



Test and Analysis of Outdoor PM_{2.5} Blocking and Air Exchange Performance of Anti-haze Window Screen

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Abstract. Atmospheric PM_{2.5} pollution has been very serious in many areas of China in recent years, jeopardizing human health. Human exposure to PM_{2.5} occurs primarily indoors, and reducing indoor PM_{2.5} concentrations is an important way to reduce human exposure to PM_{2.5}. When the atmospheric PM_{2.5} concentration is high, people tend to close doors and windows tightly to reduce the indoor PM_{2.5} concentration, but this also reduces the number of air exchanges between the room and the outdoors, so that other indoor sources of gas-phase pollutants can not diffuse in time. To this end, the market launched a nuclear pore membrane technology anti-haze screen, claiming that the efficient blocking of PM_{2.5} at the same time can allow gas molecules to pass freely, which can be a highly efficient gas exchange, and has attracted widespread attention. In this study, the air permeability and filtration performance of anti-haze screens were examined in an environmental chamber, and the concentration status of indoor and outdoor PM_{2.5} in the residence before and after the application of anti-haze screens on hazy days and the number of air changes in the room were monitored in the field. The results show that the overall PM_{2.5} penetration coefficient of the room after applying anti-haze screens is 0.15-0.21, which is smaller than the PM_{2.5} penetration coefficient (0.55-0.59) when anti-haze screens are not applied, indicating that the anti-haze screens have a certain effect of blocking outdoor PM_{2.5} under the condition of severe outdoor pollution. However, it was measured that the average air exchange capacity of anti-haze screens was 0.18m³/m²/min, which could not reach the air exchange capacity of 0.9m³/m²/min as stated in the product publicity on hazy days and could not satisfy the air exchange capacity specified in the indoor air quality standard (30m³/h/person).

Keywords: Indoor air quality, Penetration factor, Indoor/outdoor concentration ratio.

1 Introductory

In recent years, with China's rapid urbanization and industrialization, environmental problems have become more and more serious, particulate pollution is one of the most important air pollutants in China, which has an important impact on human health, atmospheric visibility, atmospheric chemical and radiation balance, and global

climate change. Especially fine particulate matter less than 2.5 microns ($PM_{2.5}$), because of its large specific surface area, it is more likely to adsorb toxic substances (e.g., heavy metals, germs, etc.), and its small size, has a stronger penetration, can reach the walls of the fine bronchial tubes, and has a greater impact on human health. Many epidemiologic and toxicologic studies have shown that $PM_{2.5}$ is closely associated with respiratory and cardiovascular diseases^{1,2}, which has attracted widespread attention. However, in recent years, with the improvement of airtightness of residential buildings, the use of more and more decorative building materials, as well as the intensification of outdoor air pollution, the types, and concentrations of indoor pollutants in residential buildings have increased dramatically, leading to a variety of residents suffering from "sick building syndrome".³ People spend more than 85% of their time indoors⁴, and human exposure to $PM_{2.5}$ occurs mainly indoors, so reducing indoor $PM_{2.5}$ concentrations is an important way to reduce human $PM_{2.5}$ exposure. Indoor $PM_{2.5}$ is mainly divided into $PM_{2.5}$ that enters indoors from outdoors and $PM_{2.5}$ generated indoors. When there is no smoking, cooking, sweeping, or other activities indoors, the $PM_{2.5}$ generated indoors is negligible, and at this time, indoor $PM_{2.5}$ mainly comes from outdoors. There are three main ways for outdoor $PM_{2.5}$ to enter indoors with airflow: mechanical ventilation, natural ventilation (entering indoors through open windows and doors), and infiltration ventilation (entering indoors through gaps in the envelope). At present, mechanical ventilation is not widely used in Chinese residences, which mainly exchange air with the outdoors through natural ventilation and infiltration ventilation. When the outdoor $PM_{2.5}$ concentration is high, people tend to close the doors and windows tightly to reduce the indoor $PM_{2.5}$ concentration, but this also reduces the number of air exchanges between the room and the outdoor area, and other indoor gas-phase pollutants (e.g., formaldehyde and other VOCs, etc.) cannot be diffused promptly. How do ventilate at the same time the $PM_{2.5}$ will be rejected out of the window? In response to this problem, the market should launch a kind of anti-haze screen window using nuclear pore membrane technology, this kind of screen window is claimed to be highly efficient in blocking $PM_{2.5}$ at the same time can allow gas molecules to pass freely, can be highly efficient gas exchange, caused people's attention and use. Shanshan Shi et al⁵ simulated and calculated the reduction effect of applying anti-haze screens on the exposure of $PM_{2.5}$ from indoor and outdoor sources in residence based on the parameter information of anti-haze screens provided by the manufacturer, but did not validate their parameters and modeling, which may overestimate the efficacy of anti-haze screens.

