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Investigating the reliability of estimating real-time air exchange rates in a building by using airborne particles, including PM1.0, PM2.5, and PM10

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Corresponding Author:	Moon Keun Kim, Prof.Dr.sc.ETH Oslo Metropolitan University Oslo, NORWAY
First Author:	Nuodi Fu
Order of Authors:	Nuodi Fu
	Moon Keun Kim, Prof.Dr.sc.ETH
	Long Huang, PhD
	Jiying Liu, Prof.Dr.
	Bing Chen, Prof.Dr.
	Stephen Sharples, Prof.Dr.
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Suggested Reviewers:	Jelena Srebric, Prof. Dr. Professor, University of Maryland at College Park jsrebric@umd.edu
	Shi Jie Cao, Prof. Dr. Professor, Southeast University shijie_cao@seu.edu.cn
	JoonHo Choi, Prof. Dr. Associate Professor, University of Southern California joonhoch@usc.edu
	Yang Seon Kim, PhD Assistant Professor, Wichita State University yang-seon.kim@wichita.edu
	Mohammad Heidarinejad, PhD Assistant Professor, Illinois Institute of Technology muh182@iit.edu
	Jae Weon Jeong, Prof. Dr. Professor, Hanyang University jjwarc@hanyang.ac.kr

Opposed Reviewers:	

Cover Letter

Date: 14 OCT 2022

Dear Professor, Dr**. Damià Barceló**, **Jay Gan, Philip Hopke,** and **Elena Paoletti**, Editor-in-Chief, And Prof. Dr. Hai Guo, Associate Editor, **the Journal, Science of the Total Environment**

We appreciate the opportunity to submit a manuscript entitled "**Investigating the reliability of estimating real-time air exchange rates in a building by using airborne particles, including $PM_{1.0}$, $PM_{2.5}$, and PM_{10}**".

Last time we submitted this paper at STOTEN, but there were small self-recycled parts from the recently published STOTEN paper by our group. Based on the editor's comments, we newly reviewed and updated the paper. We really appreciate your kindly comments and suggestions.

This study aimed to analyse the reliability of using airborne particles to estimate the real-time Air Exchange Rate (AER) of a building by considering the impact of particle size and outdoor conditions. The impact of these factors on the AER estimation accuracy has been analysed based on the on-site collected data and numerical simulations. The research outputs could be applied to maintain Indoor Air Quality (IAQ) and predict actual infiltration heat losses. Results showed that the particles with a diameter under 2.5 μm could be used as a tracer to predict the AER of a building. And a negative correlation was found between particle size and AER prediction accuracy. This is because smaller particles have a higher penetration rate, which is more accessible to enter the room with the infiltrated air. Therefore, the result of the estimated AER based on the small particle is closer to the real AER. Moreover, the outdoor particle level and the pressure differential impact positively on the accuracy of a particulate matter (PM) method of estimating the AER. In addition, the empirical correlation for $PM_{1.0}$ and $PM_{2.5,}$ based on the experiment data, was established and verified using the 5-fold Cross-Validation method. Compared with the pressurization method, the $PM_{1.0}$- and $PM_{2.5}$-based method gives a Normalized Mean Error (NME) within 10% and a correlation coefficient (r) of over 0.97. Hence, the equation can be used to estimate the real-time AER of the building and can help designers accurately predict the building's heat losses.

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To the author's knowledge, no conflict of interest, financial or other, exists. Each author has participated and contributed sufficiently to take public responsibility for appropriate portions of the content.

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Authors: Nuodi Fu, Moon Keun Kim, Prof. Dr.sc.ETH, Long Huang, Assistent Professor, Jiying Liu, Associate Prof. PhD, Bing Chen, Associate Prof. PhD, Stephen Sharples, Professor, PhD

Thank you for your time and consideration. We look forward to discussing our contribution in more detail.

With my best regards,

Corresponding Author

Moon Keun Kim, Professor. Dr.sc.ETH
Department of Civil Engineering and Energy Technology
Oslo Metropolitan University, Oslo, Norway

Title Page

Investigating the reliability of estimating real-time air exchange rates in a building by using airborne particles, including $PM_{1.0}$, $PM_{2.5}$, and PM_{10}

Nuodi Fu[1,2], Moon Keun Kim[3*], Long Huang[4], Jiying Liu[5], Bing Chen[6], Stephen Sharples[2]

[1]Department of Architecture, Xi'an Jiaotong – Liverpool University, Suzhou 215123 China

[2]School of Architecture, University of Liverpool, Liverpool L69 7ZX, United Kingdom

[3]Department of Civil Engineering and Energy Technology, Oslo Metropolitan University, Oslo 0130, Norway

[4] School of Intelligent Manufacturing Ecosystem, Xi'an Jiaotong – Liverpool University, Suzhou 215123 China

[5]School of Thermal Engineering, Shandong Jianzhu University, Jinan, 250101, China

[6]Department of Urban Planning and Design, Xi'an Jiaotong – Liverpool University, Suzhou 215123 China

*Corresponding author: Email: Moon.Kim@oslomet.no; yan1492@gmail.com Tel: +47 67 23 59 73

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Graphical Abstract

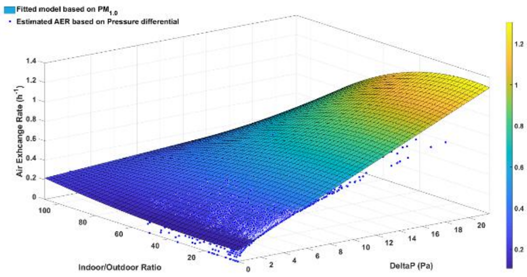

Figure A: The fitted model of AER based on the I/O ratio of $PM_{1.0}$ and pressure differential

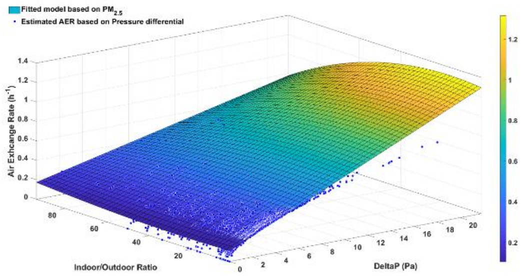

Figure B: The fitted model of AER based on the I/O ratio of $PM_{2.5}$ and pressure differential

Fitted models to estimate real time air exchange rates and airborne particles

Highlights

- the fine particles could be utilized to predict the air exchange rate (AER)
- the impact of the indoor and outdoor (I/O) ratio of particles is more substantial
- the accuracy of AER is affected by ambient air pollution levels
- this study analyzes how outdoor air pollution levels impact on indoor air quality
- the differences between I/O air contaminant levels can estimate the real-time infiltration rate

Investigating the reliability of estimating real-time air exchange rates in a building by using airborne particles, including $PM_{1.0}$, $PM_{2.5}$, and PM_{10}

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[5]School of Thermal Engineering, Shandong Jianzhu University, Jinan, 250101, China

[6]Department of Urban Planning and Design, Xi'an Jiaotong – Liverpool University, Suzhou 215123 China

*Corresponding author: Email: Moon.Kim@oslomet.no; yan1492@gmail.com Tel: +47 67 23 59 73

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1 Introduction and background

The COVID-19 pandemic continues to pose a threat to global public health. Understanding virus transmission could help reduce the spread of the disease. Airborne particles as outdoor origin air pollutants can easily bring numerous viruses, including the coronavirus, from outdoors to indoors through the building envelope via infiltration air (Prinz & Richter, 2022; Yao et al., 2020). Hence, indoor people may still suffer from outdoor pollutants, causing increased morbidity and mortality (EPA, 2019a; WHO, 2006, 2013; Yang et al., 2019). Moreover, people spend over 90% of their time on indoor activities, and thus, it is essential to control Indoor Air Quality (IAQ) to reach the healthy threshold.

Infiltration is the uncontrolled flow of outdoor air through the building envelope cracks and from a ventilation system's leakage to enter indoor environments. Under such circumstances, infiltrating air will directly bring outdoor air pollutants indoors and significantly degrade IAQ (Fu et al., 2022; Hu et al., 2020; Kim, 2022; Li et al., 2019; Liang et al., 2021; Nazaroff, 2021). Moreover, infiltration can also degrade indoor thermal comfort (Goubran et al., 2017; Happle et al., 2017; Mathur & Damle, 2021), the efficiency of the ventilation system (Fu et al., 2021a; Shi & Li, 2018b), and the performance of the acoustic insulation. Previous studies also reported that a building's heating and cooling loads would increase rapidly due to air infiltration

(Goubran et al., 2017; Han et al., 2015; Mathur & Damle, 2021). Thus, infiltrating air is undesirable if outdoor air is polluted and is also unwanted for low-carbon buildings. Accordingly, accurately predicting the air infiltration rate of a building under natural conditions could help control IAQ and estimate the heat loss of the building.

Two widely used techniques for measuring the Air Exchange Rate (AER) are tracer gas methods and fan pressurization tests. The fan pressurization test uses fans in doors (blower doors) that enable a building to be pressurized to a reference pressure to test the building's air leakage rate (CIBSE, 2016). Based on this method, the measured AER is idealized under the test conditions, which has ignored the impact of climate variation. Also, a blower door test can measure the AER of a simple building but is limited when being adapted to large-scale complex buildings, e.g. high-rise buildings. In reality, the AER varies with the actual in-service conditions because it is induced by wind pressures and stack effects (Fu et al., 2021a; Nazaroff, 2021; Park et al., 2021; Shi & Li, 2018b). For a more realistic and dynamic analysis of AER, the tracer gas method is used to investigate the variation of AER with climatic conditions since it is conducted under actual environmental conditions. This method estimates the AER through the building openings based on the decay of a tracer gas's concentration indoors within a selected time period. For precision concerns, the tracer gas is better to be of outdoor origins, such as CO, O_3, NO, NO_2, and SO_2 (ASTM, 2000; ISO, 2012). Recently, given the simplicity of not requiring the injection of a tracking gas, the occupant-generated CO_2 tracer gas method has also been commonly applied to estimate the AER of a room (Fu et al., 2022; Kabirikopaei & Lau, 2020; Park et al., 2021; Ren, Liu, Zhou, Kim, & Miao, 2022; Xiong et al., 2021).

