Infiltration Characteristic of Outdoor Fine Particulate Matter (PM$_{2.5}$) for the Window Gaps

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Abstract

Even if closing windows, atmospheric PM$_{2.5}$ can still penetrate into indoor through gaps of windows, then causing the indoor environment polluted. In order to evaluate the influence of windows with different airtightness levels on infiltration characteristic of PM$_{2.5}$, a longitudinal monitoring regarding indoor and outdoor PM$_{2.5}$ mass concentrations and meteorological parameters have been carried out in two offices located in Beijing, China from 1st July to 2nd November, 2014. Research results showed that when windows and mechanical ventilation were closed and there were no obvious indoor particle sources, the indoor PM$_{2.5}$ mass concentration, the I/O ratio and the air exchange rate causing of window gaps of the sample site with lower airtightness window were higher than the one with higher window airtightness. Furthermore, the I/O ratio and air exchange rate were both positively correlated with outdoor wind speed, while negatively correlated with outdoor relative humidity. The findings can provide meaningful reference to further research on influence of atmospheric PM$_{2.5}$ on indoor environment and help further develop approaches to control outdoor originated indoor PM$_{2.5}$.

Keywords: Window gaps; Fine particulate matter; Infiltration characteristic; Air exchange rate; Measurement research

1. Introduction

In recent years, the air pollution in Beijing-Tianjin-Hebei region (BTH Region) of China became more and more serious, and the fog haze pollution incident occurred frequently. According to the 2014 air quality report for 74
urban cities in China, the level of atmospheric pollution in the BTH region was ranking number one, with an average number of days meeting the standard requirement of only 156 among Beijing, Tianjin and Hebei. For Beijing, the annually average value of PM$_{2.5}$ mass concentration was 85.9 g/m$^3$, and the proportion of days meeting the standard requirement was only 47.1%.

Increasing epidemiological studies have reported that PM$_{2.5}$ can be directly inhaled into human’s lungs and even can penetrate into the blood circulation but difficult to remove. It is correlated positively with respiratory system diseases, cardiovascular diseases, lung cancer and other human body unhealthy risks reported by Donaldson and MacNee [1] and Oberdorster [2]. Even if closing windows and doors during haze-fog episodes, atmospheric PM$_{2.5}$ can still penetrate into indoor through window gaps causing the pollution of indoor air environment. Inferring from the results of the EPA’s Particle Total Exposure Assessment Methodology (PTEAM) study, Wallace [3] reported that approximately 75% of PM$_{2.5}$ was originated from ambient air. Research results by Matson [4], Chen and Zhao [5] and Kuo and Shen [6] showed that there were close correlation between indoor and outdoor pollutants, indoor pollutants mainly derive from outdoor sources. Meanwhile penetration through cracks has been investigated in field and controlled chambers. Tung et al. [7] estimates the penetration factor for PM$_{10}$ in an office building by using measured particle decay curve and the air exchange rate, where the measured penetration factors range from 0.69 to 0.86. According to the results of a chamber test conducted by Mosley et al. [8], a size-resolved profile for the penetration coefficient was obtained. Liu and Nazaroff [9] directly measured the particle concentrations upstream and downstream of the cracks and then calculated the corresponding penetration factors (0.02-7μm). A review by Chen and Zhao [5] has been published that addresses penetration through cracks with focus on smooth surfaces. Nevertheless, almost all of the existing models were developed for a single straight crack and they were validated by experiments in the laboratory and the shortcomings of these measurements are non-accountable fluctuations in parameters such as outdoor wind speed and relative humidity which would lead to inaccurate interpretation of penetration.

In order to evaluate the influence of windows with different airtightness levels on infiltration characteristic of PM$_{2.5}$, a longitudinal monitoring regarding PM$_{2.5}$ mass concentration and meteorological parameters(outdoor wind speed, relative humidity, temperature) have been carried out in two offices located in Beijing, China from 1st July to 2nd November, 2014. The two offices were equipped with windows with different airtightness levels (i.e. level-6 and level-4). The findings can provide meaningful reference to further research on influence of building windows on atmospheric PM$_{2.5}$ infiltration characteristic and help further develop approaches to control outdoor originated indoor PM$_{2.5}$ in the haze-fog episodes.

