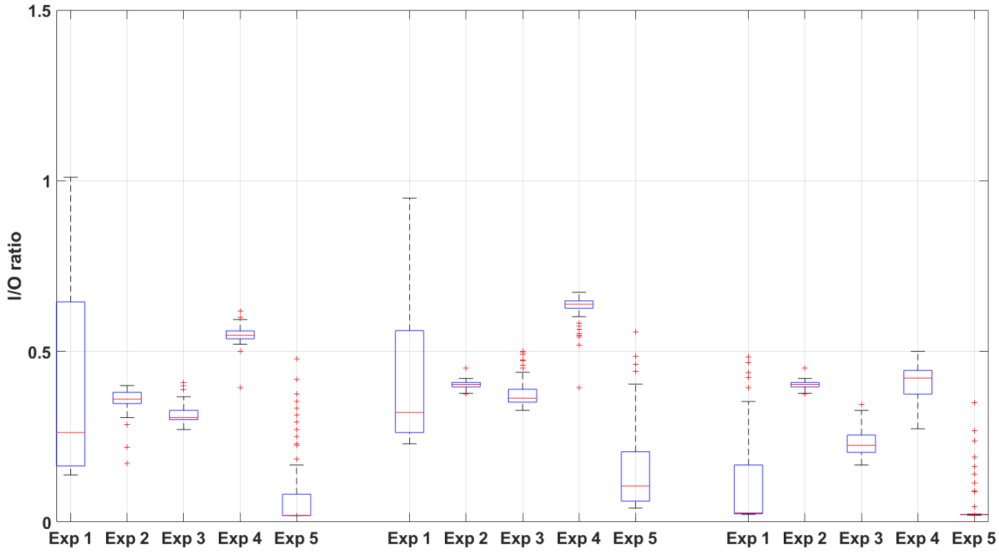

Figure 5: The value range of $PM_{1.0}$'s I/O ratio for five designed experiments (The five horizontal lines for each box in order from top to bottom: maximum value, 3rd quartile, median, 1st quartile, minimum value)

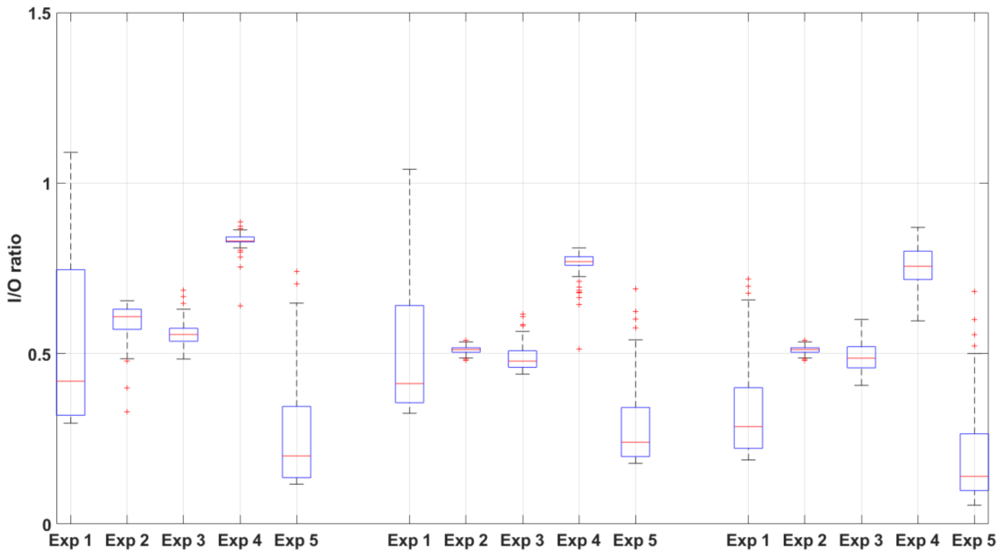

Figure 6: The value range of $PM_{2.5}$'s I/O ratio for five designed experiments

