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Passive $PM_{2.5}$ control plan of educational buildings by using airtight improvement technologies in South Korea

Sungwoong Yang, Hyeonseong Yuk, Beom Yeol Yun, Young Uk Kim, Seunghwan Wi, Sumin Kim *

Department of Architecture and Architectural Engineering, Yonsei University, Seoul 03722, Republic of Korea

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ABSTRACT

Modern people spend most of their time indoors. Therefore, controlling indoor air quality is one of the most important factors for health. The indoor fine dust concentration is affected by the outdoor fine dust concentration. When the latter is high, it increases due to immersion. Therefore, improving the sealing performance of a building is an effective strategy to reduce indoor fine dust concentration during periods of severe outdoor fine dust without considering indoor fine dust generating factors. Traditional methods of improving the airtightness of a building have focused on replacing windows or doors. However, for reasons such as constructability and economic feasibility, more diverse technologies need to be considered. Due to this necessity, this study applied technologies such as sealing film, sealing lid, and padding to the educational building, and then derived the airtight performance through the blower door experiment, and measured the fine dust concentration to evaluate the effect. As a result of the experiment, it was analyzed that air leakage was reduced by up to 37% and fine dust by 22%.

1. Introduction

Particulate matter, especially particulate matter 2.5 ($PM_{2.5}$), refers to particles with a diameter of 2.5µm or less and is known to cause various lung diseases, negatively impacting human health (Falcon-Rodriguez et al., 2016). The World Health Organization (WHO) defines $PM_{2.5}$ as a hazardous substance and publicizes its dangers of (World Health Organization, 2013). However, for $PM_{2.5}$ caused by artificial factors, the average annual concentration and short-term human impacts exceed WHO guidelines (Martins and Carrilho da Graça, 2018). The reason $PM_{2.5}$ is threatening is due to the physical size of the particles; once they enter the body they can penetrate the tissues of the alveoli, causing various diseases (Polichetti et al., 2009). Formation of $PM_{2.5}$ has become more active due to the recent increase in anthropogenic generation, and has increased in parallel with the utilization of carbon-based fuels (Claxton, 2015; Park et al., 2019). In addition, at low concentrations, there may be very harmful effects as a result of heavy metal elements (Zhang et al., 2016). The reason that $PM_{2.5}$ and particulate matter issues are linked to the indoor air quality of buildings is that modern humans live indoors for more than 80% of the day, which means that indoor air quality has a serious impact on human health (Kornartit et al., 2010; Klepeis et al., 2001).

A strategy for controlling particulate matter is shown in Fig. 1. When there is more particulate matter indoors than outdoors, it is an effective strategy to dilute the outdoor air in the room by equipping buildings with indoor systems that remove particulate matter. When the dust is worse outdoors than the indoors, it is an effective strategy to prevent the inflow of particulate matter outside and remove the particulate matter indoors through air filtration systems.

If the indoor and outdoor concentrations are similar, it is an effective strategy to remove indoor particulate matter through various air filtration equipment (Chu et al., 2017). Research to control indoor particulate matter using ventilation technology considers using a filter that can screen and remove particulate matter from the air breathed (Spilak et al., 2014; Cho et al., 2020). Wang et al. reported that the concentration of indoor particulate matter decreased according to the concentration of outdoor particulate matter, which means that the particulate matter of the building is affected by the outdoor dust concentration (Wang and Yu, 2017). In addition, the outdoor-indoor influence of $PM_{2.5}$ has been defined by a coefficient derived by numerical hydrodynamic analysis (Long et al., 2001). In particular, a study by Zuo et al. using analysis and estimation through big data reported that about

* Corresponding author.
E-mail address: kimsumin@yonsei.ac.kr (S. Kim).

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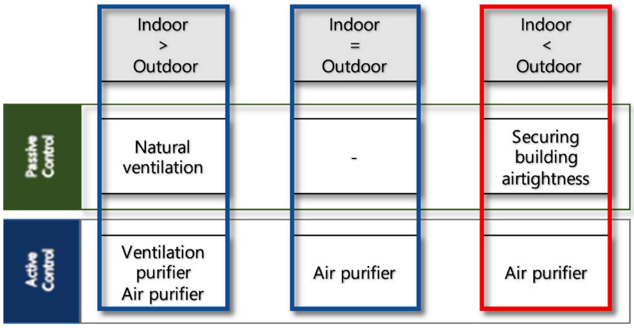

Fig. 1. Strategies from an architectural perspective for $PM_{2.5}$ control.

42–52% of particulate matter was introduced indoors (Zuo et al., 2018). In particular, from a strategic point of view, it is necessary to focus on research that considers the influence of the outdoor environment for particulate matter generated in educational buildings as fundamental in reducing particulate matter (Diapouli et al., 2008). In the case of the educational facilities or school buildings at Hangung, our focus of study, the sale of cigarettes to minors and smoking indoors are prohibited, so there is no internal PM due to smoking. This makes it possible to consider the indoor PM generated inside the school as the outdoors (Raysoni et al., 2011).

As a method for controlling indoor particulate matter, Zhong et al. conducted a study where they attempted to maintain acceptable levels of $PM_{2.5}$ by using window and roller blinds (Zhong et al., 2020). Zhang. et al. conducted an analysis on the amount of energy generated when indoor air quality relies on the use of ventilation windows (Zhang et al., 2016). These studies point out that indoor particulate matter control can reduce the burden of maintaining air quality from a passive perspective.

Wan et al. regarded the reason for indoor penetration of outdoor particulate matter as a symptom of window spacing and conducted a study on indoor particulate matter with closed windows; the ratio of the indoor particulate matter to the outdoor particulate matter concentration (I/O ratio) showed a higher tendency for the less airtight spaces than the more airtight ones (Wan et al., 2015). Li et al. identified particulate matter introduced by infiltration from outdoors as a factor that affects levels of indoor particulate matter, but did not deal with the particulate matter control strategy through improved airtightness performance (Li et al., 2017). This means that the indoor penetration of $PM_{2.5}$ has a clear relationship with the building airtightness performance, but there is still a lack of accurate evaluations of this issue. Many retrofit methods have been proposed as a way to improve airtight performance. Cho et al. gave the example of window replacement (Cho et al., 2020), while Carratt et al. reviewed the retrofit method for residential buildings (Carratt et al., 2020). Ventilation and penetration were reviewed in the retrofit method, and the technology at that level was discussed in comparison with the relatively traditional methods of air penetration. Thus, the retrofit of a particular building needs to be considered for particulate matter and technologies for improving the airtight performance of buildings need to be dealt with in various ways.