2. Methods

2.1. Measurement

The longitudinal measurement was carried out in two offices in two high-rise office buildings in Beijing, from 1st July to 2nd November, 2014. During the measurement, the windows of the sampling site were closed without ventilating system and there were no obvious indoor particle sources. In this paper, they are called sampling site 1 and sampling site 2, as shown in Figure 1. The case study buildings are located separately near two principle roads in the center of Beijing with high density of population and heavy traffic. Figure 2 shows the floor plans of the monitored rooms. The airtightness level of the window in sampling site 1 is level-6, and that for the one in sampling site 2 is level-4. Some more information about the two monitored offices has been provided in Table 1. Both two types of windows have similar characteristics in gap height, length and number of right-angle bends. The total gap depth of the windows in Sampling Site 1 is 60mm, while that for those in the Sampling Site 2 is 30mm. All the gaskets are made of rubber.
Indoor and outdoor PM$_{2.5}$ mass concentrations were monitored using LD-5C(R) line laser particle monitors and the monitoring data was uploaded to the server through a wireless network, whose sensitivity was 1 μg/m$^3$ and its counting interval was 20 min. Meteorological parameters were downloaded from Central Meteorological Observatory (update hourly), the parameters included real-time data of outdoor wind speed, relative humidity, temperature, and atmospheric pressure. We calculated arithmetic mean of a sequence of 3 data points to represent time-averaged indoor and outdoor PM$_{2.5}$ mass concentrations. In the process, we cleared abnormal datasets which may be owing to power-off, human interference; we also removed the data points with residual errors of absolute values greater than three times of the corresponding standard deviations. Outdoor PM$_{2.5}$ pollution levels were categorized into six classes according to classification standard of the China Environmental Monitoring Station.
based on daily average values, which are excellent (0-35 μg/m³), fine (35-75 μg/m³), slight pollution (115-150 μg/m³), medium pollution (115-150 μg/m³), serious pollution (150-250 μg/m³) and severe pollution (>250 μg/m³).

2.2. Infiltration ventilation characteristics of door or window gaps

Particulate matter (usually referring to the aerodynamic diameter of 0.001 to 100μm) suspended in gas medium in the form of the decentralized system with specific motion law called aerosols. According to the principle of aerosol mechanics, when outdoor air flows through the window gaps, it can be recognized as laminar flow regime, and particles is mainly affected by three resistance factors, namely the gravity sedimentation, Brownian diffusion and inertial impaction [9].

In addition, indoor particle concentration depends on the rate of particle entering and leaving indoor environment and the rate of indoor particle shifting, suspension and generation. Assuming that the indoor particle concentration is uniform and there is none of indoor disturbance, we can ignore the indoor sources and the effects of suspension etc. According to the law of conservation of mass [10], the relationship between indoor and out-door PM2.5 concentrations with steady-state condition could be written as:

\[
\frac{C_{\text{in}}}{C_{\text{out}}} = \frac{I/O}{a + k} 
\]

(1)

where \(C_{\text{in}}\) and \(C_{\text{out}}\) are indoor and outdoor particle concentrations, respectively (μg/m³), \(p\) is particle penetration coefficient (dimensionless), which can be valued of 0.8 for PM2.5 in this study referring to Chen et al. [11] and Shi et al. [12], \(k\) is particle deposition rate (1/h), which can be valued of 0.09 for PM2.5 referring to Chen et al. [13] and Riley et al. [14], \(a\) is air exchange rate per hour (1/h) which is mainly due to infiltration ventilation of window gaps in this study.

According to our team’s prior research results by Zhao et al. [15], when windows are closed and there is no obvious indoor particle sources without mechanical ventilation, we can set up the relationship between I/O ratio (the ratio of indoor and outdoor PM2.5 mass concentration) and the outdoor wind speed and relative humidity.

\[
\frac{I/O_i}{I/O} = A \left(\frac{u_i}{\exp \ln(u_i)}\right)^B \left(\frac{RH_i}{\exp \ln(RH_i)}\right)^C
\]

(2)

where \(I/O_i\), \(u_i\) and \(RH_i\) are the averaged I/O ratio, outdoor wind speed and relative humidity under steady state, respectively. \(A\) is the comprehensive permeability coefficient of window gaps, \(B\) is the correction factor for wind speed, \(C\) is the correction factor for relative humidity. Based on the method made by Zhao et al. [15], the measured data from 1st July to 2nd November, 2014 is substituted to Equation (2), then we can estimate the values of \(A\), \(B\), \(C\). In sampling site 1, \(A\), \(B\) and \(C\) are valued of 0.3705, 0.219, -0.332. In sampling site 2, \(A\), \(B\) and \(C\) are valued of 0.447, 0.301, -0.293.

Simultaneous equation of (1) and (2), we can derive equation (3) which shows the relationship between air exchange rate (a), window gaps and outdoor wind speed, relative humidity.

\[
a = \frac{k}{A \left(R(U)\right)^B \left(R(RH)\right)^C - 1}
\]

(3)

where \(R(U) = \frac{\exp \ln(u_i)}{u_i}\) (dimensionless), \(R(RH) = \frac{\exp \ln(RH_i)}{RH_i}\) (dimensionless).