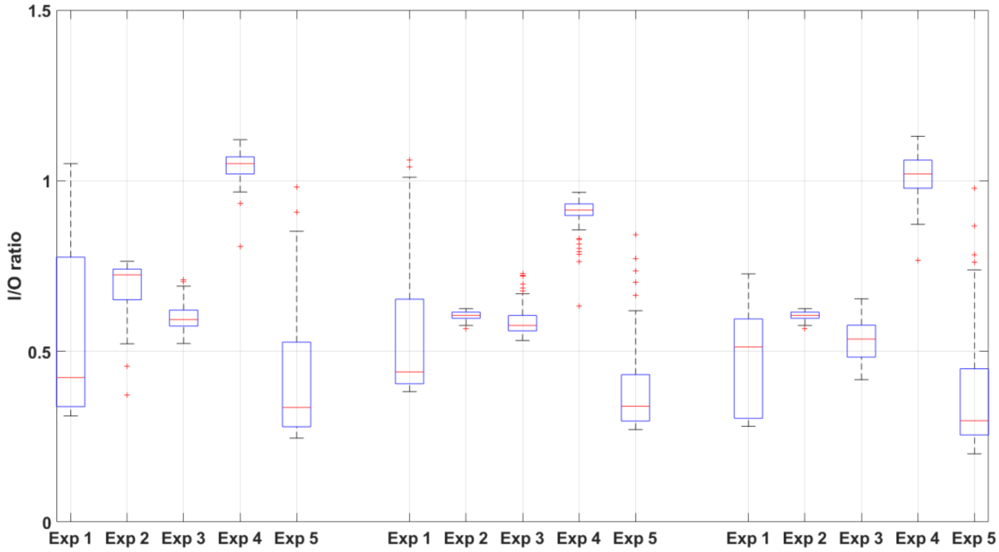

Figure 7: The value range of PM_{10}'s I/O ratio for five designed experiments

3.2 The impact of outdoor particles on indoor air quality

The wind direction and speed in the outdoor environment vary with time, which results in a challenge in measuring real-time wind-effect induced pressure differentials. Further, the IPL is highly correlated with room infiltration rate, and thus the inaccuracy of room infiltration would cause an error in estimating the IPL. Hence, a comparison study was conducted that used the total pressure differential, tested by the manometer, and the stack-induced pressure differential measured based on the temperature differential to examine the extent of the impact of the wind-induced pressure differential on IAQ. Figure 8 presents the variation of the pressure differences between indoors and outdoors during the experiments regarding the two methods. Then, the comparison results of measured and estimated indoor particles levels are shown in Figure 9, Figure 10, and Figure 11.

The figures indicate that the indoor particle variation trend had meshed well with the mass balance model when the indoor wind environment was steady, but this phenomenon is not evident if the OPL is low. Compared to the larger size particle, the measured indoor $PM_{1.0}$ level is lower than the estimated value, which proves that the real impact of the outdoor $PM_{1.0}$ is lower than the estimated one. Moreover, the measured indoor PM_{10} level is close to the estimated value if no occupant behaviour impacts exist. However, the measured indoor PM_{10} level is significantly higher than the estimated one if the impacts of human behaviours are considered. In other words, it was found that PM_{10} is much easier to introduce indoors with airflow than smaller particles.

In addition, the measured indoor $PM_{2.5}$ level has meshed well with the stack and wind effect based estimated value compared to the other two particles, which means that the indoor $PM_{2.5}$ level is significantly correlated with the pressure differential. For a closed space with no emission sources, the outdoor particles that enter the indoor environment by infiltrating air through the building envelope are the primary sources of the indoor particles. Further, the infiltrating air is caused by the pressure differential. Hence, in theory, the indoor particle variation trend should follow the fluctuation of the pressure difference between indoors and outdoors. However, from Figures 8 to 11, the results present that the infiltration rate has no evident impact on the short-period IPL.

In summary, the smaller particles have less chance to impact IAQ than the expected when indoor environment is stable. When considering the impact of human-building interaction, the indoor particles level with a larger size was notably higher than the estimated value. Moreover, the removal efficiency of the used PAP is higher for the smaller size than the larger particles.

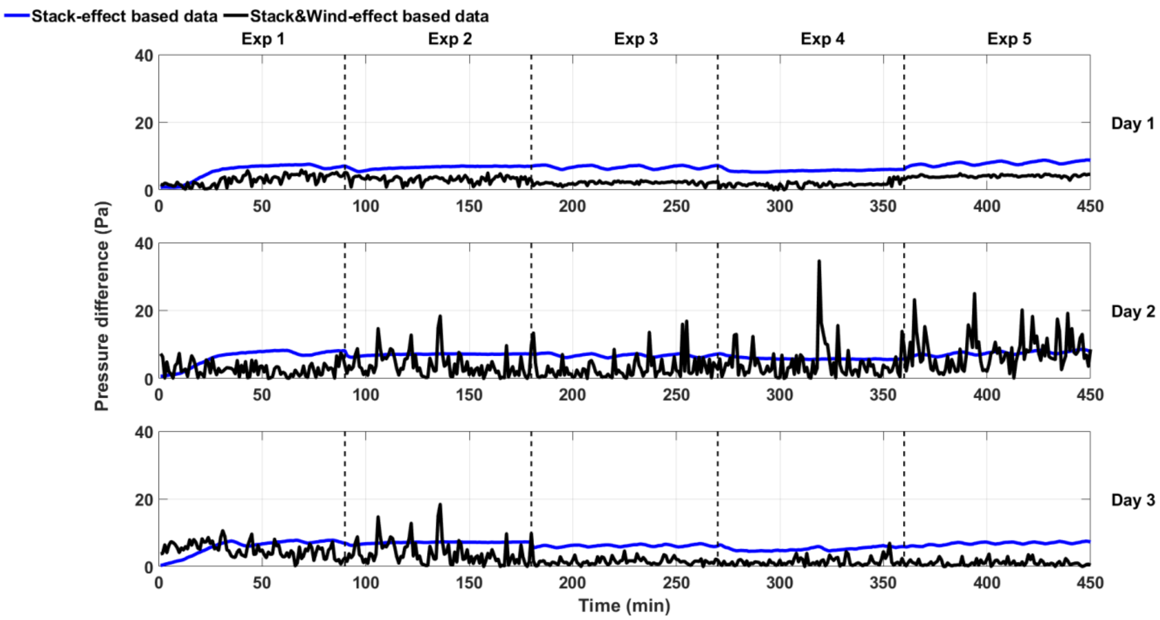

Figure 8: Comparison of the total pressure differential tested by manometer and the stack-induced pressure differential based on the temperature difference