In recent years, more attention has been paid to assessing the AER using indoor and Outdoor Particle Levels (OPL). This method is based on the mass balance of Particulate Matter (PM), which follows the principle that a building is in a steady state and the amount of air flowing in and out is balanced. Thus, the AER can be determined by knowing the inlet and outlet airflow rates. Serfozo et al. (2014) compared the AER estimation results based on the PM_{10}-based method with the CO_2-based method, and they found that the two results showed high agreement with each other. Ni et al. (2017) successfully predicted the average AER of a test room based on a steady-state indoor $PM_{2.5}$ level, with AER results based on the CO_2 decay method also being used as the baseline.

Moreover, two novel PM-based methods have been developed to measure the AER of a room, which is the $PM_{2.5}$-based Clean Air Delivery Rate (CADR) method and the $PM_{2.5}$-based PM-up method. Liu et al. (2021) justified that the developed CADR method is a feasible option to replace the CO_2 decay method to measure the AER of a building. In this new method, they introduced a Portable Air Purifier to analyse the dynamic process of indoor $PM_{2.5}$ level, and then the average AER can be predicted by fitting the created numerical model. Further, the PM-up method has been developed by Hu et al. (2022) to overcome the disturbance created by normal human indoor activities to ensure the AER could be measured accurately. The central highlighted point in this study was that they created a bounce-up process of indoor $PM_{2.5}$ levels by turning on the air cleaner at the beginning and then turning it off. During the bounce-up process, the indoor $PM_{2.5}$ level is only affected by the outdoor particles because of air change with the outdoor air. Thus, the average AER of the tested room can be determined by fitting the measured indoor $PM_{2.5}$ level in that period with the numerical model, and the accuracy of the estimated results has been analyzed by comparing them with the CO_2 decay method (Hu et al., 2022).

Previous research is focused on predicting the average AER of a selected room. However, as previously discovered, the AER will highly impact on IAQ and the heating loss of a building. Hence, the average value of the AER is not ideal for estimating the Indoor Particle Level (IPL) and heat loss. Thus, real-time AER is required to control indoor air quality better and predict the actual heat loss, and there is rare research on airborne particles to predict real-time AER. Moreover, previous research also reported that the size of particles, whose diameter is between 0.3 and 10 μm, would significantly influence the accuracy of this method for assessing the infiltration rate (Shi et al., 2017). The reason is that the larger particles are easier to lose due to the deposition and resuspended mechanism and more difficult to penetrate through building cracks (Fu et al., 2022; Lai & Nazaroff, 2000; Qian & Ferro, 2008; Serfozo et al., 2014; Wang et al., 2022; Zhao & Wu, 2007; Zong et al., 2022). Hence, it is expected that the accuracy of the PM-based AER estimation method is highly correlated to particle size. However, most previous research only explored the possibility of predicting the AER of a room based on one size of particles. Therefore, new research is required to compare the accuracy of estimating AER based on different particle sizes, including $PM_{1.0}$, $PM_{2.5}$ and PM_{10}, under various outdoor conditions.

This study explored the effects of particle size on the accuracy of assessing the real-time AER based on the airflow mass balance method while considering different outdoor conditions. Figure 1 shows the mindmap of this research. This study illustrates the possibility of estimating the AER of a room using air pollution level differences between indoor and outdoor conditions. Especially a high-rise building, because the conventional methods, such as the blower door test and the tracer gas test, are quite challenging to estimate how surrounding environments impact on the actual AER in each room. The results can be used to explore how reliable airborne particles are in predicting real-time AER. This would allow users to accurately estimate the indoor pollution rate and the heat loss of a building.

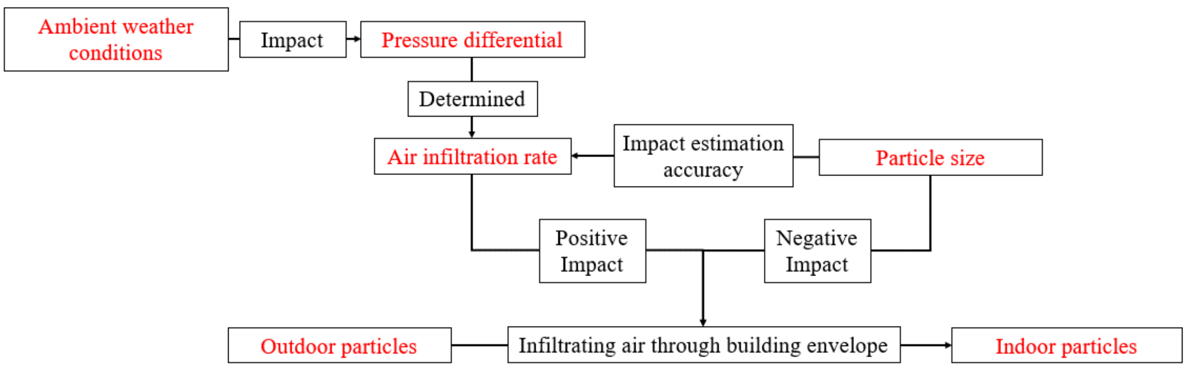

Figure 1: The mindmap of this research

2 Methodology

The methodologies for analyzing the accuracy of estimating AER based on the airborne particles' mass balance method can be divided into five steps: 1) On-site data collection of indoor and outdoor particle level; 2) Established numerical model to fit with the measured IPL according to the mass balance equation; 3) Using the established model to analyze the collected data; 4) Develop empirical correlation based on collected data to determine the real-time AER; 5) Validate the empirical correlation based on the cross-validation method.

2.1 Detailed information on the targeted building

The target building is in Suzhou, Jiangsu Province, China, and it is a naturally ventilated building that is 12-floor, around 63 metres high. A room on the 3rd floor of the building, 10.4 m above the ground floor, was used to conduct the experiments. The target building faces north-south, and the tested room is chosen from the building's north part. Detailed information on the tested building and room is displayed in Figure 2. Furthermore, the targeted building is surrounded by a pedestrian and vehicle road on a relatively open site.

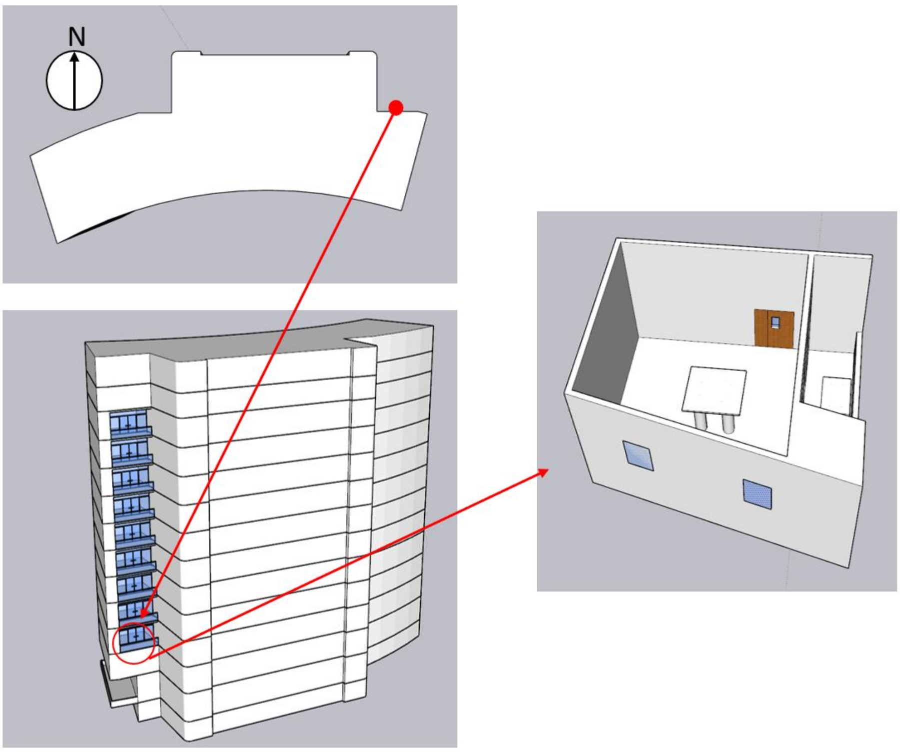

Figure 2：The target building and test room

2.2 Blower door test

According to the standard EN 13829 (CEN, 2001), the pressurization method is suggested to assess a room's airtightness, and this method has been widely and successfully used in previous studies (Ji & Duanmu, 2017a, 2017b; Ji et al., 2017; Ji et al., 2020; Ren, Liu, Zhou, Kim, & Song, 2022). Hence, the blower door test was applied to determine the tested room's airtightness, and experiments were performed strictly with the standard. Figure 3 shows the utilized Retrotec 5000 test system in this test method. The system consists of three parts: a cloth panel, a Model 5000 fan, and a 32-DM digital manometer control device. The cloth panel is used to seal the opening and set the rest part of the system, the fan is used to pressurize and depressurize the test room at the required airflow rates, and the control device is applied to control the whole system.