Chen et al. reported on airtight performance according to type of opening and found that the airtight performance of a sliding-type opening was the worst according to the experimental results (Chen et al., 2020). This means that the airtightness of the building may be affected by the shape of the opening. Provan and Yonger have conducted research on more detailed and diverse windows (Provan and Younger, 1986). In the research, airtightness performance according to the opening shape of the horizontal pivot, vertical pivot, side hung, top hung, bottom hung, tilt-and-turn, horizontal slider, and vertical slider were analyzed, with sliding type showing the worst performance in terms of dust control. In the case of Korean schools, as a law, sliding doors are required to prevent safety accidents in educational facilities. This can be the cause of having a relatively low airtight performance, as previous experiments have also shown (School Safety Accident Prevention and Compensation, 2014).

Therefore, the goals of this study are as follows. First, a strategy has been used to improve airtightness as a way to reduce particulate matter. This is effective when preventing outer particulate matter from entering the interior. The methods to reduce particulate matter at this time are window replacement and airtight performance improvement technologies. The reduction of particulate matter due to the improvement of airtightness performance is analyzed, and quantitative comparisons are made to determine which building components were reduced and how.

2. Methodology

2.1. Objective experimental building

Experiments were conducted on actual buildings to analyze the impact of particulate matter through improved airtightness performance. The building to be tested was conducted on a five stories school building. Information about the area where the building is located is shown Table 1.

The target building where the experiment was conducted is shown in the images in Fig. 2. They show (a) the overall appearance of the five-story building and (b) the interior of the science lab.

In the case of the science, the internal window is completely covered by a storage space for the experimental equipment. In addition, it is finished with tiles, and in the case of (c), represents a technical family class, where a duct is installed for cooking, while (d) represents the interior of the library and has the largest number of doors and windows. In the case of (e), it represents a music room. In order to avoid disturbing other classrooms, the inner window was removed and soundproofing material was installed. In the case of (f), it represents the interior of the art room and has the same structure as a general classroom. The information of the target spaces where the experiment was conducted is shown Table 2.

The size and shape of the outdoor window, interior window, and door are shown in Fig. 3. Each component has a measurement area and is defined as P1, P2, P3, and P4, according to the number of point. In the case of the science and music rooms, there are no indoor windows due to the purpose and use. The area of library is wider than other rooms and has more outer and inner windows. The technical and family rooms were later relabeled under the name TechFam.

2.2. Experimental items and measurement method

Fig. 4 shows the overall experimental procedure. First, experiments are classified into pre-diagnosis, performance improvement through technical use, and measurement after improvement. For pre-diagnosis, the airtightness performance of the classroom was measured. While evaluating the airtightness of the space, the major air leakage areas are diagnosed and the technology to be applied is calculated. After pre-diagnosis, window replacement is carried out and airtight performance and particulate matter are measured. After applying various techniques to improve airtight performance, the airtight performance

Table 1
Geographical characteristics of the experimental target building.

Classification	Contents	Description
Country	Republic of Korea	–
City	Dongducheon, Namyangju	–
Latitude	37.93°	–
longitude	127.04°	–
Orientation	East	–
Köppen Climate	Dwa	The climate is dry in winter and hot in summer.

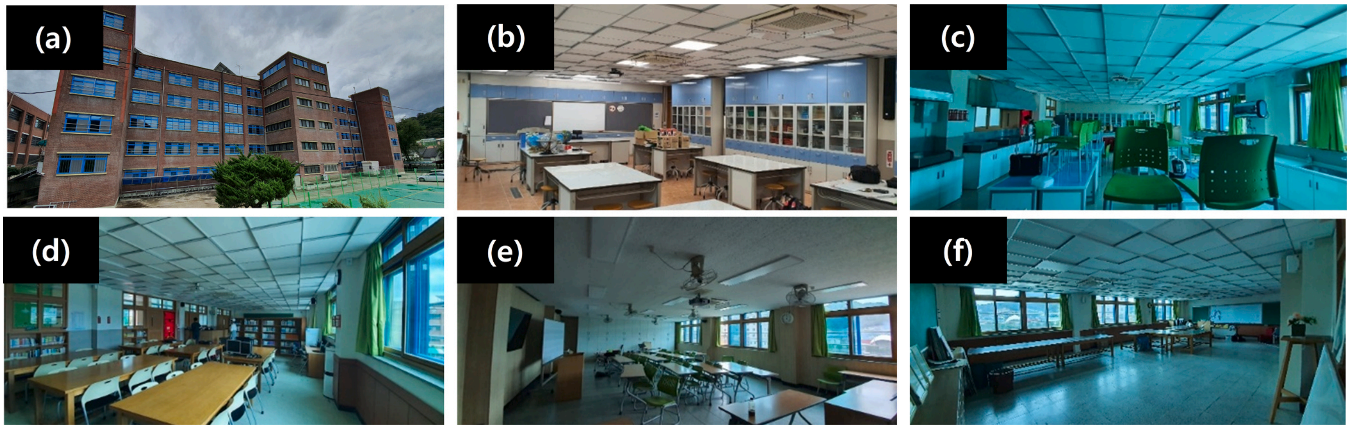

Fig. 2. (a) Overall view of the building, (b) science classroom, (c) technical and family classroom, (d) library, (e) music classroom, and (f) art classroom.

Table 2
Spatial information of the classroom to be tested.