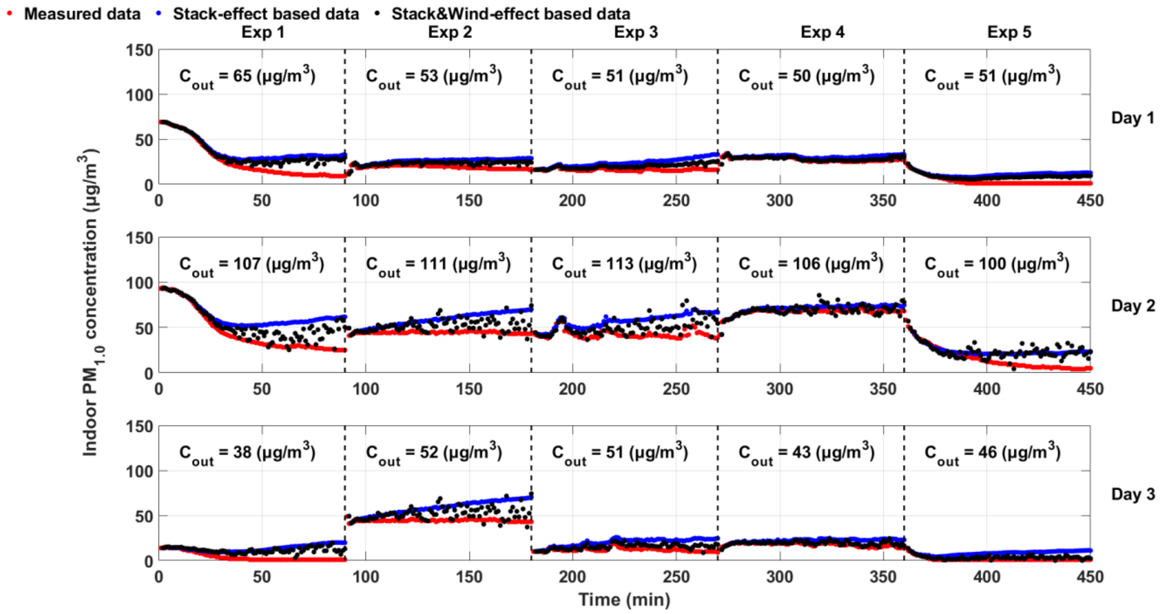

Figure 9: Comparison of measured and estimated indoor $PM_{1.0}$ level (the red curve represents the real-time measured IPL, the blue and black curve represents the estimated IPL based on the stack-induced pressure differential and the total pressure differential)

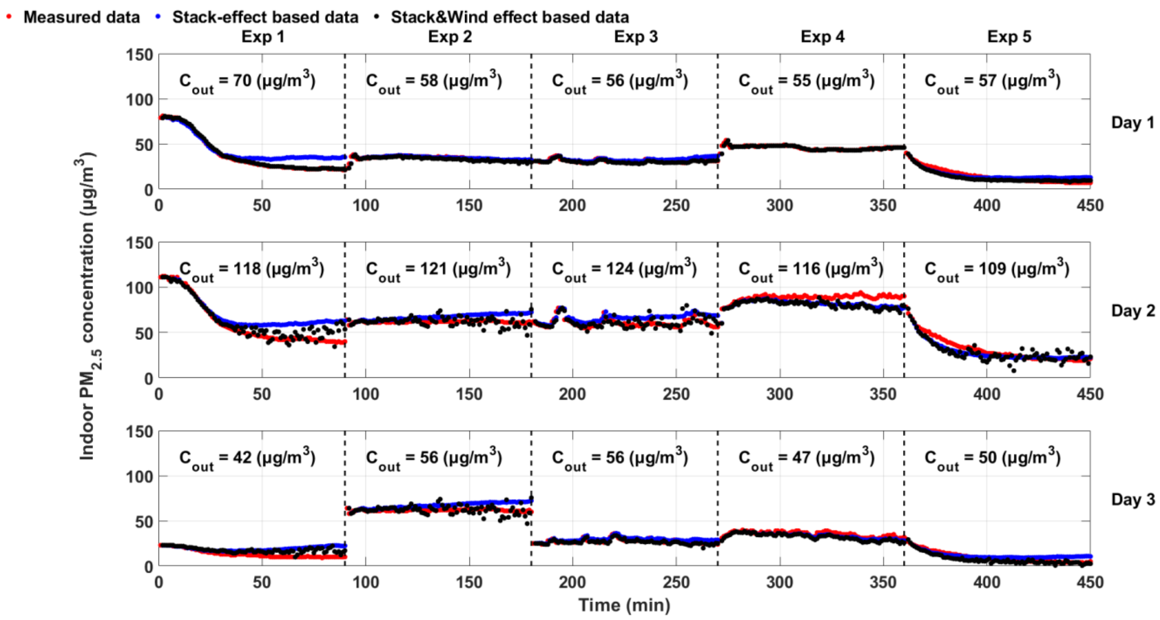

Figure 10: Comparison of measured and estimated indoor $PM_{2.5}$ level (the red curve represents the real-time measured IPL, the blue and black curve represents the estimated IPL based on the stack-induced pressure differential and the total pressure differential)