Ten tests were done to measure the air exchange rate for the chosen room to minimise the measurement error, and the ten test results varied within a range of ±5%. Then the average of the results was utilized in this study and is displayed in Table 1. ASHRAE Handbook (ASHRAE, 2017) reported that a room's AER is a function of the pressure differential, which can be determined as:

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

where AER is the air change rate due to the infiltration rate in h^{-1}, and V is the volume of the selected room in m^3. Then, the average value was calculated and applied for the exponent n and the airflow coefficient, c, in $m^3/(s \cdot Pa^n)$. Thus, based on the results of blower door tests, Equation (1) can be rewritten as:

$$AER = 0.146 \times (\Delta p)^{0.5966} \quad (2)$$

Equation (2) shows the correlation between the AER of the selected room and the pressure differential and its visualized results presented in Figure 4. Moreover, a manometer is used to measure the pressure differential during the experimental period, and then the value can be applied to Equation (2) to get the real-time AER of the room.

Figure 3: The Retrotec 5000 test system

Table 1：The results of the airtightness test for the selected room

Air flow coefficient ($m^3/(h*Pa)$)	Air exchange rate at 50 Pa (h^{-1})	ELA[1] 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

Hint: 1. Effective Leakage Area (ELA)

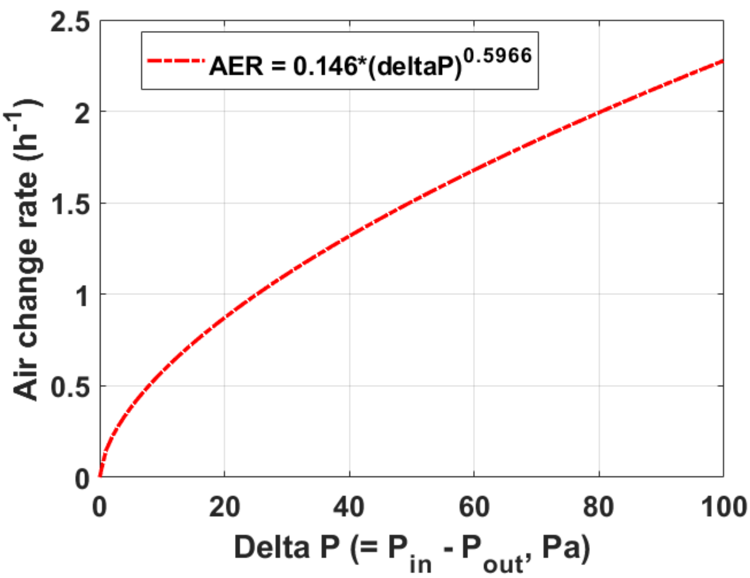

Figure 4: The relationship between the AER and pressure differential of the selected room

2.3 Experiment design

The on-site measurements were conducted from 1st to 11th June 2022. The selected room was trapezoidal in shape and naturally ventilated. In order to ensure that any particle could only get indoors through the building envelope with the infiltrated air, the doors, windows, and obvious leakages of the room were closed and sealed during the experiment. Each experiment was conducted for 245 minutes to ensure that the IPL reached a steady state. Moreover, the measured data in the first 5 mins were not considered during the data analysis to avoid the influence of people's motions on the final results.

During the experiments, the indoor and outdoor particles level were collected simultaneously. Before every experiment, all instruments were calibrated according to the manufactory's handbook. Moreover, from Figure 5, tables A and B were used to place the calibrated instruments to collect data. Table A is located in the middle of the room, and table B is on the balcony of the room, is 1.5m away from the room, and both tables are 0.9m above the floor. The monitors were set to record data every minute, and the recorded data were the average values of the data that was collected every 10s.

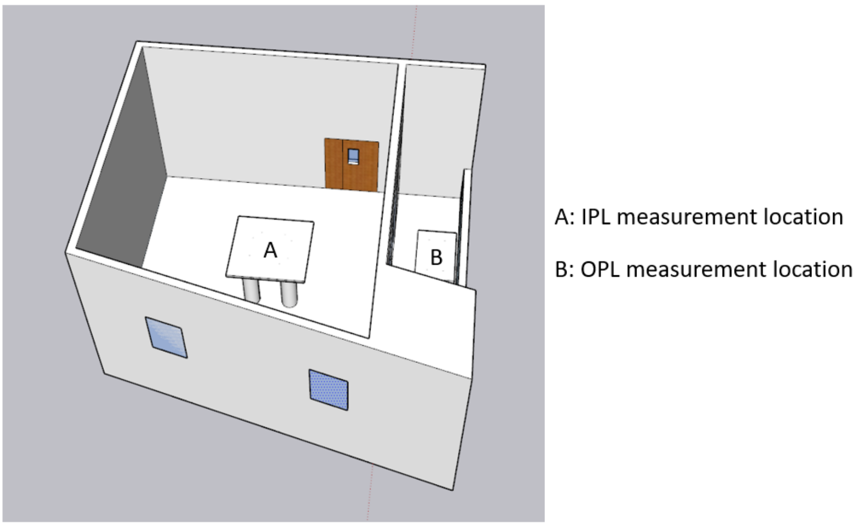

Figure 5: Details of the setup for the experiments in the test room

2.4 Instrumentation

In this study, the TSI Model 8534 DustTrak Aerosol Monitor was applied to measure the indoor and outdoor particle concentrations. It is a handheld instrument, and the 90° light scattering technique is used, in which the amount of scattered light is proportional to the volume concentration of an aerosol. Several widely accepted papers have used this instrument to measure atmospheric particles (Fu et al., 2021a, 2021b; Liu et al., 2018; Wu et al., 2002). Moreover, the instrument was calibrated for Arizona Test Dust by the manufacturer. Table 2 presents the testing instruments with their manufacturer-reported accuracy, resolution, and detection range.

Table 2: Detailed information regarding the testing instruments in this study

Parameter	Instrument	Range	Accuracy	Resolution
Pressure differential	Vadias QDF70A-VD-S	-100 - 100 Pa	0.5% FS	0.1 Pa
$PM_{1.0}$	TSI Model 8534 DustTrak	0.001 – 150 mg/m^3	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 ℃

2.5 Indoor particles' mass balance model

The indoor particle level can be modelled as a function of source terms (S_i) and loss terms (L_i) and can be described, following by Equation (3) as (Ben-David & Waring, 2016; Fu et al., 2021a, 2021b; Kim & Choi, 2019; Liu et al., 2021; Serfozo et al., 2014):

$$\frac{dPM_{in,t}}{dt} = S_i - L_i \times PM_{in,t} \quad (3)$$

where $PM_{in,t}$ is the indoor pollutant level at time t in μg/m^3. Because the tested room is an office room, and thus the indoor PM emission sources were neglected in this study (EPA, 2019b), and the particles were uniformly distributed indoors (Huang et al., 2017). Therefore, the indoor particles are entirely from the outdoor particles that penetrate the building with the infiltration air. Moreover, the particle resuspension rate caused by human activities can be ignored in a steady-state indoor environment compared with the deposition rate (Shi & Li, 2018a), and thus, Equation (3) can be described as:

$$\frac{dPM_{in,t}}{dt} = p \times Q \times PM_{out,t} - (Q + \beta) \times PM_{in,t} \quad (4)$$

where P is the particle's penetration factor (no units), Q is the AER of the building in h^{-1}, $PM_{out,t}$ is the outdoor particle level at time t in $\mu g/m^3$, and β is the deposition rate in h^{-1}. Equation (5) represents the mass balance equation's dynamic solution that describes the indoor PM level (Diapouli et al., 2013; Quang et al., 2013; Ruan & Rim, 2019; Yu et al., 2014).

$$PM_{in,t} = \frac{p \times Q}{Q+\beta} \times PM_{out,t} + (PM_{in,0} - \frac{p \times Q}{Q+\beta} \times PM_{out,t}) \times e^{-(Q+\beta) \times t} \quad (5)$$

Then, the equation can be rewritten as:

$$PM_{in,t} = a + b \times e^{-c \times t} \quad (6)$$

Hence, the decay of the IPL should be shown as an exponential curve along with the time. According to previous studies, it is reasonable to assume that these coefficients, including p, Q, and β, are constant within a short time slot, such as one hour (Sun et al., 2019; Xiang et al., 2021). According to the previous studies, the particle penetration rate is set to 0.9, 0.8, 0.63 for $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, respectively (Chen et al., 2012; Liu & Nazaroff, 2001; Stratigou et al., 2020; Tran et al., 2015). The deposition rate is set to 0.14, 0.31, 0.7 h^{-1} for $PM_{1.0}$, $PM_{2.5}$, PM_{10}, respectively (Chen et al., 2012; He et al., 2005; Stratigou et al., 2020; Tran et al., 2015). Further, by substituting the measured OPL and these factors into Equation (5), the IPL can be estimated. The comparison between measured and estimated IPL can illustrate the possibility of using airborne particles to predict the AER of a building.

2.6 Method assessing index

In order to evaluate the comparison of different sizes of the PM-based method with the pressurization method and the comparison of two different PM-based methods with the pressurization method, two statistical indices are introduced, the Normalized Mean Error (NME) and the correlation coefficient (r) (Liu et al., 2021).

NME evaluates models by observation, ensuring the results in a relative sense. Moreover, NME is calculated by characterizing the mean magnitude of model error over a spatiotemporal scale. Accordingly, a smaller NME indicates a better agreement between the two assessing methods, and 30% was chosen as the baseline for NME evaluation in this study (Liu et al., 2021). The NME can be defined as:

$$NME = \frac{\sum |P_i - O_i|}{\sum O_i} \tag{7}$$

where P_i and O_i are the air exchange rate estimated by the PM-based and pressurisation methods in h^{-1}. Further, the correlation coefficient is used to assess the variability of two compared methods in an entire range, and the closer that r is to unity, the better the agreement between the two methods (Liu et al., 2021). In this study, the baseline value of r is set to 0.4, and it can be defined as:

$$r = \frac{\sum[(P_i - \bar{P})(O_i - \bar{O})]}{\sqrt{\sum(P_i - \bar{P})^2}\sqrt{\sum(O_i - \bar{O})^2}} \tag{8}$$

where $\bar{P}$ and $\bar{O}$ are the mean values of the AER in h^{-1} estimated by PM-based and pressurization methods, respectively.