Classification	Number of floors	Area (m^2)	Door	Outer window	Inner window	Height
Science	1	97.5	2	3	–	2.7
Technical and family	2	97.5	2	3	3	2.7
Library	3	135	4	4	4	2.7
Music	5	97.5	2	3	–	2.7
Art	5	97.5	2	3	2	2.7

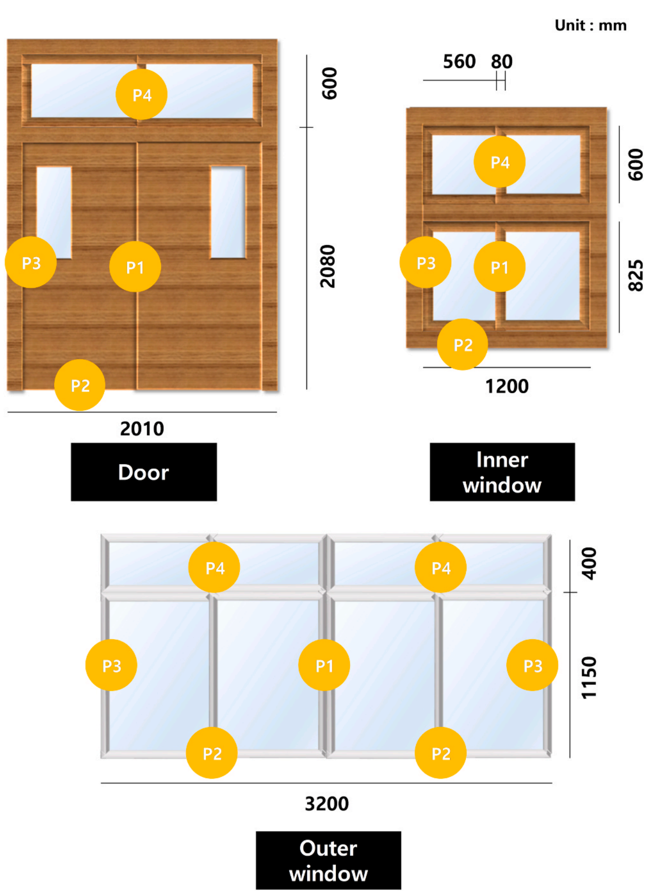

Fig. 3. Building component information and measurement points to be improved.

and particulate matter levels are measured again and the effect of the improvement is analyzed.

2.2.1. Airtight performance measurement method

A blower door test was conducted to measure airtight performance according to ISO9972 (ISO 9972:2015, 2015; Allard et al., 2012), and the average of the results was measured by the decompression method and the pressurization method. To evaluate the occurrence of infiltration through parts of the building, thermal imaging cameras were used and wind speed measurement was performed. Thermal imaging camera and wind speed measurement were conducted while maintaining the pressure difference between indoors and outdoors at 50 Pa. Due to the artificial large pressure difference, fluid movement occurs in areas such as the outer windows and doors. The subsequent large heat exchange phenomenon that occurs is detected to diagnose major infiltration sites. In addition, to quantify the relative evaluation of the occurrence of infiltration, the wind speed for each part was measured using a wind speed meter. Fig. 5 shows the instrument used in the experiment: (a) shows the blower door test device and the measurement scene; (b) shows the thermal imaging camera device used (872 Testo model); (c) shows the equipment used for wind speed measurement (Testo 440 model).

2.2.2. Particulate matter measurement methodology

For particulate matter, both indoors and outdoors were measured simultaneously. TSI's Optical Particle Sizer 3330 (OPS 3330) model was used as a measuring device. The measurement range was carried out for particles of up to 10 μm by dividing from 0.3 μm particles to each section. The measured value was analyzed by deriving the number of particles present at a constant flow rate. In the case of the experimental environment, particulate matter particles were generated after a one-hour stabilization period to avoid fluctuations in the concentration of particulate matter before the experiment. In the case of particulate matter particles, a candle made of paraffin was burned for ten minutes, after which the stability of the particulate matter was analyzed. After ensuring conditions were sufficiently stable, the difference in the concentration of outdoor particulate matter and indoor particulate matter and how the indoor concentration was affected compared to the outdoor particulate matter concentration were analyzed.

2.3. Technology for improving building airtight performance

To improve airtight performance, technology was applied to the major airtight performance improvement positions based on the results of thermal imaging camera analysis. Fig. 6 shows a photograph of the thermal imaging camera. In the case of outdoor windows, the window frame showed a low temperature, and in an environment of 50 Pa, the temperature sharply dropped due to the penetration of outside air at the

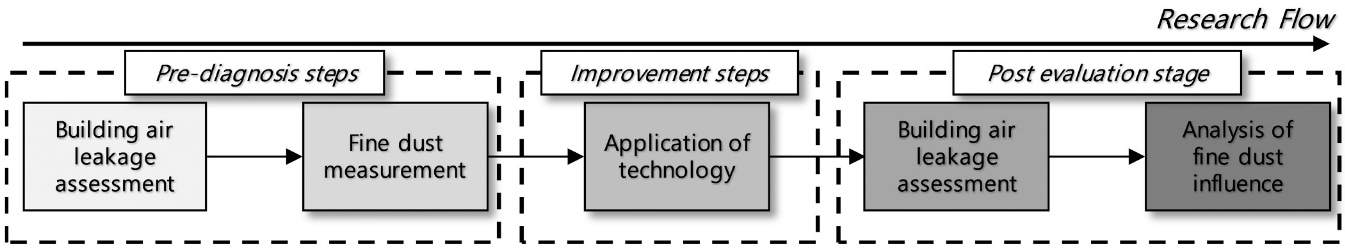

Fig. 4. Research flow and the overall experimental procedure.

Fig. 5. Instruments for measuring airtightness: (a) blower door test, (b) Testo 872, (c) Testo 440.

junction, indicating the need for improvement. In the case of the entrance door, it was determined that infiltration occurs in the area where the door and the door overlap and the gap between the frame and the door. In the case of interior windows, such as doors, thermal bridges occurred in gaps between windows and windows as well as between frames and windows. Based on these results, it was decided that these junctions needed improvement.

The improvement of airtight performance was made in two stages steps. First, in the case of the outer window, the frame was changed from a single polyvinyl chloride (PVC) window to a double window. Second, after the replacement of windows and doors, additional diagnosis was conducted and then it was used technology to improve airtightness performance.

Fig. 7 shows the technology installed in each area: (a) shows the technology installed on the outer window: an acrylic windbreaker to prevent infiltration that may occur at the bottom of the window, a windbreaker pad to fill the space of the window frame, a windbreaker made of hairy material installed on the overlapping part of the window, and cap-type technology on the side structure of the window were introduced to prevent infiltration from occurring. In the case of (b), these technologies were applied to the inner window, which were relatively smaller in size than the outer window. Moreover, the structural performance was weak, so a soft and flexible technology was applied. Urethane-type windshield was used for the space between the door and the frame on the side, and a ring-type windshield was used between the gap and the gap of the window. Similar to the principle applied to the outer window, a cover-type windbreaker was installed in the side gap of the window, and a material composed of a soft material was used. In the case of the entrance door, a urethane material windbreak material was used to reduce the infiltration between the door and the door, and a urethane material windshield material was also used between the side frames of the door. In addition, an acrylic windshield was used at the top and bottom. These materials can be easily obtained and constructed, and have the advantage of low unit price.