The number of air changes is a common indicator for evaluating the quality of indoor air and an important basis for estimating the amount of ventilation in the room, China has a clear requirement for the minimum amount of ventilation and air changes in the building, GB 50096-2011 "Code for Residential Design" requires that the number of air changes in the residential fresh air without a centralized fresh air supply system should be $1h^{-1}$; DBJ 11-602-2006 "energy-saving design standards for residential buildings" requires that the number of times of ventilation and air exchange in winter in Beijing is not less than $0.5 h^{-1}$, and the number of times of air exchange in summer when using air conditioners to cool down is not less than $1h^{-1}$;

GB/T 18883-2002 "indoor air quality standards" in the standard fresh air volume of the residence is 30m³/h/person.

In addition to the number of air changes, the penetration coefficient (P) and settling coefficient (K) of PM_{2.5} are also important parameters for the study of indoor PM_{2.5} concentration. The penetration coefficient characterizes the ability of PM_{2.5} to enter the indoor area through the gaps of the enclosure structure and can be used to characterize the haze-blocking performance of the actual enclosure structure.

In this paper, the air permeability and filtration performance of anti-haze screens were tested in the environmental chamber, and the air exchange and haze-blocking performance of anti-haze screens in practical applications were detected by the CO₂ attenuation method⁶ and the least-squares method, to help consumers to further understand the anti-haze screens and prevent haze scientifically and rationally.

2 Experimental equipment and methods

The anti-haze screen is composed of a PET (polyester) film with dense straight-through tapered micropores and a screen mesh, the thickness of the PET film is 0.01mm, the pore size is between 10nm-12μm, and the pore density is as high as 4*10⁵-10¹²/cm². Fig. 1 shows the appearance of the anti-haze screen tested.

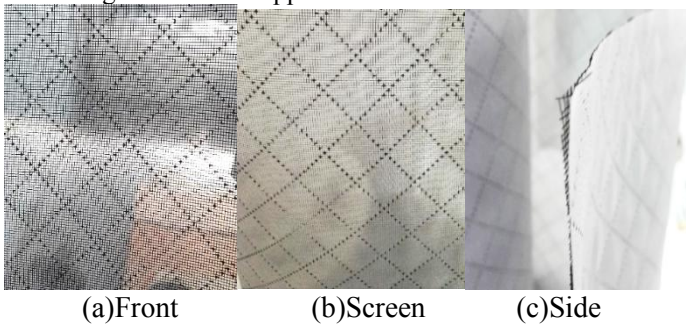


Fig. 1. Anti-haze screen window appearance.

The duct and environmental chamber experimental setup is shown in Figure 2. The air duct experiments were conducted according to GB 14295-2008 and ASTM D2986 - 95a R99 using a digital manometer and dust particle counter in the air duct to test the resistance of the anti-haze screens and the efficiency of the PM_{2.5} once through. The environmental chamber experiment tested the air exchange performance of anti-haze screens by CO₂ attenuation method, injecting high concentration of CO₂ into the experimental cabin (70cm × 50cm × 50cm) equipped with anti-haze screens (15cm diameter circular hole) on both sides to be examined, placing it in the 30m³ environmental chamber simulating the outdoor atmospheric conditions, and using the QD-W1 CO₂ concentration detector of Qingdao Jianhuan to continuously measure the CO₂ concentration inside and outside of the small cabin. concentration inside and outside the cabin was continuously measured by the QD-W1 CO₂ concentration detector.