3 Results and discussion

3.1 Measured indoor particle level

According to the dynamic solution of the mass balance equation, the IPL will experience exponential decay if there are no indoor emission sources. Hence, the measured IPL in this study should be fitted using the exponential function, as shown in Equation (6). The measured IPL and its fitted curve, and selecting one day as an example, are shown in Figure 7, Figure 8, and Figure 9 for $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, respectively. Further, Figure 6 displays the outdoor conditions during the data collection period.

It can be seen in Figure 6 that the outdoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} levels experienced the same variation trend during the day, which is higher in the morning and lower in the afternoon. This variation trend indicates that the OPL was negatively correlated with the outdoor air temperature, and this phenomenon was also found during the seasonal change, as the OPL was higher in winter and lowered in summer (Fu et al., 2021a, 2021b). From the measured data, the outdoor PM_{10} level in Suzhou is usually the highest, followed by $PM_{2.5}$ and $PM_{1.0}$. Moreover, the temperature differential is decreased first and then increased. This is because the experiments started at 8:00 in the morning, and thus the indoor air temperature had decreased to a lower level due to the night cooling, which caused a higher temperature differential at the beginning.

According to Figure 7 to Figure 9, a high correlation between the measured and modelled indoor particles level was found, and the coefficient of determination R^2 was always higher than 0.99, and also in the rest of the experiments where R^2 ranged between 0.992 to 0.999. As discussed, the outdoor PM_{10} level was usually the highest among the three chosen particle sizes, and the same law was also found indoors under steady-state conditions, which indicated that the indoor particles' level was strongly correlated to the outdoors levels. Moreover, from the graph, the IPL could be 3-5 times higher than the OPL even if there are no indoor particle emission sources since the room has not been used for a while, and thus the indoor air is contaminated (EPA, 2019b).

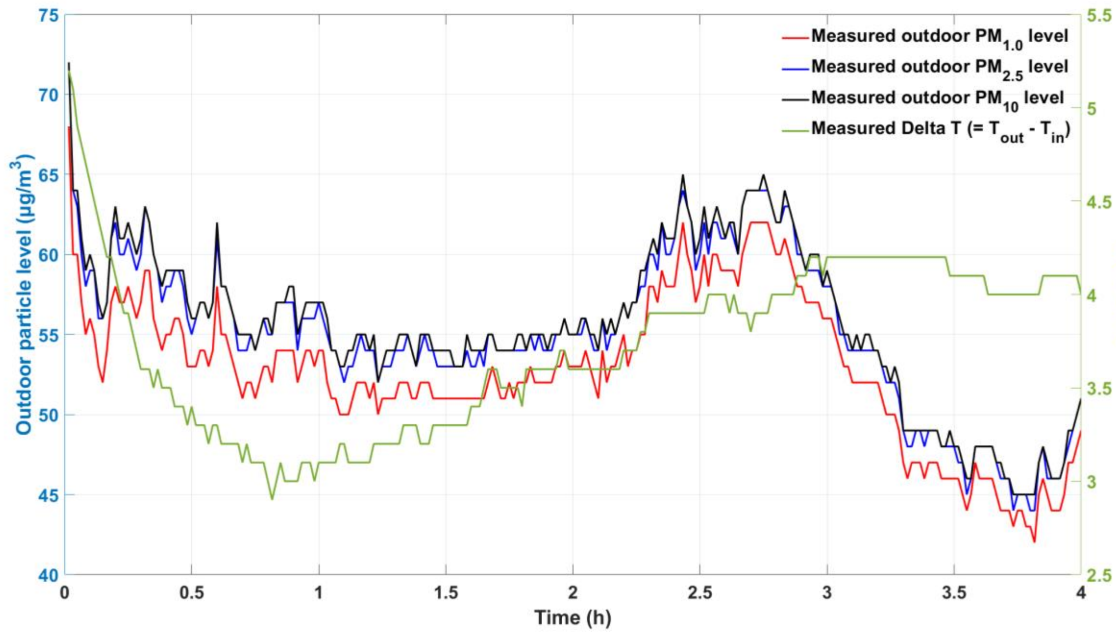

Figure 6: The outdoor particle level on the selected day and the temperature difference between indoors and outdoors in the selected room