3. Results and discussion

3.1. Airtight performance measurement result

Fig. 8 shows the results of airtightness performance evaluation

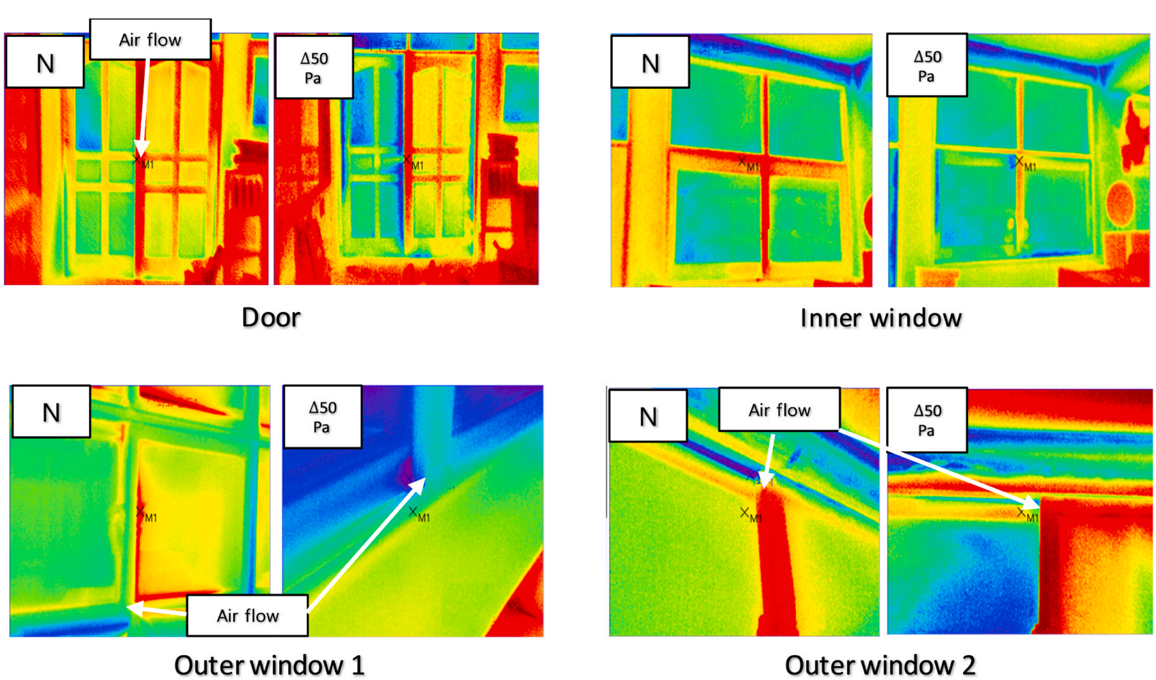

Fig. 6. Infrared thermal image of building components.

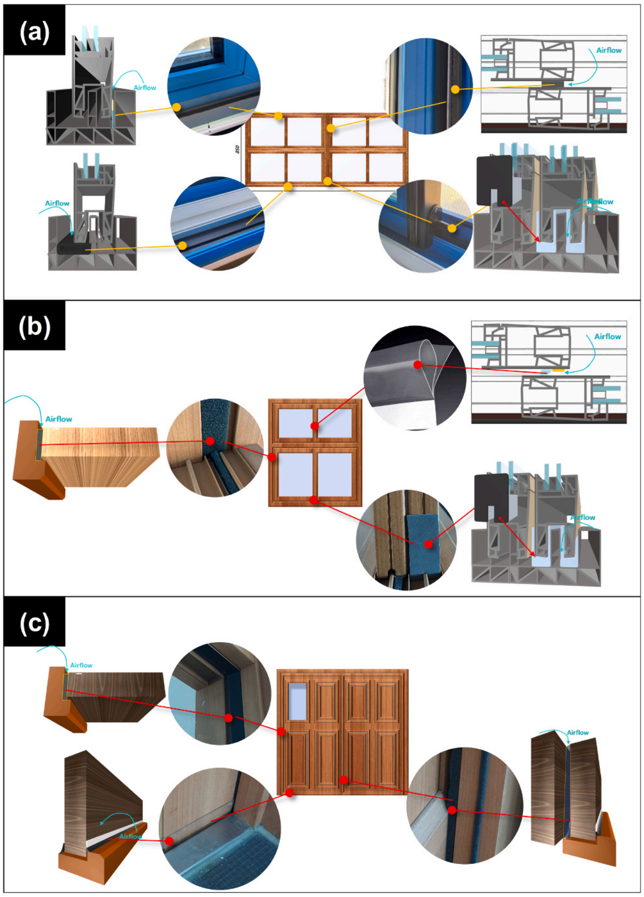

Fig. 7. Technology applied to each building component: (a) outer window, (b) inner window, (c) entrance door.

through two stages of airtightness improvement. In the Science lab, the existing ventilation amount was 25.79 ACH50 (air change per hour at 50 pressure difference), which was reduced to 22.36 ACH50 through window improvement, improving airtightness performance. In the case of TechFam (Technical and family), the initial ventilation frequency was 26.54 ACH50, which reduced to 24.4 ACH50 after the window was replaced, and the airtight performance was found to have improved. In the case of Library, the original ventilation frequency of 23.99 ACH50 was improved to 19.34 ACH50 after the window replacement. In the case of Music, the ventilation frequency was 13.55 ACH50, which also improved to 10.3 ACH50 after the window enhancement.

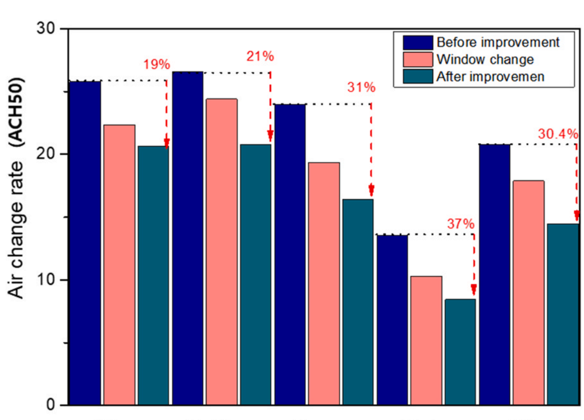

Fig. 8. Changes in building airtight performance according to technology application.