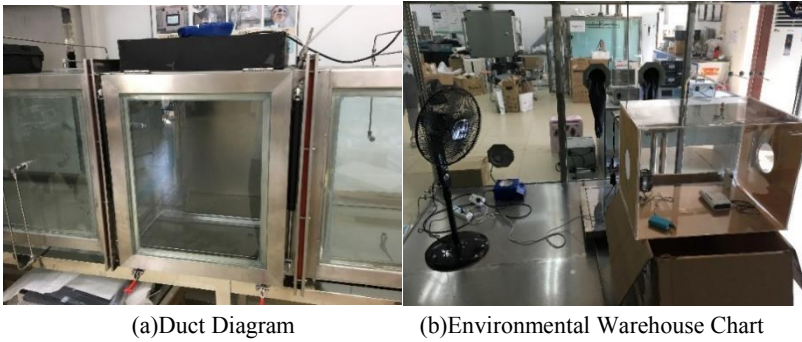


Fig. 2. Experimental setup diagram.

The field monitoring was carried out in a neighborhood in Haidian, Beijing, where the unit has 34 floors and the test household is located on the 30th floor. Three rooms were selected for measurement at the same time, with only one external wall and one casement window in each room, and the anti-haze screens were installed at the casement window. The number of air changes and $PM_{2.5}$ concentration in the room on hazy days with and without the use of anti-haze screens were measured separately, and all other doors and windows were closed during the measurement period, with no personnel activities and no indoor sources of $PM_{2.5}$ in the room. The corresponding room and anti-haze screen information is shown in Table 1. Use CO_2 as a tracer gas to calculate the number of room air changes, close the doors and windows before the start of the test, use high-purity CO_2 cylinders to release CO_2 in each room so that the concentration reaches about 3000ppm, and use the QD-W1 CO_2 concentration detector to continuously measure the indoor and outdoor CO_2 concentration to calculate the number of air changes in each room. At the same time, the indoor and outdoor $PM_{2.5}$ concentrations were continuously measured by TSI AM510 and Qingdao Jianhuan QD-W1 $PM_{2.5}$ Concentration Detector, the indoor and outdoor temperature and humidity were recorded by TIANJIANHUAYI Temperature and Humidity Self-recording Instrument, and the outdoor wind speed was detected by TIANJIANHUAYI Wind Speed Self-recording Instrument. The placement of the instruments in each room was not close to the window, and the placement height was 1.2 m (about half of the height of the room). The equipment was calibrated and aligned before the experiment, and the relative errors of all equipment were within 10% after calibration.

Table 1. Testing Room Information Sheet.

Room	Room volume(m^3)	Anti-haze screen area(m^2)
Room1	33.58	0.43
Room2	21.71	0.40
Room3	25.35	0.27

2.1 Calculation of the number of air changes

In this paper, CO₂, which is stable, safe, non-toxic, and easy to detect, is used as a tracer gas, and the tracer gas concentration decay method is utilized to calculate the number of air changes. First release CO₂ gas in each room (or small cabin) and mix the CO₂ gas in the measurement area evenly to ensure that the CO₂ in the area reaches a certain concentration, close the doors and windows, and then analyze the change in CO₂ concentration for a certain period in an unoccupied state after that, to obtain the number of air exchanges in the room. The principle of the tracer gas method for measuring room ventilation is based on the fact that the tracer gas satisfies the mass conservation equation. When there is no source of CO₂ release in the room, according to the conservation of mass equation, the amount of CO₂ change in the room is:

$$V \frac{dC_{in}}{dt} = Q(C_{out} - C_{in}) \quad (1)$$

Where V is the room volume, m³; C_{in} is the indoor CO₂ volume fraction, ppm; t is the time, s; Q is the ventilation volume, m³/s; and C_{out} is the outdoor CO₂ volume fraction, ppm;

Substituting the indoor CO₂ concentration at the initial moment and integrating Eq. (1) yields:

$$(C_{in} - C_{out}) = (C_{in,0} - C_{out})e^{-\frac{Q}{V}t} \quad (2)$$

The differential form can be obtained as follows:

$$\Delta C = n\Delta t(C_{out} - C_{in,0}) \quad (3)$$

where ΔC is the change in indoor CO₂ concentration during the time period, n is the number of air changes, times/h, and $n = Q/V$.