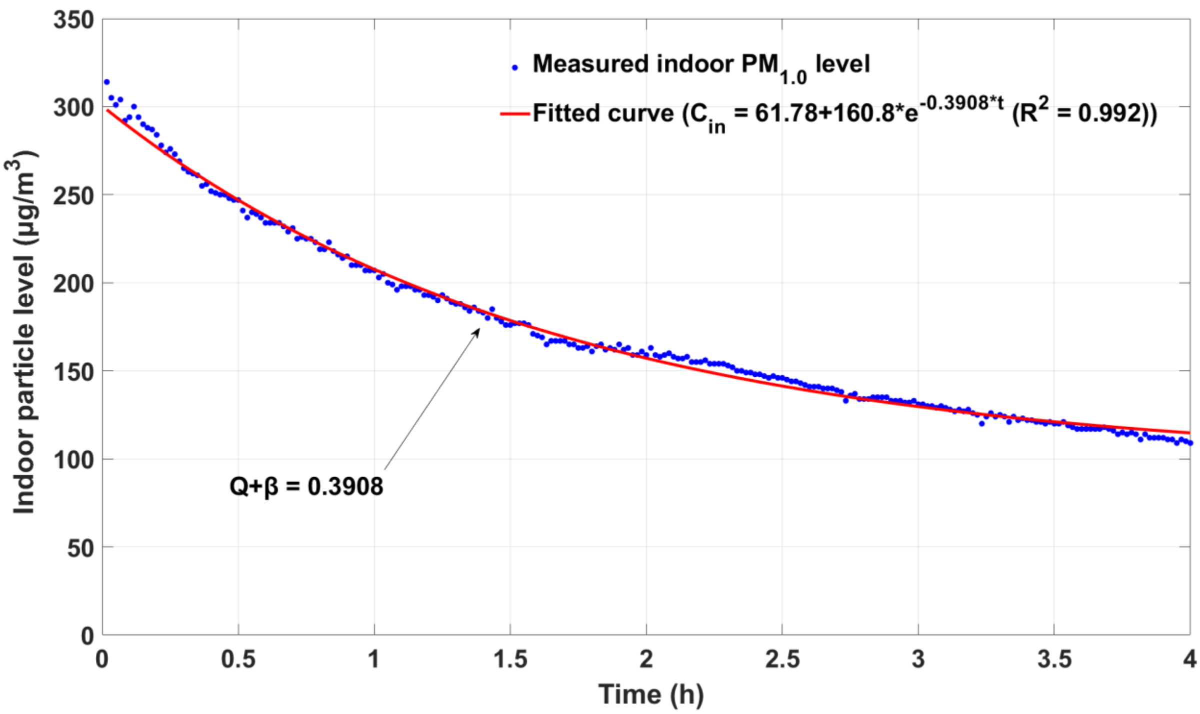

Figure 7: The measured indoor $PM_{1.0}$ with the fitted curve

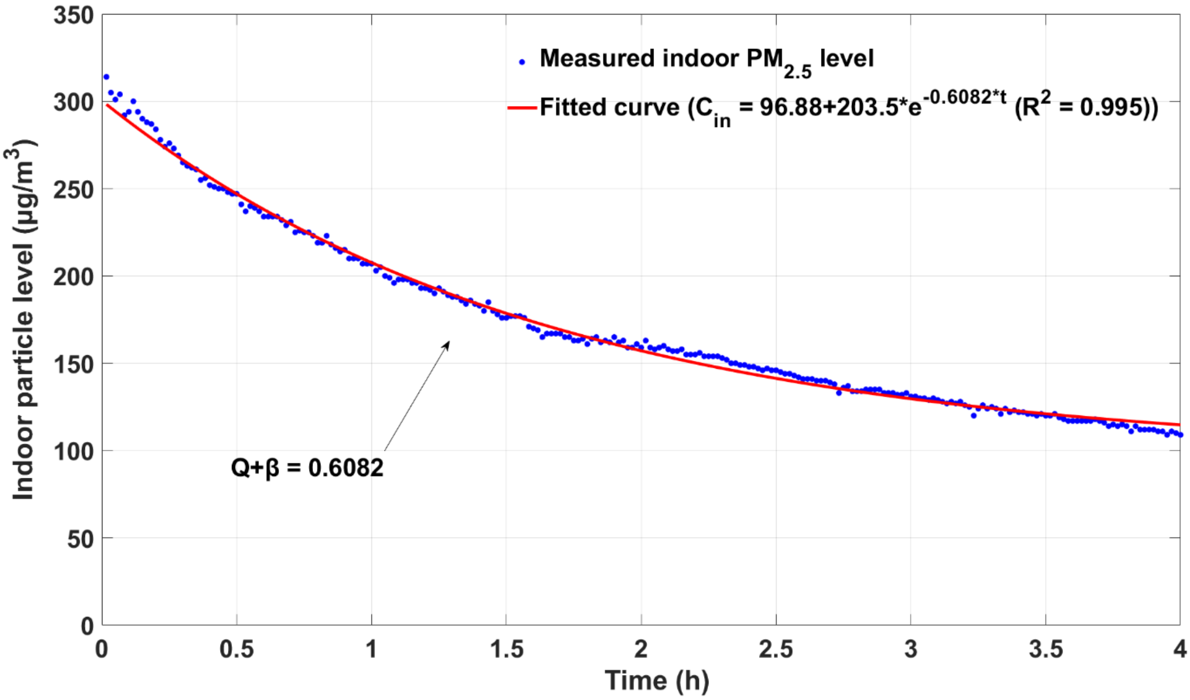

Figure 8: The measured indoor $PM_{2.5}$ with the fitted curve

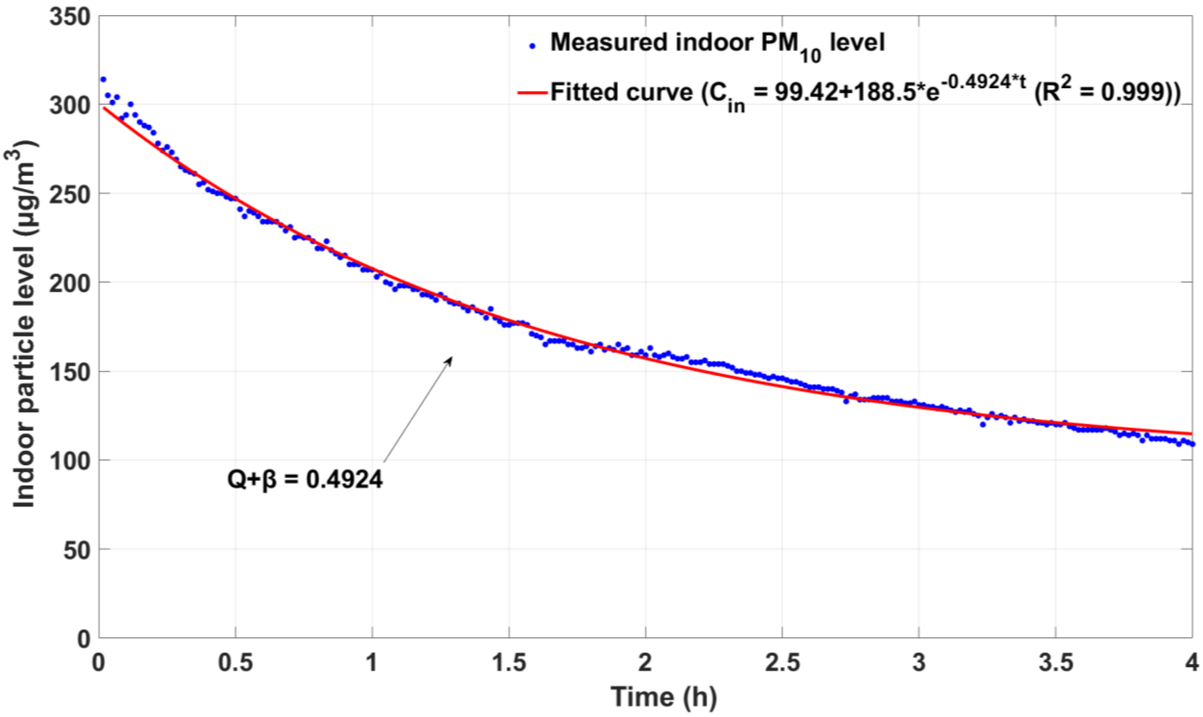

Figure 9: The measured indoor PM_{10} with the fitted curve

3.2 The impact of particle size on the accuracy of estimating real-time AER

A comparative study between the measured and estimated IPL was conducted to investigate the reliability of using airborne particles to predict the AER of a building, and the results are displayed in Figure 10, Figure 11, and Figure 12. According to the graphs, predicting the AER based on the smaller particles is generally more accurate than for the larger ones. This is because $PM_{1.0}$ and $PM_{2.5}$ have a smaller size and higher penetration rate, making it easier for them to enter the room with the infiltrated air. Thus, the result of the estimated AER based on the small particle is closer to the real AER. Moreover, the estimated indoor PM_{10} level is always lower than the measured value. Thus, the PM_{10}-based predicted AER is easily underestimated, and the results show high agreement with previous studies, i.e. that the larger particle has a higher deposition rate and lower penetration rate, which highly impacts on its ability to get in or out of the room.

It can be seen from the graphs that the lower bound of the estimated IPL is lower than the measured ones, and according to Figure 13, this phenomenon occurs when the IPL has reached a steady state. The results indicate that the actual IPL is higher than expected. Thus, using a steady-state IPL to predict the AER may cause an increased error and underestimated results. Moreover, this phenomenon is more notable when the particle's size increases.

Table 3 presents the results of using two selected statistical indices to evaluate the comparison of estimated and measured IPL. Based on the analysis, the results show a good agreement with the results in the graphs showing that the predicted indoor $PM_{1.0}$ concentration was always the closest to the measured one, followed by $PM_{2.5}$ and PM_{10}. The error between estimated and measured indoor $PM_{1.0}$ levels varied from 9.41% to 18.32%, below the criterion value of 30%. In comparison, the NME value for comparing estimated and measured indoor $PM_{2.5}$ levels ranged between 15.28% and 38.17%, which sometimes does not meet the criteria but which is generally acceptable. However, for PM_{10}, the NME value was significantly over the standard value, from 35.5% to 96.62%. Furthermore, from Table 3, the correlation coefficient (r) value can be seen to be at least over 0.87, which indicates that the estimated IPL had a better agreement in variability over the entire range of the measured one.

According to the data analysis, the smaller particle, $PM_{1.0}$ and $PM_{2.5}$, are suggested to be used as a tracer for predicting the real-time AER of a building.

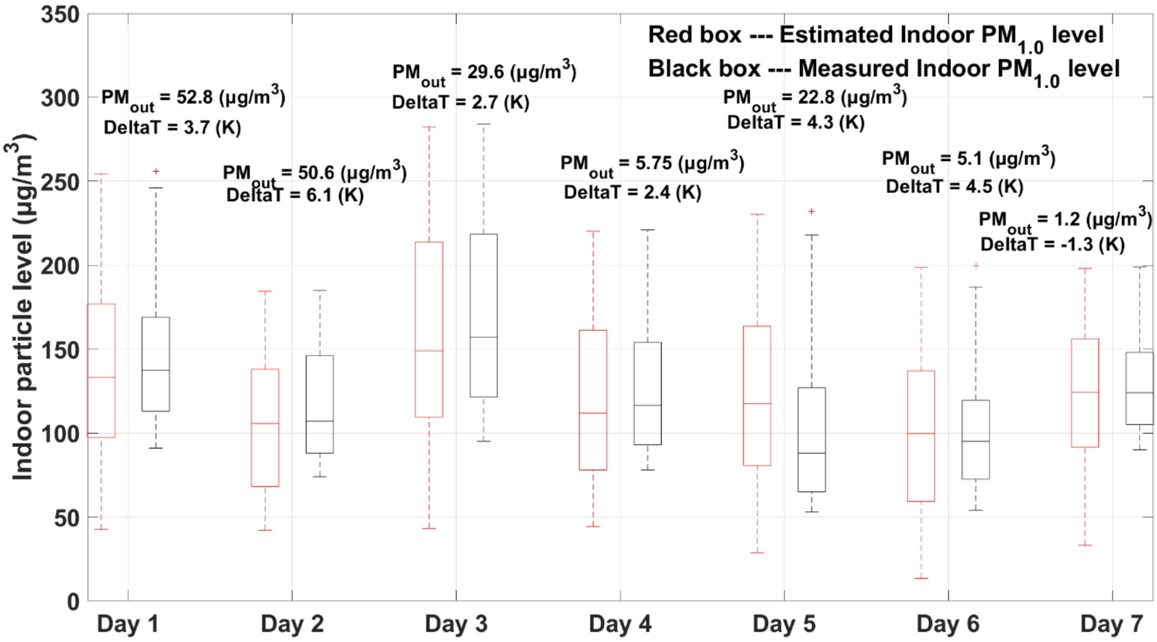

Figure 10: Comparison between the measured and predicted indoor $PM_{1.0}$ concentration (For each box, the five horizontal lines in order from bottom to top are the minimum value, 1st quartile, Median value, 3rd quartile, and maximum value)

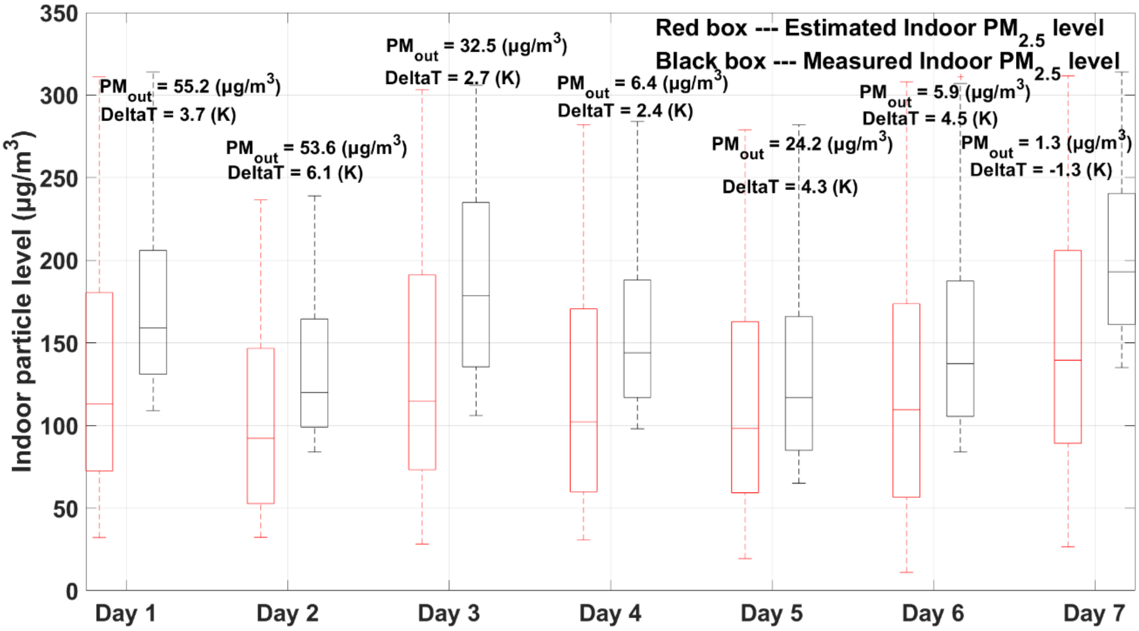

Figure 11: Comparison between the measured and predicted indoor $PM_{2.5}$ concentration (For each box, the five horizontal lines in order from bottom to top are the minimum value, 1st quartile, Median value, 3rd quartile, and maximum value)