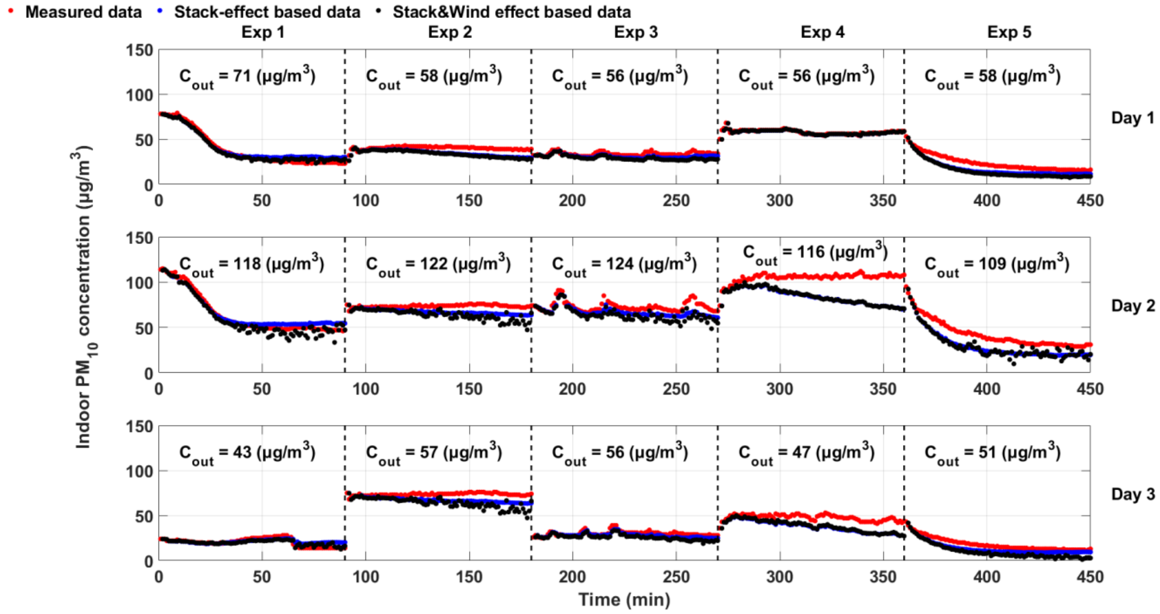

Figure 11: Comparison of measured and estimated indoor PM_{10} level (the red curve represents the real-time measured IPL, the blue and black curve represents the estimated IPL based on the stack-induced pressure differential and the total pressure differential)

3.2.1 The accuracy analysis of two estimation methods

In order to investigate the level impact of the wind-effect induced pressure differential on estimating the IPL, the stack-effect induced pressure differential and the total pressure differential were considered separately. A comparison of the accuracy of two estimate methods regarding different particle sizes is presented in Figure 12, Figure 13, and Figure 14.

It can be seen that the total pressure differential based estimate of IPL is closer to the measured data compared to the stack effect based method, which indicates that the wind effect cannot be ignored when assessing the short-period indoor particle concentration. Based on the analysis, the pressure difference based method is more accurate in estimating the larger particle's indoor level. From Table 4, the chance of the outdoor particles entering the indoor environment is less than the expected value if there is no other factor impact on IAQ in a closed space. Moreover, the use of the air purifier would significantly impact the accuracy of the estimated results, and the estimated error would be increased if the outdoor air was relatively clean. Hence, it is suggested that the wind-effect induced pressure differential should be considered when predicting the real-time IPL.

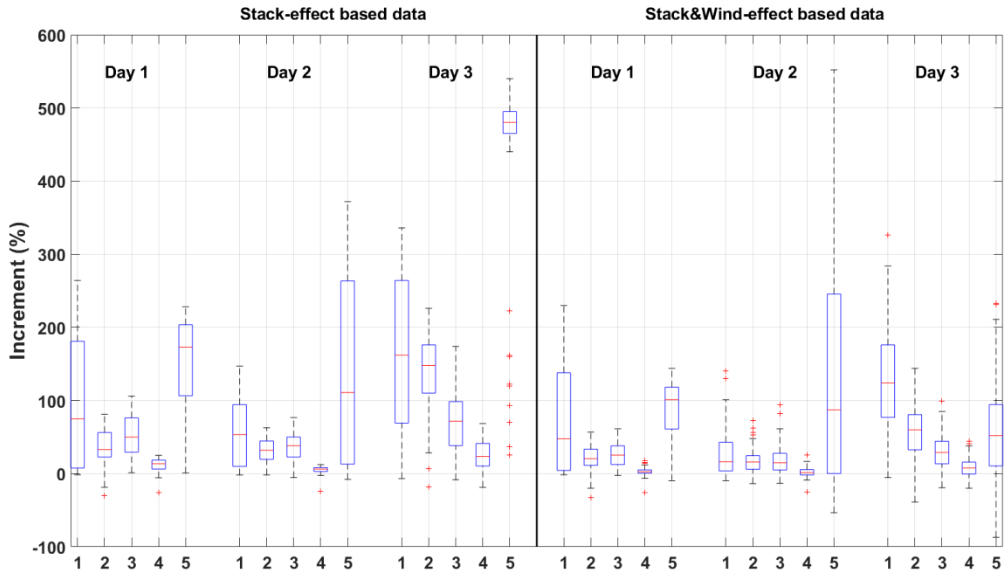

Figure 12: Comparison of the accuracy of two estimate methods regarding indoor $PM_{1.0}$ level. (The $Increment\ (\%) = \frac{Estimated\ indoor\ particle\ level - Measured\ indoor\ particle\ level}{Measured\ indoor\ particle\ level} \times 100$)