The relationship between moment-to-moment CO₂ concentration in the room moment-to-moment CO₂ concentration $C_{in}(k-1)$ can be obtained as follows:

$$C_{in}(k) = C_{in}(k-1) + \left\{ \frac{n\Delta t}{3600} [C_{out} - C_{in}(k-1)] \right\} \quad (4)$$

Where 3600 is the conversion factor, s/h; Δt is the interval between τ_k moment and τ_{k-1} moment, s.

At the kth moment, the actual measured CO₂ concentration in the room is $C_{in}(k)$, and the predicted CO₂ concentration in the room is $C'_{in}(k)$; at the k-1st moment, the actual measured CO₂ concentration in the room is $C_{in}(k-1)$, and the predicted CO₂ concentration in the room is $C'_{in}(k-1)$, then we have the following equation:

$$C'_{in}(k) = C'_{in}(k-1) + \left\{ \frac{n\Delta t}{3600} [C_{out} - C'_{in}(k-1)] \right\} \quad (5)$$

The least squares objective function is:

$$\min_{k=0}^{k=m} [C_{in}(k) - C'_{in}(k)]^2 \quad (6)$$

The couplings (4) to (6) can be solved to find the air change volume of the room in the corresponding period.

2.2 PM_{2.5} Penetration factors

The penetration coefficient of PM_{2.5} refers to the ability of outdoor PM_{2.5} to enter indoors through infiltration ventilation through the enclosure structure, which is used in this study to indicate the haze-blocking ability of the enclosure structure and haze-proof screens. The equation for the change in indoor PM_{2.5} concentration is:

$$\frac{dC_{in}}{dt} = nPC_{out} - nC_{in} - KC_{in} \quad (7)$$

where C_{in} is the indoor PM_{2.5} concentration, $\mu\text{g}/\text{m}^3$; C_{out} is the outdoor PM_{2.5} concentration, $\mu\text{g}/\text{m}^3$; t is the time, h; n is the number of air exchanges, h^{-1} ; P is the PM_{2.5} penetration coefficient; and K is the PM_{2.5} settling factor, h^{-1} .

A similar process to the CO₂ derivation can be obtained:

$$C'_{in}(k) = C'_{in}(k-1) + \{\Delta t[nPC_{out} - (n+K)C'_{in}(k-1)]\} \quad (8)$$

The least squares objective function is:

$$\min_{k=0}^{k=m} [C_{in}(k) - C'_{in}(k)]^2 \quad (9)$$

Since the doors and windows were closed and there was no activity in the room during the test, the indoor airflow was not disturbed much, and the value of K in each room can be considered as a constant ⁷, which was taken as $0.09/\text{h}$ ⁸. The range of variable P is:

$$0 < P < 1 \quad (10)$$

The room penetration coefficient P can be calculated by substituting the number of air changes n calculated by the CO₂ attenuation method into the calculations in (8)-(10).

3 Results and analysis

3.1 Environmental chamber test results

During the test period, the average temperature of the experimental cabin was 24.5°C , the relative humidity RH was 45.6%, and the number of air exchanges in the cabin of the experimental cabin with anti-haze screens installed was 6.11 h^{-1} under the conditions of wind speed of about $2\sim 2.5 \text{ m/s}$, and the ventilation capacity of anti-haze screens per unit area was about $0.5 \text{ m}^3/\text{m}^2/\text{min}$. At air volumes of $249.7 \text{ m}^3/\text{h}$ (wind speed 0.409 m/s) and $33.4 \text{ m}^3/\text{h}$ (wind speed 0.055 m/s), the corresponding pressure drops were 20 Pa and 1.7 Pa , respectively, and the efficiency of the sub-granularity once-through is shown in Fig. 3.