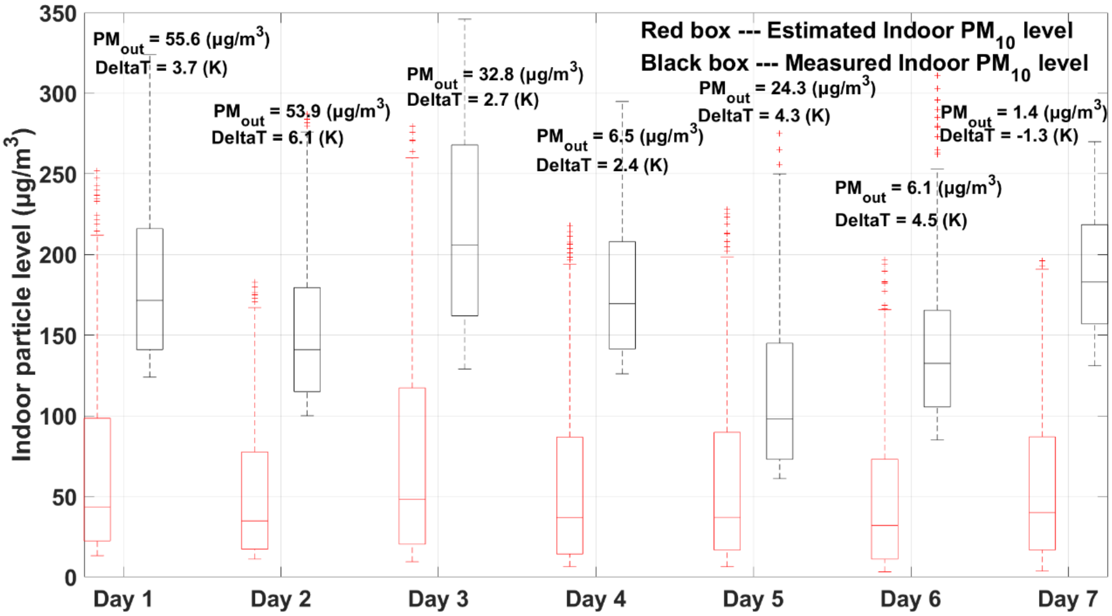

Figure 12: Comparison between the measured and predicted indoor PM_{10} concentration (For each box, the five horizontal lines in order from bottom to top are the minimum value, 1st quartile, Median value, 3rd quartile, and maximum value)

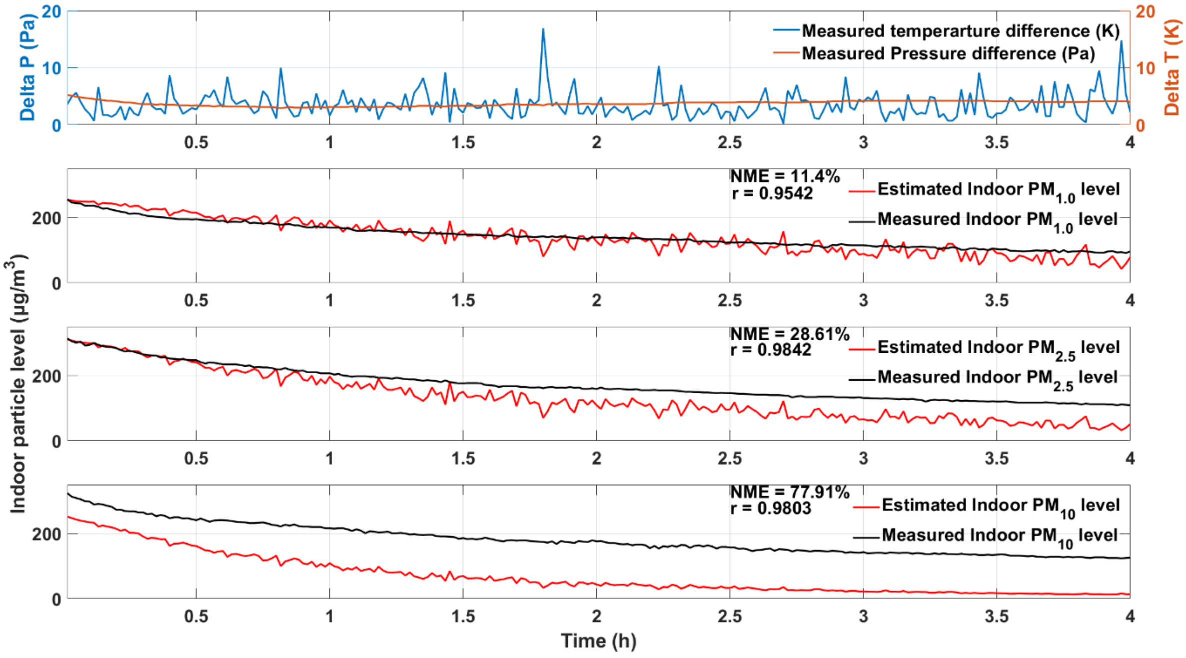

Figure 13: Time-varied estimated and measured IPL, selected one day as an example

Table 3: The accuracy analysis of using airborne particles to estimate the real-time AER

		Outdoor level (μg/m^3)	ΔT (K)	NME (%)	r
Day 1	$PM_{1.0}$	52.8 (42 - 68)[1]	3.7 (2.9 - 5.2)[2]	11.4	0.9542
	$PM_{2.5}$	55.2 (44 -72)		28.61	0.9842
	PM_{10}	55.6 (45 - 72)		77.91	0.9803
Day 2	$PM_{1.0}$	50.6 (41 - 65)	6.1 (5.6 - 8.5)	9.41	0.9564
	$PM_{2.5}$	53.6 (42 - 70)		19.88	0.9824
	PM_{10}	53.9 (43 - 71)		68	0.9834
Day 3	$PM_{1.0}$	29.6 (22 - 34)	2.7 (1.8 - 3.2)	14.98	0.9223
	$PM_{2.5}$	32.5 (24 - 39)		38.17	0.9611
	PM_{10}	32.8 (24 - 39)		96.62	0.9502
Day 4	$PM_{1.0}$	5.75 (2 - 10)	2.4 (1.5 - 4.7)	11.4	0.9392
	$PM_{2.5}$	6.4 (3 - 11)		26.28	0.9717
	PM_{10}	6.5 (3 - 11)		81.26	0.9585
Day 5	$PM_{1.0}$	22.8 (16-39)	4.3 (3 - 8.6)	18.32	0.9013
	$PM_{2.5}$	24.2 (17 - 42)		15.28	0.9637
	PM_{10}	24.3 (17 - 42)		35.05	0.9815
Day 6	$PM_{1.0}$	5.1 (3 - 7)	4.5 (3.5 - 6.6)	13.99	0.8716
	$PM_{2.5}$	5.9 (4 - 9)		25.23	0.9459
	PM_{10}	6.1 (4 - 9)		64.93	0.9782
Day 7	$PM_{1.0}$	1.2 (1 -4)	-1.3 (-2.5 – 0.2)	9.82	0.9082
	$PM_{2.5}$	1.3 (1 -4)		35.42	0.9756
	PM_{10}	1.4 (1-5)		89.3	0.9563

Hint: 1. From left to right, the three values represent the average, minimum, and maximum outdoor particle level during the experiments.

2. From left to right, the three values represent the average, minimum, and maximum temperature difference between indoors and outdoors.

3.3 The impact of outdoor conditions on the accuracy of estimating real-time AER

According to the mass balance equation, the IPL is a function of the OPL and AER, and the AER of a building is highly related to the pressure difference between indoors and outdoors. Hence, it is reasonable to believe that the value of these two factors may impact upon the accuracy of estimating IPL. To this end, Spearman's rank correlation coefficient ρ for ranked data was used to evaluate the relationship between the NME, which represents the error between measured and estimated IPL, and these two factors. This section used the instantaneous NME value to compare with the measured OPL and pressure differential, and the results are shown in Table 4. According to the statistical analysis, the OPL and pressure differential will significantly influence the predicting accuracy of the IPL and also affect the accuracy of predicting AER.

Table 4 illustrates that the particles' Indoor/Outdoor (I/O) ratio significantly and negatively impacts on the NME between measured and estimated IPL. The results indicate that the accuracy in estimating AER will increase when the I/O ratio of particles increases, and this pattern is more noticeable in larger particles as the ρ value is closer to unity. However, this trend was not visible when the OPL was extremely low, such as on Day 7, and the influence was more significant on the larger particles than on the smaller ones. From Table 3, the results on Day 7 indicate that the estimated indoor $PM_{2.5}$ and PM_{10} levels were discrete from the actual value since the NME value exceeds the baseline value of 30%, while the NME value for $PM_{1.0}$ is only around 10%. The finding indicates that the $PM_{1.0}$-based method can still have acceptable performance in predicting AER when the OPL is extremely low. One of the possible reasons is that outdoor $PM_{1.0}$ is the dominant source of indoor $PM_{1.0}$ particles in a building with no cooking allowed (Lee et al., 2006). For indoor $PM_{2.5}$ and PM_{10}, the low outdoor level may cause its impact to be decreased with results in the IPL being affected by other factors, such as resuspension and deposition mechanisms (Stratigou et al., 2020).