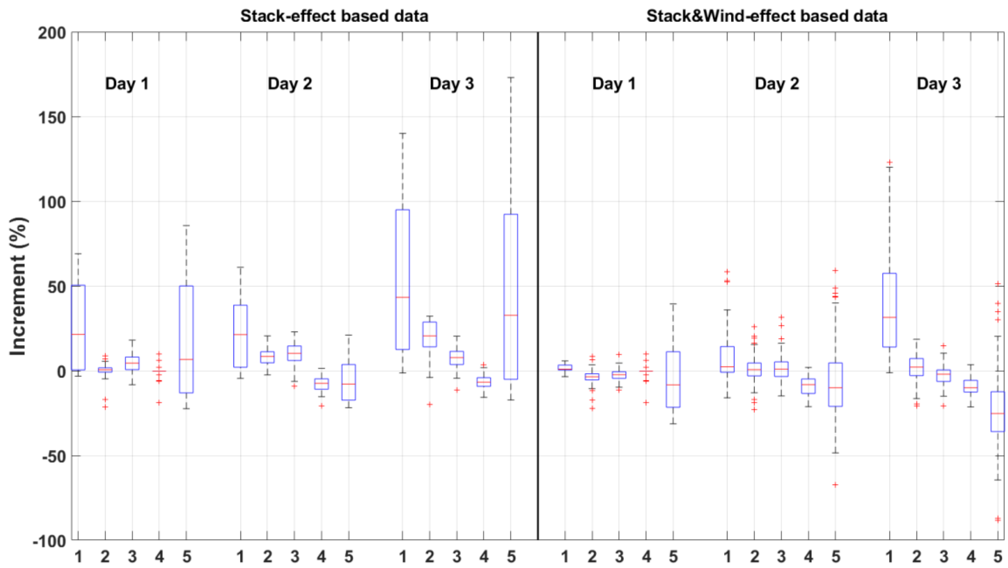

Figure 13: Comparison of the accuracy of two estimate methods regarding indoor $PM_{2.5}$ level. (The $Increment\ (\%) = \frac{Estimated\ indoor\ particle\ level - Measured\ indoor\ particle\ level}{Measured\ indoor\ particle\ level} \times 100$)

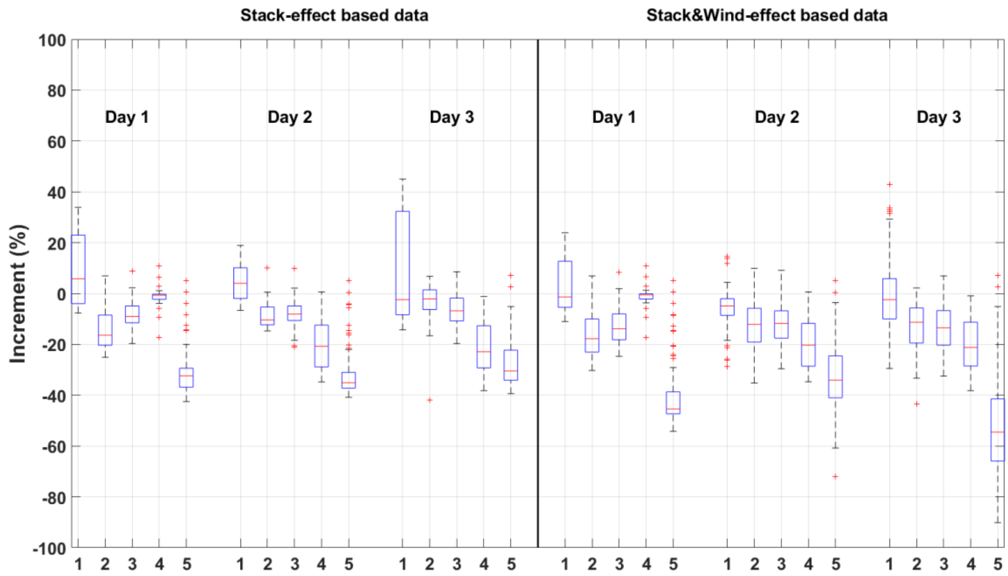

Figure 14: Comparison of the accuracy of two estimate methods regarding indoor PM_{10} level. (The $Increment\ (\%) = \frac{Estimated\ indoor\ particle\ level - Measured\ indoor\ particle\ level}{Measured\ indoor\ particle\ level} \times 100$)

Table 4: The average estimated error of two pressure differential based methods regarding three particles sizes

	$PM_{1.0}$		$PM_{2.5}$		PM_{10}	
	Stack	Stack&Wind	Stack	Stack&Wind	Stack	Stack&Wind
Exp. 1	156%	107%	56%	23%	23%	7%
Exp. 2	69%	42%	10%	-0.4%	-9%	-14%
Exp. 3	53%	25%	8%	-1%	-8%	-13%
Exp. 4	15%	5%	-5%	-6%	-14%	-14%
Exp. 5	267%	102%	29%	-9%	-33%	-41%

3.3 The numerical model for estimating steady-state indoor particle level

In section 3.2, the dynamic impacts of outdoor air pollution and air infiltration rate were analyzed. For the purpose of conducting a quantitative analysis of the influence of outdoor air pollution and infiltration rate on IAQ, the IPL numerical model was constructed for all three particles based on the measured indoor and outdoor particle concentrations and real-time air infiltration rate. The numerical model is shown below:

PM$_{1.0}$: $C_{in} = 16.11 - 4.275 \times \lambda_i - 0.4632 \times C_{out} + 0.1706 \times \lambda_i \times C_{out} + 0.005672 \times C_{out}^2$

PM$_{2.5}$: $C_{in} = 22.56 - 19.76 \times \lambda_i - 0.5694 \times C_{out} + 0.6906 \times \lambda_i \times C_{out} + 0.005724 \times C_{out}^2$

PM$_{10}$: $C_{in} = 28.42 - 9.799 \times \lambda_i - 0.4864 \times C_{out} + 0.3548 \times \lambda_i \times C_{out} + 0.005253 \times C_{out}^2$

According to Figures 15 to 17, the fitted model's coefficient of determination (R^2) regarding +three different particles was around 0.97, which indicates the numerical model had meshed well with the measured data. It can be seen that several discrete points caused the error of the fitted model. After analysis of the input data, the discrete data are concentrated at the early stage of the experiment. This is because the pressure differential between indoors and outdoors is varied at the beginning of the experiment and causes the rapid fluctuation of the IPL. Moreover, the 4-fold Cross-Validation was used to verify the fitted numerical model.

It was found from the fitted model that the increased infiltration rate has the most significant impact on indoor PM$_{2.5}$ level, and the outdoor pollution level has an evident influence on indoor PM$_{10}$ level. Compared to the larger particles, the indoor PM$_{1.0}$ level was less affected by the outdoor pollution rate and room infiltration. In addition, if outdoor air is contaminated and the airtightness of the building is poor, then the occupants are more susceptible to indoor PM$_{2.5}$ than other sizes of particles.