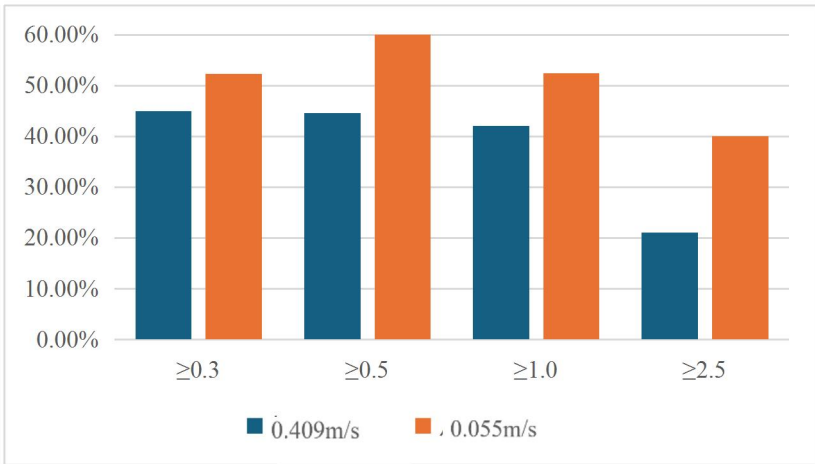


Fig. 3. Particle size primary passage efficiency of anti-haze screens at different wind speeds.

3.2 Actual residential monitoring results

Failure to use anti-haze screens. On hazy days, all doors and windows were closed in each room without the use of anti-haze screens, and the number of air changes and PM_{2.5} penetration factor were measured in each room. During the test period, the average indoor temperature was 20.6°C and the relative humidity RH was 32.1%; the average outdoor temperature and relative humidity were -3.5°C and 72.7%, respectively, with a northwest wind of 0.84 m/s. The average temperature and relative humidity were -3.5°C and 72.7%, respectively. The PM_{2.5} concentration in each room at the beginning of the measurement ranged from 70-85 μg/m³, and the average outdoor PM_{2.5} concentration over the 8 hours of the test was 162 μg/m³. The results of the calculation of the number of air changes in each room are shown in Table 2. The data in Table 2 indicate that the rooms themselves have good airtightness, but the number of air changes when closing the doors and windows is far from meeting the requirements of each standard.

Table 2. Number of air changes in each room and PM_{2.5} penetration factor.

Room	Without anti-haze screens		In the case of using anti-haze screens	
	Number of room air changes (times/h)	Penetration factor P ₂	Number of room air changes n ₀ (times/h)	Penetration factor P ₀
Room1	0.14	0.59	0.16	0.18
Room2	0.19	0.55	0.21	0.20
Room3	0.11	0.57	0.17	0.23

Using the number of indoor and outdoor air changes in the room and the indoor and outdoor PM_{2.5} concentration, the PM_{2.5} penetration coefficient can be obtained, and

the calculated penetration coefficients of each room are shown in Table 2, which shows that the PM_{2.5} penetration coefficients of each room without haze screens are between 0.5 and 0.6, which is consistent with the penetration coefficients obtained from other literature⁸, which indicates that the enclosure has a certain haze-blocking ability by itself.

Use of anti-haze screens. After the installation of anti-haze screens in each room, the number of air changes and PM_{2.5} penetration coefficients were measured in each room with the anti-haze screens enabled. At this time, the average outdoor PM_{2.5} concentration was 470 µg/m³, and a purifier was used to reduce the PM_{2.5} concentration in each room from 120 µg/m³ to the background concentration of the previous experiment. During the test period, the average indoor temperature was 20.2°C, RH=42.5%; the average outdoor temperature was 1.1°C, RH=68.6%, and the wind was 0.24m/s from the northwest.

The results of the calculation of the number of air changes in each room and the calculated PM_{2.5} penetration coefficient of each room after the use of anti-haze screens are shown in Table 2, and the number of air changes in the room after enabling the anti-haze screens is slightly larger than the number of air changes without using the anti-haze screens, which indicates that the anti-haze screens have a certain degree of air change capability. The overall penetration coefficient of the enclosure after the use of anti-haze screens is between 0.1 and 0.3, which is smaller than the penetration coefficient of PM_{2.5} when the anti-haze screens are not used, indicating that there is a certain enhancement of the haze-blocking ability of the room after the use of anti-haze screens.

In the case of steady state without indoor sources, Eq. (7) can be simplified to obtain:

$$C_{in} = \frac{nC_{out}}{n+K} P \quad (11)$$

In the case of the same outdoor PM_{2.5} concentration and the same number of air changes in the room, the concentration of PM_{2.5} in the room can be reduced more when applying anti-haze screens:

$$\Delta = \frac{C_{in,a} - C_{in,b}}{C_{out}} = \frac{n}{n+K} (P_a - P_b) \quad (12)$$

In the formula, the subscript a indicates the indoor concentration and the overall room penetration coefficient when the anti-haze screen is not applied, the subscript b indicates the indoor concentration and the overall room penetration coefficient when the anti-haze screen is applied, and the other meanings are the same as above.