In the case of Art, the initial ventilation frequency was 20.8 ACH50, which improved to 17.87 ACH50 after the window replacement. In the science room, which has no inner window, airtight performance is lowered due to the indoor fume hood and the piping of the floor for use of water, and the ventilation frequency was considered relatively high. In the case of the technical home room, all inner windows were present and ducts installed for ventilation during cooking, showing the highest ventilation frequency among all rooms. The library has the most entrances and windows installed, and the amount of ventilation was considered high compared to the high volume. The music room has no indoor window or separate ducts and pipes, so it had the lowest ventilation frequency. The art room has no separate duct, but had a higher ventilation frequency than the music room due to the presence of an inner window.

Airtightness performance was improved in all rooms due to the replacement of windows, which was further boosted by applying additional technology. In the case of Science, as a result of improving airtightness performance, ventilation frequency decreased to 20.66 ACH50 and ventilation volume decreased by 19%. In the case of TechFam, as a result of applying all airtight performance technologies, ventilation frequency was reduced to 20.77 ACH50, a decrease of 21%. In the case of the library, which had many windows and doors, a decrease of up to 31% was noted, and in the case of music, the largest decrease was shown: 37%. In TechFam, Library, and Art, all of which had inner windows, the effect of additional technical improvement was higher, and in Science and Music, which did not, the effect in window improvement was relatively high.

These results can be discussed in more detail through wind speed measurements for each section, as shown in Table 3.

In the case of Science, a wind speed of 1.5 m/s, which was the highest among the average airflow from the outer window, was generated, but decreased to a maximum of 0.3 m/s due to the replacement of the outer window. In the case of TechFam, a wind speed of up to 1.1 m/s was recorded, which decreased to 0.2 m/s after the window replacement. In the case of Library, a wind speed of up to 1.3 m/s occurred, but airflow of only up to 0.3 m/s occurred after window replacement. In the case of Music, the maximum wind speed of 1.3 m/s decreased to 0.3 m/s, and in the case of Art, the maximum wind speed decreased from 1.5 m/s to 0.3 m/s. In the case of the entrance door and the inner window, on average, higher airflow was generated than that of the outer window. As a result of applying additional technology, airflow was not measured in other rooms except for Science, TechFam, and Library at the door. Also, the flow rate decreased by 0.3–0.1. As for the inner window, as a result of applying the technology, the airflow was not measured, except in the case of TechFam.

Considered in conjunction with the previously analyzed airtight performance results, the above results are proven valid when related to the reduction effect by a larger addition to technology in the classroom with indoor windows. In addition, relatively uniform airflow occurred in the part divided into other parts, and because other parts of the room were blocked, relatively more airflow was generated than before, indicating that the flow velocity of the corresponding part increased.

Chan et al. found that the average wall for low-income people (Chan et al., 2013). It has been reported that strengthening can reduce leakage by approximately 20–30%. Sinnott reported that building airtightness was improved through retrofit. In this study, it was reported that the installation of double-glazed windows had a significant positive influence and reduced air permeability by up to 39% (Sinnott and Dyer, 2012). In addition, it has been reported that the effect of up to 40% or more can be achieved from sealing windows and gaps in buildings composed of concrete walls (Tiberio and Branchi, 2013).

3.2. Analysis of indoor influence of outdoor particulate matter

To analyze the influence of indoor particulate matter on particulate matter, particle-by-particle analysis was performed. Fig. 9 shows the

Table 3
Wind speed measurement result for each room according to technology application.

Classification	Average wind speed measurement result (m/sec) before applying the technology															
	Door				Outer window				Inner Window				Other parts*			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
Science**	2.9	3.3	0.9	1.1	0.6	0.5	1.5	1.0	–	–	–	–	1.1	0.6	0.4	0.9
TechFam ***	3.3	3.1	2.8	0.2	1.1	0.9	0.9	0.8	2.5	4.5	2.2	1.2	0.9	0.9	–	–
Library	3.2	2.7	0.5	1.6	0.5	0.5	1.1	1.3	4.3	2.5	1.0	0.6	–	–	–	–
Music	2.3	1.4	1.9	0.9	1.3	1.1	0.6	2.5	–	–	–	–	–	–	–	–
Art	2.5	2.1	0.8	1.8	1.2	0.6	0.9	1.5	2.3	0.9	1.6	1.3	–	–	–	–
Classification	Average wind speed measurement result (m/sec) after changing window															
	Door				Outer window				Inner Window				Other parts*			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
Science**	2.8	3.5	1.0	1.1	0.2	0.1	0.2	0.3	–	–	–	–	1.3	0.7	0.5	1.1
TechFam ***	3.5	3.1	2.9	0.4	0.1	0.1	0.2	0.2	2.3	3.6	2.6	1.4	1.2	1.3	–	–
Library	3.3	2.6	0.7	1.6	0.3	0.2	0.1	0.3	3.8	2.6	1.0	0.8	–	–	–	–
Music	2.3	1.4	2.0	0.8	0.2	0.1	0.3	0.2	–	–	–	–	–	–	–	
Art	1.9	2.2	0.7	1.8	0.1	0.2	0.1	0.3	2.0	1.1	1.6	1.4	–	–	–	–
Classification	Average wind speed measurement result (m/sec) after applying airtight technologies															
	Door				Outer window				Inner Window				Other parts*			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
Science**	0.1	0.3	–	–					–	–	–	–	1.5	1.0	1.2	1.1
TechFam ***	0.2	0.1	–	–	–	–	–	0.1	0.2	–	–	–	1.2	1.1	–	–
Library	0.1	–	–	–	–	0.2	–	–	–	–	–	–	–	–	–	–
Music	–	–	–	–	–	–		–	–	–	–	–	–	–	–	–
Art	–	–	–	–	–	–	0.2	–	–	–	–	–	–			

*For other parts, the average value of the flow velocity generated in the space such as duct, piping, and fume hood were used.
** Science defines floor piping as P1, P2, P3 and fume hood as P4.
*** TechFam, cooking duct is defined as P1, P2.

ratio of the amount of particle distributions. In the case of (a), the measurement results of particulate matter indoors and outdoors in a stable state before the experiment are shown.