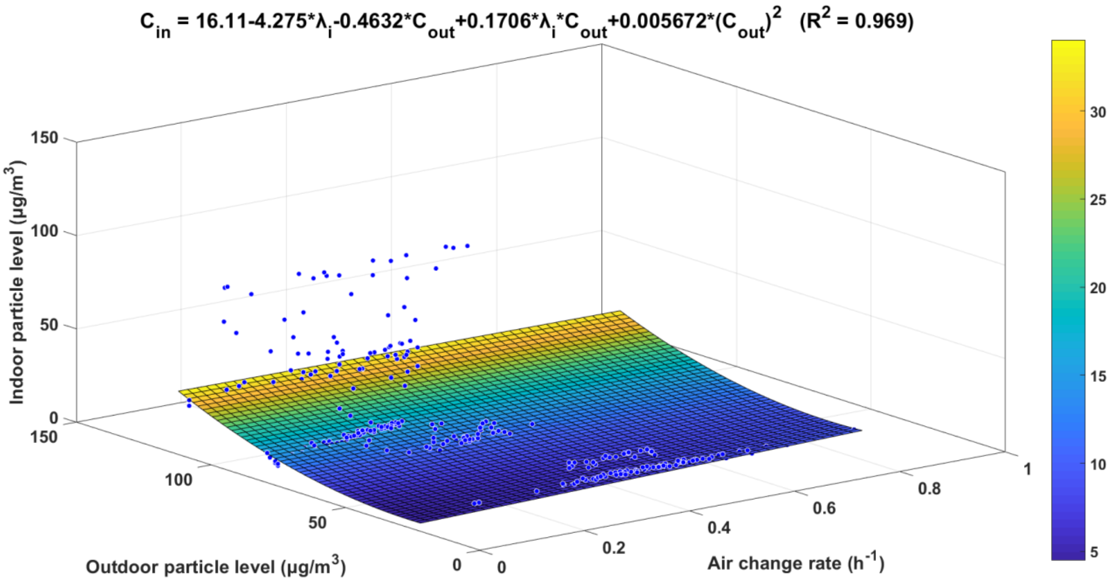

Figure 15: The numerical model for the indoor PM$_{1.0}$ concentration

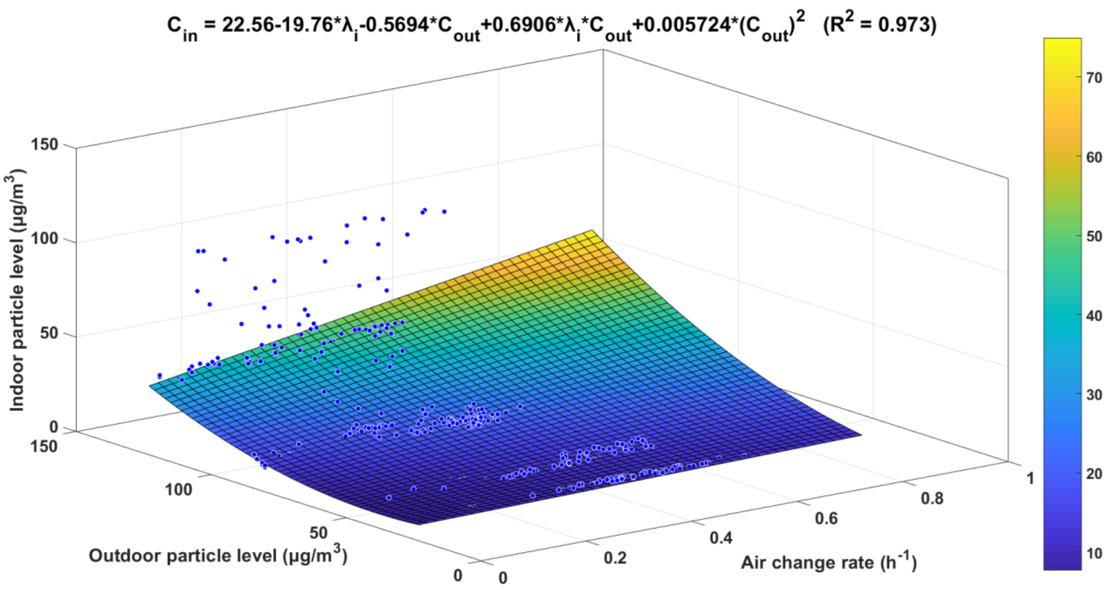

Figure 16: The numerical model for the indoor $PM_{2.5}$ concentration

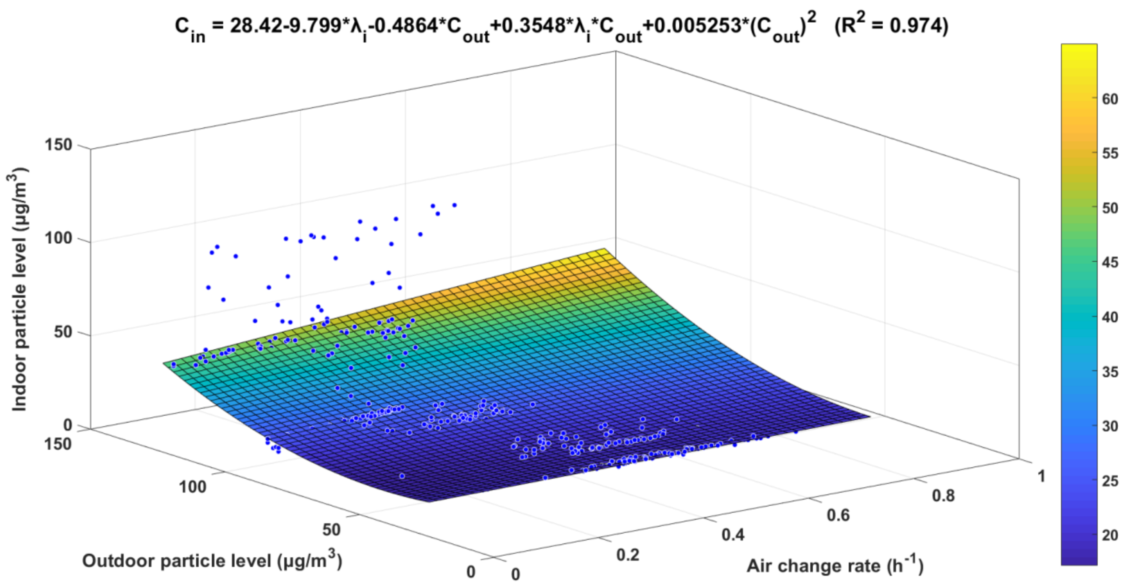

Figure 17: The numerical model for the indoor PM_{10} concentration

3.3.1 The combined effect of the room infiltration and outdoor particle level on IAQ

Based on the data provided by the China Meteorological Bureau, the hourly average outdoor $PM_{2.5}$ and PM_{10} levels in Suzhou range between 0 and 300 μg/m³ (Wang, 2021). However, there is a lack of measured data for the outdoor $PM_{1.0}$ concentration. In this study, it is assumed that the value range of outdoor $PM_{1.0}$ is the same as $PM_{2.5}$ since, in China, $PM_{1.0}$ is the primary component of $PM_{2.5}$ (Yang et al., 2020). Moreover, the airtightness of the tested room generally varied from 0 to 1 ACH and rarely went over 1 ACH under natural conditions. In this instance, these data were used to illustrate the air infiltration rate and OPL's combined effect on IAQ was analyzed based on the fitted model, as shown in Figure 18. Compared to the ambient PM standard, the indoor PM control standard lacks development since only a few countries have established the indoor PM control standard. The existing recommended concentration limit for indoor $PM_{2.5}$ level is mainly aimed towards industrial environments (Liu et al., 2017), and there is no standard for $PM_{1.0}$. Therefore, the World Health Organization (WHO) Air Quality IT-1 level of 35 μg/m^3 for $PM_{2.5}$ was chosen to evaluate the indoor $PM_{1.0}$ and $PM_{2.5}$ levels, and 70 μg/m^3 for assessing indoor PM_{10} level (WHO, 2006). The red curve in the figures represents the limit value of indoor particles suggested by WHO, and the area under the red curve means the IPL has met the standard.

The results indicated that the IPL could be higher than the OPL at a leaky building if the outdoor air has deteriorated. Thus, an effective method, such as using the PAP, is recommended to control the indoor particles in a leaky building if outdoor pollution levels are high. Further, compared to $PM_{1.0}$ and PM_{10}, $PM_{2.5}$ has more chance of being introduced indoors with the infiltrated air. One of the possible reasons is that the large and small particles are easier to be influenced by other mechanisms during the progress that infiltrates through the building envelope.