In this case, the overall PM_{2.5} penetration coefficient of each room was reduced by 64.26% on average after applying anti-haze screens to reach the steady state compared with that without applying anti-haze screens, indicating that the haze-blocking ability of the room was significantly improved after using anti-haze screens.

With the use of anti-haze screens, PM_{2.5} entering the room and indoor-outdoor air exchange consists of two parts: passing through anti-haze screens and passing through gaps in the enclosure other than anti-haze screens:

$$n_0P_0 = n_1P_1 + n_2P_2 \tag{13}$$

$$n_0 = n_1 + n_2 \tag{14}$$

where n_0 is the total number of air changes in the room after using anti-haze screens, h^{-1} ; n_1 is the number of air changes through anti-haze screens, h^{-1} ; n_2 is the number of air changes through gaps in enclosures other than screens, h^{-1} ; P_0 is the penetration coefficient of PM_{2.5} into the overall room after using anti-haze screens; P_1 is the penetration coefficient of PM_{2.5} through screens; P_2 is the penetration coefficient of PM_{2.5} through gaps in other enclosures other than screens. the penetration coefficient of other enclosure gaps.

For the same room, in the absence of wind on a hazy day, the PM_{2.5} penetration coefficient through gaps in the envelope other than screens is considered to be unchanged, so that the data in Table 2 can be used as P_2 . Under windless conditions, the penetration coefficient of PM_{2.5} through the anti-haze screen was measured to be 0.12, i.e. $P_1 = 0.12$. They are substituting $P_1=0.12$ and P_0 in Table 2 into Eqs. (13)-(14) calculates the air exchange volume n_1 of the anti-haze screen and the air exchange volume n_2 through the gaps of the enclosure other than the anti-haze screen at this time. The air exchange capacity of the anti-haze screen is obtained from the air exchange through the anti-haze screen n_1 and the area of the anti-haze screen. As shown in Table 3, the average air-exchange capacity of the anti-haze screen was measured to be 0.18m³/m²/min, which did not reach the air-exchange capacity of 0.9m³/m²/min as stated in the product promotion. In addition to the number of air changes for the anti-haze screens, the number of air changes for the other enclosures in the room is less than the number of air changes in the case of no anti-haze screens in Table 2 because the temperature difference between indoors and outdoors at this point is smaller, and the outdoor wind speed is smaller.

Table 3. Number of air changes in each room and PM_{2.5} penetration factor.

Room	Number of air changes in other enclosures n_2 (times/h)	Number of air changes in anti-haze screens n_1 (times/h)	Anti-haze screen window air exchange capacity (m ³ /m ² /min)
Room1	0.02	0.14	0.18
Room2	0.04	0.17	0.16
Room3	0.04	0.13	0.21

4 Conclusion

1. Filtration Efficiency of Anti-Haze Screens in Duct Experiment:

- (1). Nominal filtration efficiency (>90%) not achieved.

- (2). Pressure drops at wind speeds of 0.409m/s and 0.055m/s: 20Pa and 1.7Pa, respectively.
2. Environmental Chamber Experiment:
 - (1). Wind speed: 2~2.5m/s.
 - (2). Air exchange capacity of the anti-haze screen: 0.5m³/m²/min.
 - (3). Below nominal 0.9m³/m²/min air exchange capacity of the product.
3. PM2.5 Penetration Coefficient
 - (1). After application of anti-haze screens: 0.15-0.21.
 - (2). Without anti-haze screens: 0.55-0.59.
 - (3). Indicates certain effectiveness in blocking outdoor PM2.5 under severe outdoor pollution conditions.
4. Anti-Haze Screen Air Exchange Capacity on Hazy Days
 - (1). Outdoor wind speed <1m/s.
 - (2). Average air exchange capacity: 0.18m³/m²/min.
 - (3). Limited unit area air exchange capacity in 4 × 3 × 2.5 m³ double room.
 - (4). Requirement for meeting new air volume and room winter air exchange standards: at least 5.5 m² and 1.4 m² of anti-haze screen area, respectively.

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