Particles of 0.3–0.5 µm occupied an average of more than 80%, and as a result of adding the particles of 0.5–0.7 µm, the average number of particles of 95% had a size of between 0.3 and 0.7 µm. However, as a result of burning a candle, the number of particles of 0.3–0.5 µm increased to an average of over 90%, and the number of particles corresponding to 0.3–1.0 µm accounted for about 98%. Therefore, the main target particles in the experiment are fine particles corresponding to 0.3–1.0 ㎛ (Fig. 9, (b)). Fig. 9 shows the indoor concentration versus the outdoor concentration of the total particle number (PN) of each room. (Fig. 10).

The influence of indoor particulate matter on outdoor particulate matter tended to decrease sequentially as the technology was applied. In the case of Science, the reduction effect due to the window replacement was greater, and the maximum reduction was 15% due to the application of technology. In the case of TechFam, the effect of additional

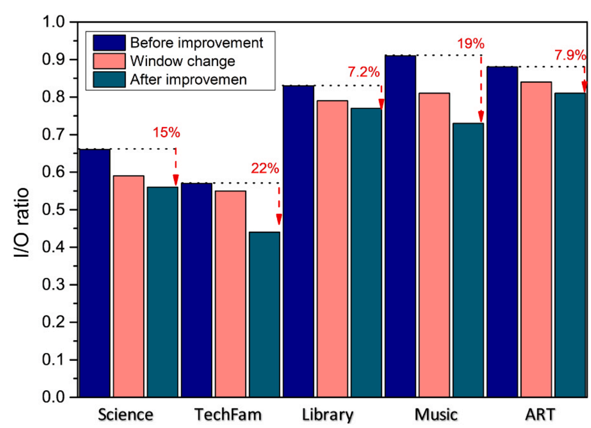

Fig. 10. Ratio of indoor particulate matter to outdoor particulate matter.

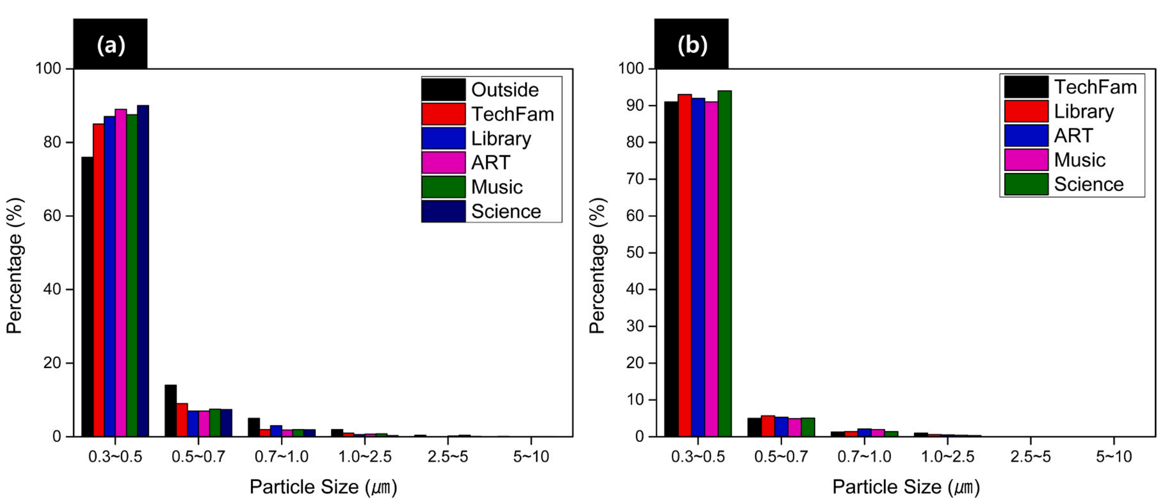

Fig. 9. Distribution of PM particles in experiment areas for (a) natural state, (b) after PM occurrence.

technical use was greater than the effect of window replacement, with a total decrease of 22%.

In the case of Library, the total dust concentration decreased by 7.2%; this was the weakest effect. This is related to the number of floors; even in the case of Music and Art, which were located on the 3rd and 5th floors, respectively, a relatively high influence of particulate matter was found. Music decreased by 19%, while Art decreased by 7.9%. The distribution of particulate matter in each analyzed room is shown in Fig. 11. × means the state where the technology has not been applied; △ means the state where the windows are replaced; and ○ means the state where all the technology has been applied. In the case of Science, the concentration at 0.3–0.5μm decreased the most. In the case of 0.5–0.7μm, it increased or was almost the same level, which is considered to be an error in the ratio caused by the relatively small number of particles measured in the 0.5–0.7μm range. In the case of TechFam, a tendency almost similar to that of the existing total PN was measured in the particles in the 0.3–0.5μm range. The particles in the 0.5–0.7 range also decreased, and the degree of change was insignificant for the remaining particles. In the case of Library, similar results to TechFam were obtained, and the 0.3–0.5 μm particles showed the greatest influence on Music and Art. These results imply that in the case of particulate matter particles in the range of 0.3–1.0 μm, the influence of particulate matter introduced from outdoors can be reduced through improved airtightness. In addition, as a result of the introduction of technology to improve airtight performance, including window replacement, we found an all-round effect of improving airtightness performance and reducing the influence of particulate matter in all cases. Wu et al. reported that the ratio to the outdoors may decrease as the airtightness of a building is improved, and when comparing the results of an independent room, the corresponding result is shown (Wu et al., 2017). In addition, the case of