Based on the data analysis, for all three sizes of particles, the increase of the room airtightness will help to dilute the IPL when the outdoor level is under 30 μg/m^3. It was also found that there was a negative linear impact of the air infiltration rate on the IPL when the outdoor level was over 30 μg/m^3. Moreover, a non-linear negative impact of outdoor particles on indoor air quality was found when the OPL was over 30 μg/m^3. In higher outdoor air pollution levels over 150 μg/m^3 and lower infiltration levels below 0.3 ACH, the $PM_{1.0}$ pollutants significantly dominate indoor pollution levels. This study estimates that smaller particles penetrate building facades more easily than bigger particles in lower air infiltrated conditions.

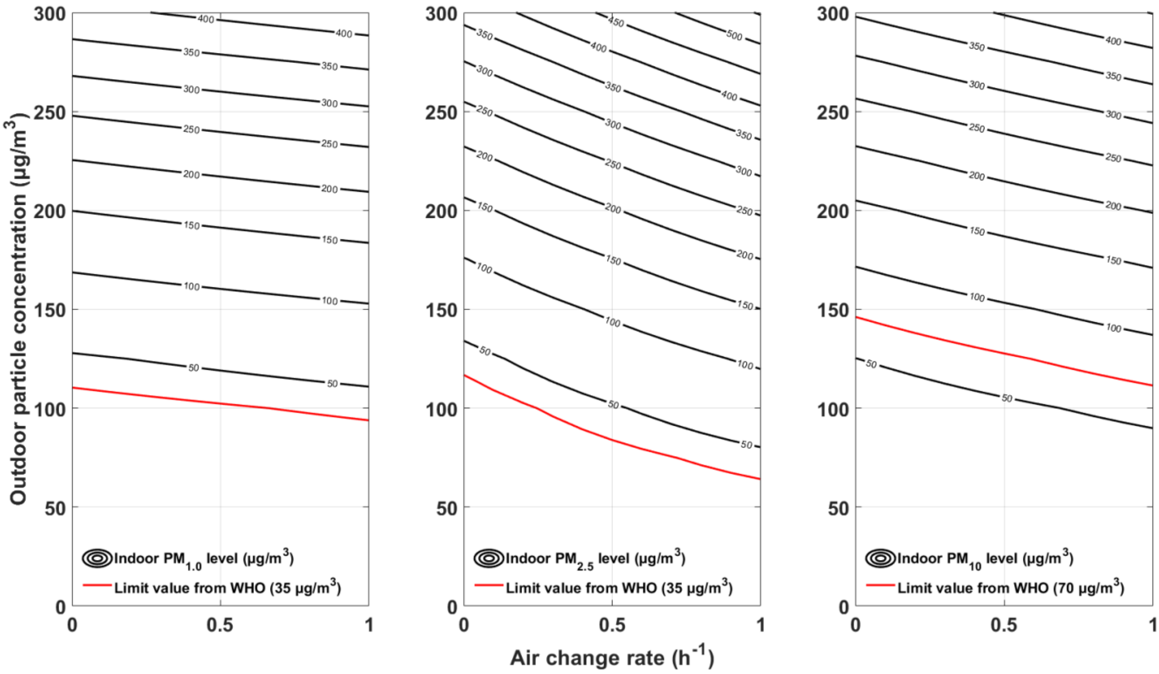

Figure 18: The combined effect of the airtightness and outdoor particle level on indoor air quality

4 Conclusion

An experimental-based study was conducted to explore the impact of the outdoor particles, room infiltration, and occupants' behaviours on IAQ. The experiments were conducted in a 12-storey building in Suzhou. Based on the European standard EN13829, the blower door test was applied to assess the airtightness of the chosen room, and the results were used to evaluate the impact of room infiltration on the IPL. The results indicated that all of these elements substantially impacted IAQ in a building.

Occupant behaviour was the primary mechanism that determined the IPL. Based on the experimental results, human-building interactions, such as the door and window opening behaviour, would notably increase the number of outdoor particulate matter introduced to the building, whatever the outdoor air pollution levels. Therefore, it is suggested not to use unfiltered natural ventilation, especially for areas with high outdoor pollution. Moreover, the results indicated that an air purifier could efficiently reduce the IPL when outdoor air is contaminated. However, for energy-saving concerns, the PAP should be used properly and reference made to the dominant indoor particles to select the filter class.

Numerical simulation was used to conclude that the IPL is exponentially correlated to the OPL, fitting with the mass balance model. According to the simulation results, this study estimates that the smaller particles do not always have more chance to enter the indoor environment through the building envelope than the larger ones. However, the larger particles significantly dominated indoor pollution levels when the building was under unfiltered natural ventilation conditions. Hence, to determine the primary indoor pollutants, the specific conditions of the building should be considered.

The simulation results indicated that the air infiltration rate had a positive linear impact on IAQ if the OPL was under 30 μg/m^3, while a negative linear effect was found when outdoor air deteriorated. Based on the analysis, smaller particles more easily penetrate building facades than bigger particles in lower air infiltration conditions. In other words, occupants may significantly suffer from the $PM_{1.0}$ pollutants in an airtight building when the OPL is the same and high.

Acknowledgement

The author(s) disclosed receipt of the following financial support for the research, authorship, and or publication of this article: This work was supported by the Research Development Fund (RDF 15–02-32 and RDF 20-01-16) of Xi'an Jiaotong - Liverpool University, the Department of Civil Engineering and Energy Technology of Oslo Metropolitan University, the UK ICE Research Development Enabling Fund (ICE-RDF-2020) and the Natural Science Foundation of Zhejiang Province (LY19E080001).

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