Moreover, the pressure differential positively impacts on the accuracy of estimating IPL and predicting AER based on airborne particles. Spearman's rank correlation coefficient analysis shows that the significance of the pressure differential's negative impact is lower than the I/O ratio's impact, as the ρ value is small. Based on the results, the impact of pressure differential is more substantial on the accuracy of estimating smaller particles' IPL since the ρ value is decreased when particle size increases. In addition, the pressure difference between indoors and outdoors mainly consists of stack-effect and wind-effect. However, from Figure 13, the measured IPL has not followed the variation of the measured pressure differential, and its fluctuation is better fitted with the temperature differential. The results indicate that the wind effect's impact on the IPL can be neglected, which shows a better agreement with the previous result that the stack effect is the dominant force in driving the AER in a high-rise building (Fu et al., 2021b).

Accordingly, both factors negatively impact on the NME between measured and estimated IPL, which means both factors positively impact estimating IPL and predicting AER based on airborne particles. Moreover, the I/O ratio has a more notable impact on larger particles, while the impact of pressure differential has a more significant impact on smaller particles. However, considering all factors, the smaller particles, with sizes smaller than 2.5 μm, are suggested to be used as a tracer to predict the AER of a building.

Table 4: The results of the correlation analysis based on Spearman's rank correlation coefficient for ranked data

NME value		I/O ratio	Delta P
$PM_{1.0}$	Day 1	$\rho = -0.4494; p < 0.001$	$\rho = -0.2105; p < 0.001$
	Day 2	$\rho = -0.7523; p < 0.001$	$\rho = -0.7645; p < 0.001$
	Day 3	$\rho = -0.6351; p < 0.001$	$\rho = -0.4376; p < 0.001$

	Day 4	ρ = -0.3883; p < 0.001	ρ = -0.2152; p < 0.001
	Day 5	ρ = -0.1496 p < 0.001	ρ = -0.4578; p < 0.001
	Day 6	ρ = -0.4567; p < 0.001	ρ = -0.1114; p < 0.001
	Day 7	ρ = -0.2917; p < 0.001	ρ = -0.2743; p < 0.001
$PM_{2.5}$	Day 1	ρ = -0.8187; p < 0.001	ρ = -0.3022; p < 0.001
	Day 2	ρ = -0.8604; p < 0.001	ρ = -0.7426; p < 0.001
	Day 3	ρ = -0.7887; p < 0.001	ρ = -0.4786; p < 0.001
	Day 4	ρ = -0.8438; p < 0.001	ρ = -0.4398; p < 0.001
	Day 5	ρ = -0.5748; p < 0.001	ρ = -0.2996; p < 0.001
	Day 6	ρ = -0.7114; p < 0.001	ρ = -0.4180; p < 0.001
	Day 7	ρ = -0.0305; p <0.05	ρ = -0.3247; p < 0.001
PM_{10}	Day 1	ρ = -0.8468; p < 0.001	ρ = -0.4951; p < 0.001
	Day 2	ρ = -0.9107; p < 0.001	ρ = -0.5826; p < 0.001
	Day 3	ρ = -0.9494; p < 0.001	ρ = -0.2914; p < 0.001
	Day 4	ρ = -0.9251; p < 0.001	ρ = -0.3045; p < 0.001
	Day 5	ρ = -0.8466; p < 0.001	ρ = -0.1546; p < 0.001
	Day 6	ρ = -0.9203; p < 0.001	ρ = -0.1995; p < 0.001
	Day 7	ρ = 0.2025; p < 0.05	ρ = -0.1707; p < 0.001

3.4 The empirical correlation for predicting the air exchange rate

As discussed, the particle size, I/O ratio, and pressure differential significantly impact on estimating IPL and predicting the AER based on the airborne particles. Moreover, the pressure difference is the dominant force driving the AER and impacts upon the IPL. Hence, the aim is to use a function that contains a pressure differential and the I/O ratio of particles to describe the AER of a building. It is worth mentioning that the data on Day 7 were removed when establishing the numerical model since it was inaccurate based on the analysis. Moreover, the I/O ratios for $PM_{1.0}$ and $PM_{2.5}$ are applied to establish the numerical model because the PM_{10}-based AER estimation method has been shown to be less accurate. The numerical model was constructed based on the AER, determined by the measured pressure differential, measured I/O ratio of $PM_{1.0}$ and $PM_{2.5}$, and measured pressure differential. The results are displayed in Figure 14 and Figure 15. Moreover, the experimental data-based empirical correlations are shown in Equations 9 and 10.

For $PM_{1.0}$: $$AER = 0.112 + 0.05305 \times |\Delta P| - 0.002567 \times \frac{I}{O} + 0.000918 \times |\Delta P| \times \frac{I}{O} + 5.635 \times 10^{-5} \times \frac{I}{O}^{\,2} - 1.713 \times 10^{-5} \times |\Delta P| \times \frac{I}{O}^{\,2} - 2.108 \times 10^{-7} \times \frac{I}{O}^{\,3} \quad (R^2 = 0.9891) \qquad (9)$$

For PM2.5: $AER = 0.1101 + 0.05332 \times |\Delta P| - 0.001842 \times \frac{I}{O} + 0.0007822 \times |\Delta P| \times \frac{I}{O} + 2.419 \times 10^{-5} \times \frac{I}{O}^{2} - 1.206 \times 10^{-5} \times |\Delta P| \times \frac{I}{O}^{2} + 4.524 \times 10^{-8} \times \frac{I}{O}^{3} \quad (R^2 = 0.9891)$ (10)

where AER is the air exchange rate in h^{-1}, ΔP is the pressure differential in Pa, and $\frac{I}{O}$ is the indoor/outdoor particles level's ratio, no units.

It can be seen from Figure 14 and Figure 15 that the error of the fitted model occurred due to several discrete points. Based on the analysis of the input data, those discrete points were mainly collected at the stage that the IPL has not reached a steady state, and the reason has been discussed in Section 3.2. In addition, in order to verify the developed numerical model, the 5-fold Cross-Validation was applied.

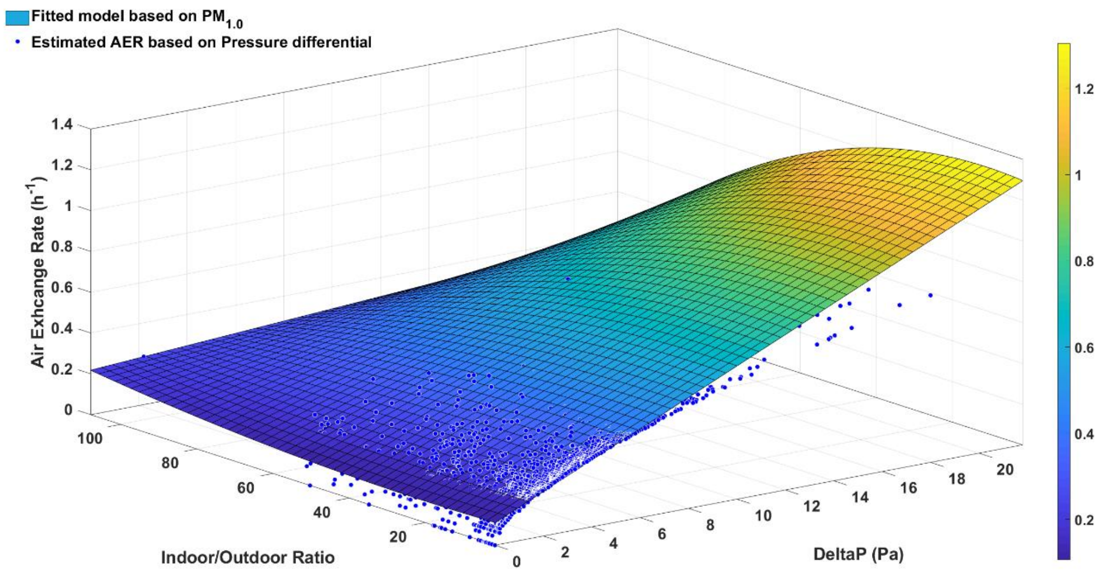

Figure 14: The fitted model of AER based on the I/O ratio of $PM_{1.0}$ and pressure differential