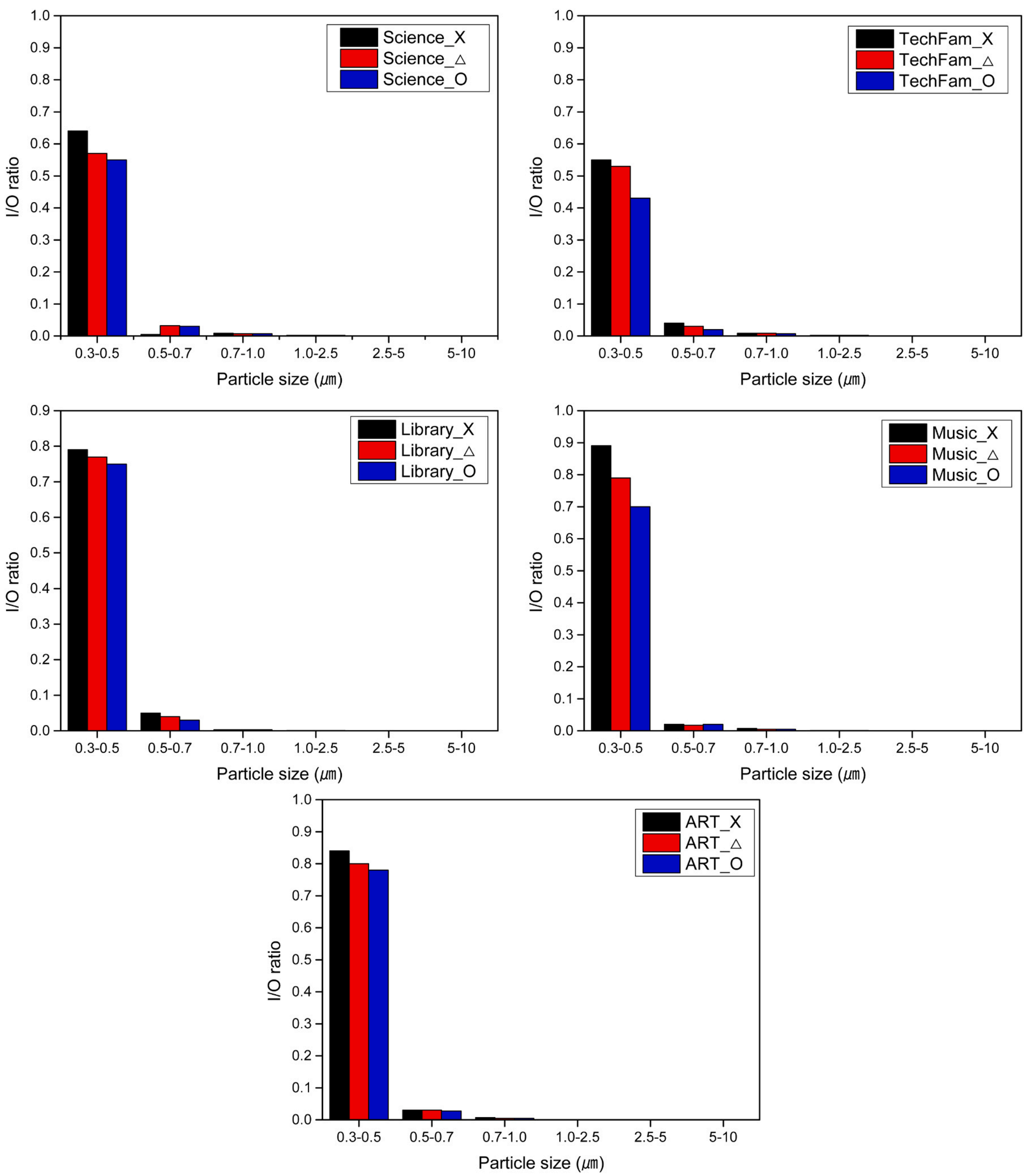

Fig. 11. Ratio of each I/O ratio according to particle size.

indoor particulate matter compared to outdoor particulate matter in one study showed that the higher the outdoor wind speed, the higher the I/O ratio (Zhou et al., 2016). The reason for this drop can be found in other floors.

4. Conclusion

This study attempted to improve airtight performance by applying window and airtight performance improvement technology, after which the change in the concentration of particulate matter according to airtightness improvement was evaluated. Results showed that airtightness performance was enhanced by the application of window improvements and airtightness improvement technology by up to 37%. In the case of particulate matter particles, the majority were in the 0.3–1.0 μm range. The I/O ratio decreased with the improved building airtightness performance, and in the case of particulate matter particles, there was an equal decline even for particles in the 0.3–0.7 µm range. In this study, there was a limit to simultaneous and multiple measurements; therefore, a follow-up study for data construction by securing measurement points needs to be conducted. Future research analysis could include an expanded sample of test subjects.

CRediT authorship contribution statement

Sungwoong Yang: Writing – original draft. **Hyeonseong Yuk:** Formal analysis. **Beom Yeol Yun:** Methodology. **Young Uk Kim:** Visualization. **Seunghwan Wi:** Conceptualization. **Sumin Kim:** Supervision, Funding acquisition.

Declaration of Competing Interest

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.

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References

Allard, I., Olofsson, T., Hassan, O.A.B., 2012. Methods for air tightness analysis for residential buildings in nordic countries. WIT Trans. Ecol. Environ. 311–322. https://doi.org/10.2495/ARC120281.

Carratt, A., Kokogiannakis, G., Daly, D., 2020. A critical review of methods for the performance evaluation of passive thermal retrofits in residential buildings. J. Clean. Prod. 263, 121408 https://doi.org/10.1016/j.jclepro.2020.121408.

Chan, W.R., Joh, J., Sherman, M.H., 2013, Analysis of Air Leakage Measurements from Residential Diagnostics Database.

Chen, Z., Chen, C., Wei, S., Liu, Z., Cao, G., Du, Y., Li, G., Zhu, J., Ma, Y., Wang, Y., 2021. Repeated subarachnoid administrations of allogeneic human umbilical cord mesenchymal stem cells for spinal cord injury: a phase 1/2 pilot study. Cytotherapy 23, 57–64. https://doi.org/10.1016/j.scs.2020.102087.

Cho, H.M., Yang, S., Wi, S., Chang, S.J., Kim, S., 2020. Hygrothermal and energy retrofit planning of masonry façade historic building used as museum and office: a cultural properties case study. Energy 201, 117607. https://doi.org/10.1016/j.energy.2020.117607.

Chu, Y., Xu, P., Yang, Z., Li, W., 2017. Existing building retrofitting for indoor PM2.5 concentration control on smog days: case study in China. Procedia Eng. 205, 3222–3227. https://doi.org/10.1016/j.proeng.2017.10.290.

Claxton, L.D., 2015. The history, genotoxicity, and carcinogenicity of carbon-based fuels and their emissions. Part 3: diesel and gasoline. Mutat. Res. - Rev. Mutat. Res. https://doi.org/10.1016/j.mrrev.2014.09.002.

Diapouli, E., Chaloulakou, A., Mihalopoulos, N., Spyrellis, N., 2008, Indoor and outdoor PM mass and number concentrations at schools in the Athens area, in: Environ. Monit. Assess. https://doi.org/10.1007/s10661–007-9724–0.

Falcon-Rodriguez, C.I., Osornio-Vargas, A.R., Sada-Ovalle, I., Segura-Medina, P., 2016. Aeroparticles, composition, and lung diseases. Front. Immunol. 7, 3. https://doi.org/10.3389/fimmu.2016.00003.

ISO 9972:2015, 2015, Thermal performance of buildings – determination of air permeability of buildings – fan pressurization method, 3, p. 26.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J. V., Hern, S.C., Engelmann, W.H., 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J. Expo. Anal. Environ. Epidemiol. 11, 231–252. https://doi.org/10.1038/sj.jea.7500165.

Kornartit, C., Sokhi, R.S., Burton, M.A., Ravindra, K., 2010. Activity pattern and personal exposure to nitrogen dioxide in indoor and outdoor microenvironments. Environ. Int. 36, 36–45. https://doi.org/10.1016/j.envint.2009.09.004.

Li, Z., Wen, Q., Zhang, R., 2017. Sources, health effects and control strategies of indoor fine particulate matter (PM2.5): a review. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2017.02.029.

Long, C.M., Suh, H.H., Catalano, P.J., Koutrakis, P., 2001. Using time- and size-resolved particulate data to quantify indoor penetration and deposition behavior. Environ. Sci. Technol. 35, 2089–2099. https://doi.org/10.1021/es001477d.

Martins, N.R., Carrilho da Graça, G., 2018. Impact of PM2.5 in indoor urban environments: a review. Sustain. Cities Soc. 42, 259–275. https://doi.org/10.1016/j.scs.2018.07.011.

Park, J.H., Jeon, J., Lee, J., Wi, S., Yun, B.Y., Kim, S., 2019. Comparative analysis of the PCM application according to the building type as retrofit system. Build. Environ. 151, 291–302. https://doi.org/10.1016/J.BUILDENV.2019.01.048.

Polichetti, G., Cocco, S., Spinali, A., Trimarco, V., Nunziata, A., 2009. Effects of particulate matter (PM(10), PM(2.5) and PM(1)) on the cardiovascular system. Toxicology 261, 1–8. https://doi.org/10.1016/j.tox.2009.04.035.

Provan, T.F., Younger, J.D., 1986. Air infiltration characteristics of windows. Energy Build. 9, 281–292. https://doi.org/10.1016/0378-7788(86)90033-2.

Raysoni, A.U., Sarnat, J.A., Sarnat, S.E., Garcia, J.H., Holguin, F., Luvano, S.F., Li, W.W., 2011. Binational school-based monitoring of traffic-related air pollutants in El Paso, Texas (USA) and Ciudad Juárez, Chihuahua (México). Environ. Pollut. 159, 2476–2486. https://doi.org/10.1016/j.envpol.2011.06.024.

School Safety Accident Prevention and Compensation, 2014. Article 10, Paragraph 1. Natl. Law Inf. Cent. 〈https://www.law.go.kr/〉.

Sinnott, D., Dyer, M., 2012. Air-tightness field data for dwellings in Ireland. Build. Environ. 51, 269–275. https://doi.org/10.1016/j.buildenv.2011.11.016.

Spilak, M.P., Karottki, G.D., Kolarik, B., Frederiksen, M., Loft, S., Gunnarsen, L., 2014. Evaluation of building characteristics in 27 dwellings in Denmark and the effect of using particle filtration units on PM2.5 concentrations. Build. Environ. 73, 55–63. https://doi.org/10.1016/j.buildenv.2013.11.020.

Tiberio, A.J., Branchi, P., 2013, A study of air leakage in residential buildings, in: Conf. Exhib. - 2013 Int. Conf. New Concepts Smart Cities Foster. Public Priv. Alliances, SmartMILE 2013. https://doi.org/10.1109/SmartMILE.2013.6708180.

Wang, Z., Yu, Z., 2017, PM2.5 and Ventilation in a Passive Residential Building, in: Procedia Eng. https://doi.org/10.1016/j.proeng.2017.10.226.

Wan, Y., Chen, C., Wang, P., Wang, Y., Chen, Z., Zhao, L., 2015, Infiltration Characteristic of Outdoor Fine Particulate Matter (PM2.5) for the Window Gaps, in: Procedia Eng. https://doi.org/10.1016/j.proeng.2015.08.1050.

World Health Organization, 2013, Review of evidence on health aspects of air pollution – REVIHAAP Project: Technical Report. https://doi.org/10.1007/BF00379640.

Wu, Y., Chen, C., Du, Y., Chen, Z., Li, Y., 2017, Investigation of Indoor and Outdoor PM2.5 Pollution Situation in Beijing, in: Procedia Eng. https://doi.org/10.1016/j.proeng.2017.10.358.

Zhang, N., Jin, W., He, J., 2016, Experimental Study on the Influence of Ventilated Window on Indoor Air Quality and Energy Consumption, in: Procedia Eng. https://doi.org/10.1016/j.proeng.2016.06.394.

Zhang, Y., Ji, X., Ku, T., Li, G., Sang, N., 2016. Heavy metals bound to fine particulate matter from northern China induce season-dependent health risks: a study based on myocardial toxicity. Environ. Pollut. 216, 380–390. https://doi.org/10.1016/j.envpol.2016.05.072.

Zhong, X., Zhang, Z., Wu, W., Ridley, I., 2020. Comprehensive evaluation of energy and indoor-PM2.5-exposure performance of residential window and roller blind control strategies. Energy Build. https://doi.org/10.1016/j.enbuild.2020.110206.

Zhou, Z., Liu, Y., Yuan, J., Zuo, J., Chen, G., Xu, L., Rameezdeen, R., 2016. Granulometric and magnetic properties of deposited particles in the Beijing subway and the implications for air quality management. Sci. Total Environ. 568, 1059–1068. https://doi.org/10.1016/j.rser.2016.06.018.

Zuo, J.X., Ji, W., Ben, Y.J., Hassan, M.A., Fan, W.H., Bates, L., Dong, Z.M., 2018. Using big data from air quality monitors to evaluate indoor PM2.5 exposure in buildings: case study in Beijing. Environ. Pollut. 240, 839–847. https://doi.org/10.1016/j.envpol.2018.05.030.