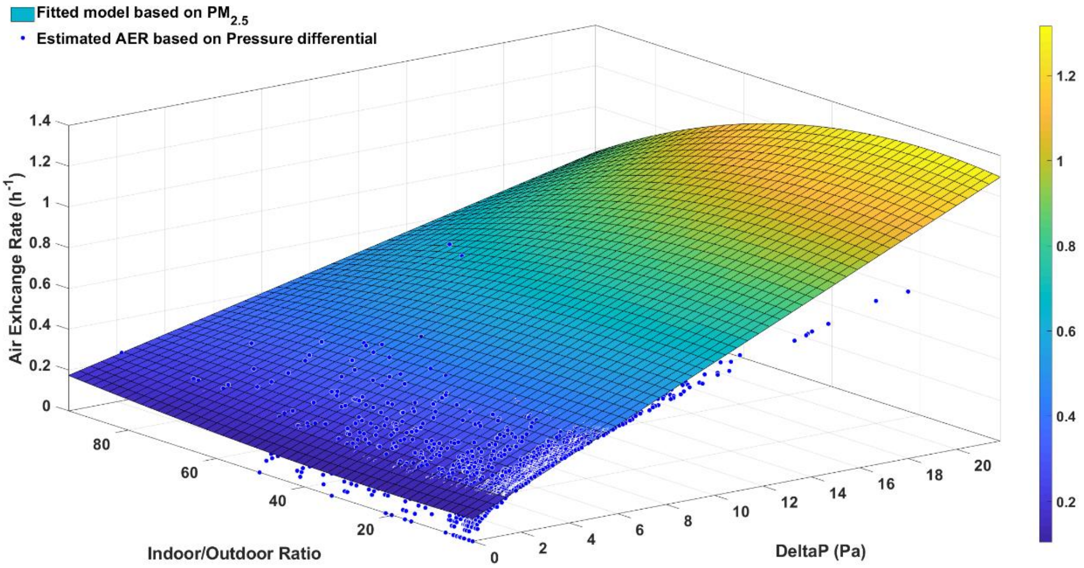

Figure 15: The fitted model of AER based on the I/O ratio of $PM_{2.5}$ and pressure differential

3.4.1 Accuracy analysis

In order to assess the accuracy of the numerical model, the extra group of data collected in the previous work were used to verify the empirical correlation. The measured data in different seasons were input into Equations (9) and (10) to get the estimated real-time AER, and Figure 16, with a selected one day as an example, presents the comparison results of the estimated real-time AER with the measured value. Table 5 compares all estimated AER with the actual AER by using the NME and r values.

Figure 15 shows that the estimated AER based on the established numerical model fits well with the measured real-time AER. Compared with the actual AER, the $PM_{1.0}$-based method gave an NME of 2.3% and an r of 0.9879, while the $PM_{2.5}$-based method gave an NME of 2.4% and an r of 0.9896. It can be seen that the accuracy of estimating the real-time AER is generally the same, which also can be proved according to Table 5. This may be because in China $PM_{1.0}$ is the dominant component of $PM_{2.5}$ (Chen et al., 2017; Yang et al., 2020). Moreover, Table 5 indicates that the established equation performed well in all other cases under different outdoor conditions and seasons, even when the outdoor particle level was relatively low, such as on Day 3 in the spring. Hence, the empirical correlation can be used to determine the real-time AER based on the airborne particles and help designers accurately predict the building's heat loss.

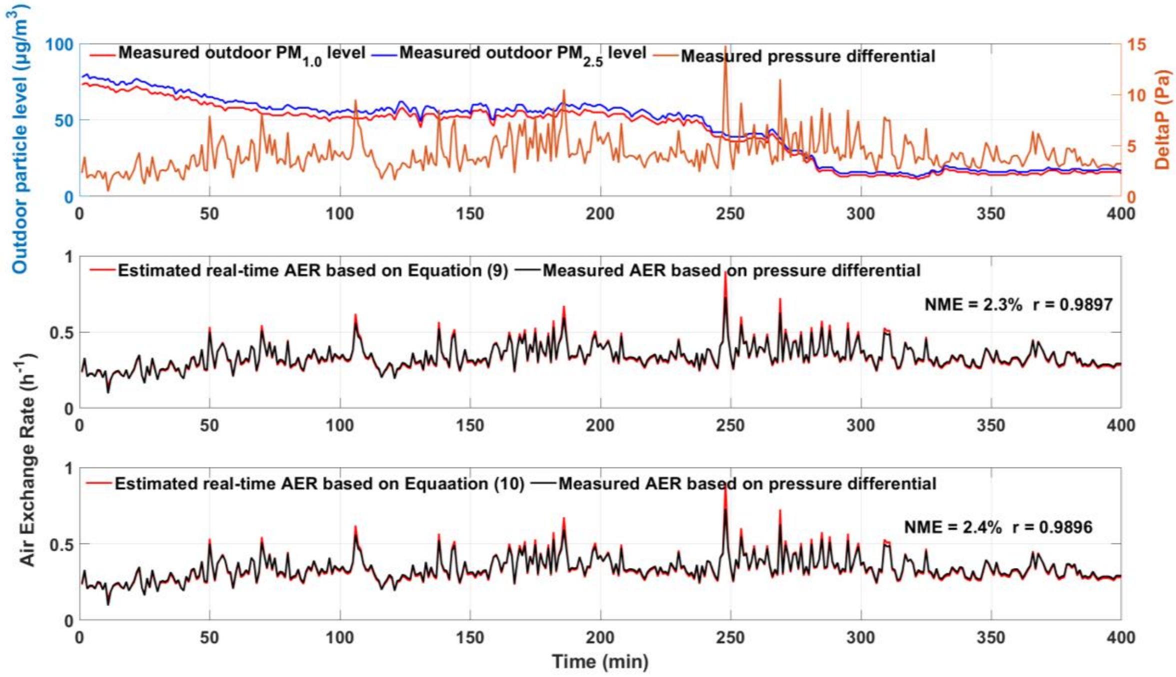

Figure 16: The comparison of the estimated real-time AER with the measured value

Table 5: Accuracy analysis of the numerical model

		Average outdoor level (μg/m^3)	Average deltaP (Pa)	NME (%)	r
Winter Day 1	$PM_{1.0}$	64.96	2.94	4.37	0.991
	$PM_{2.5}$	70.46		4.42	0.991
Winter Day 2	$PM_{1.0}$	107.10	2.73	7.93	0.980
	$PM_{2.5}$	117.63		7.87	0.980
Winter Day 3	$PM_{1.0}$	38.18	4.92	3.54	0.989
	$PM_{2.5}$	42.24		3.68	0.989
Spring Day 1	$PM_{1.0}$	43.63	4.01	3	0.986
	$PM_{2.5}$	46.28		3.11	0.986

Spring Day 2	$PM_{1.0}$	40.31	4.16	2.3	0.990
	$PM_{2.5}$	43.59		2.42	0.990
Spring Day 3	$PM_{1.0}$	8.10	1.32	7.48	0.976
	$PM_{2.5}$	9.22		7.04	0.976

4 Conclusion

An experimental- and numerical simulation-based study was conducted to explore the reliability of using airborne particles as a tracer to predict the AER of a building. In this study, the blower door test was used to determine the airtightness of the selected room, and the experiment results were utilized to assess the real-time AER. The results indicated that particle size and outdoor conditions impacted significantly on the accuracy of estimating the IPL and predicting the real-time AER.

Based on the analysis, it was found that the AER estimation accuracy based on particles has a significantly negative correlation with the particle size, and thus particle sizes under 2.5 μm are suggested to be used as a tracer to predict the AER. This is because the smaller particles have a higher penetration rate, which is more accessible to enter the room with the infiltration air, and thus the result of the estimated AER based on the small particle is closer to the real AER. Moreover, the I/O ratio of particles and pressure differential positively impact on AER estimation accuracy, and the impact of the I/O ratio of particles is more substantial than the pressure differentials. However, it is worth mentioning that the accuracy of using the particle-based method to estimate AER is decreased when the outdoor particle level is decreased, while this influence is lowered as the particle size is decreased.

Furthermore, an experiment data-based empirical correlation was established for $PM_{1.0}$ and $PM_{2.5}$, and both numerical models were verified using the 5-fold cross-validation method. The empirical correlations have proved that it is reliable to predict the real-time AER under various outdoor conditions using the data collected in the previous work. Hence, the equation can be used to determine the real-time AER of a building according to the measured IPL, OPL, and pressure differential. It is suggested to use small size particles as the tracer to measure the real-time AER of a high-rise building since the tracer gas method is limited, and also, the real-time AER could precisely predict the heat loss of the building.

In addition to the contributions of this study, some technical limitations are also present to be explored via further research investigation. Firstly, the IPL is also impacted by the deposition and resuspension rate, and these two mechanisms are correlated to human indoor activities. However, this study only concerned the scenario in which the selected room is unoccupied, and thus, further research is required to investigate how human activities disturb the accuracy of using particles as the tracer to measure the AER of a building. An office room was chosen for this analysis with a focus on its air pollution level and the impact of AER. However, since the estimated air pollution levels and air infiltration levels may be different, depending on neighbouring rooms' air pressures and pollution levels, the building's façade opening ratio, ventilation system performance and occupants' behaviour, a further study should carefully consider other elements, such as indoor air pollution sources, air purifier, construction material, wind velocity and direction, and other system facilities. These would be crucial, especially when indoor air quality and occupants' health in buildings are significantly affected by surrounding environments. Also, another parameter may need to be considered for estimating AER during low levels of outdoor particle seasons. Moreover, other actual air contaminant types should be considered to indicate the sources of air contaminants. In a future study, AER could be estimated using other air contaminant sources such as Sulphur Oxides (SOx) and Nitrogen Oxides (NOx), which also come from the surrounding outdoor environment.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Corresponding Author:

Moon Keun Kim, Prof. Dr.sc.ETH,
Department of Civil Engineering and Energy Technology
Oslo Metropolitan University

14. OCT. 2022

Co Authors:

Nuodi Fu
Moon Keun Kim, Prof. Dr.sc.ETH
Long Huang, Assistent Professor
Jiying Liu, Associate Prof. PhD
Bing Chen, Associate Prof. PhD
Stephen Sharples, Professor, PhD

Author Contributions Statement

Nuodi Fu carried out the conceptualization, methodology, analysis, and writing. Moon Keun Kim carried out conceptualization, methodology, project management, reviewing and editing. Long Huang carried out experiments, reviewing and editing. Jiying Liu carried out methodology, reviewing and editing. Bing Chen carried out project administration and reviewing. And Stephen Sharples carried out supervising, reviewing, and editing.