Above all, from Equation (3), it can be seen that when outdoor wind speed and relative humidity are known, a can be obtained by using outdoor monitoring data as inputs.
3. Result and discussion

3.1. Comparison and analysis of windows with different airtightness on indoor air quality

Figure 3 shows the variation of indoor PM$_{2.5}$ mass concentrations in the two sample sites as the atmospheric environment under the condition of different PM$_{2.5}$ pollution levels. We can see that there is a good linear correlation of indoor and outdoor PM$_{2.5}$ mass concentrations and the indoor PM$_{2.5}$ mass concentration increases with the increasing of the outdoor PM$_{2.5}$ mass concentrations. It reflects that indoor PM$_{2.5}$ average mass concentration of sample site 2 is always higher than sample site 1. When the outdoor PM$_{2.5}$ mass concentration is less than 150µg/m$^3$ (medium pollution level), the indoor PM$_{2.5}$ average mass concentrations at both two sampling sites are less than 75µg/m$^3$ (fine level). When the outdoor PM$_{2.5}$ mass concentration is ranging from 150 to 250µg/m$^3$ (serious pollution), the indoor air quality at sampling site 1 is still fine level while sampling site 2 slightly polluted. When the outdoor PM$_{2.5}$ mass concentration is ranging from 250 and 500µg/m$^3$ (severe pollution), indoor PM$_{2.5}$ mass concentrations of both two sampling sites are higher than the threshold value of 75µg/m$^3$, and indoor air quality at sampling site 1 is slightly polluted and that sampling site 2 is severe polluted. The measured results show that the higher the window airtightness is, the more effectively it pre-vents the outdoor PM$_{2.5}$ from infiltrating into indoors.

Fig. 3. the variation of indoor and outdoor PM$_{2.5}$ mass concentrations

3.2. Influence of outdoor wind speed

Wind plays a positive role on advection, transport and diffusion of atmospheric pollutants. Research results by Lang et al. [16] report that the diffusion dominates when outdoor wind speed is less than 6m/s, and outdoor wind speed is negatively correlated with atmospheric pollutants concentration.

Figure 4 describes the influence of outdoor wind speed on indoor and outdoor PM$_{2.5}$ mass concentrations and I/O ratio during the measurement. It shows that indoor and outdoor PM$_{2.5}$ mass concentrations decline with the increasing of outdoor wind speed at both sample sites, furthermore, the indoor PM$_{2.5}$ mass concentration of sample site 2 is higher than sample site 1. Additionally, the I/O ratio increases with the increasing of outdoor wind speed at both sample sites, and the I/O ratio of sample site 2 is always higher than that of sample site 1 and the difference value between the two sample sites becomes bigger and bigger along with the outdoor wind. When the outdoor wind speed is less than 1 m/s (namely below the light air), the I/O ratio of sample site 1 is 0.36, while sample site 2 is 0.43. When the outdoor wind speed is higher than 5m/s, the I/O ratio of sample site 1 is about 0.46, while the sample site 2 is as high as 0.71 with a big increase comparing to that of sample site 1.

The variation of air exchange rate (a) with outdoor wind speed is reflected in figure 5, and a is calculated by equation (3). It shows that a of sample site 2 is positively correlated with outdoor wind speed, and the influence of outdoor wind speed on a of sample site 1 is not as obvious as the effects of sample site 2. Additionally, a of sample
site 2 is always higher than a of sample site 1 and the difference value of a between the two sample sites becomes bigger and bigger along with the outdoor wind, which is similar to the variation of I/O ratio in figure 4. When the outdoor wind speed is less than 1 m/s (namely below the light air), the a of sample site 1 is 0.05/h, and sample site 2 is 0.06/h. When the outdoor wind speed is higher than 5m/s, a of sample site 1 is about 0.17/h with a little increase, while the sample site 2 is as high as 0.78/h.

3.3. Influence of outdoor relative humidity

Generally, a higher relative humidity can accelerate the formation of atmospheric particles to a certain extent, mainly acting on the formation of secondary species and the growth process because of condensation and coagulation by Fromme et al. [17].

The influence of outdoor relative humidity on indoor and outdoor PM$_{2.5}$ mass concentrations and I/O ratio during the measurement is reflected in figure 6. We can see that indoor and outdoor PM$_{2.5}$ mass concentrations increase with the increasing of outdoor relative humidity at both sample sites. Furthermore, the indoor PM$_{2.5}$ mass concentration and I/O ratio of sample site 2 are always higher than sample site 1. In addition, the I/O ratio declines
with the increasing of outdoor relative humidity at both sample sites, and the I/O ratio of sample site 2 is always higher than that of sample site 1 and the difference value between the two sample sites becomes less and less along with the outdoor relative humidity. The I/O ratio of sample site 2 declines from 0.7 to 0.45 with the increasing of outdoor relative humidity, while the I/O ratio variation of sample site 1 is not obvious, it is about 0.45.

Figure 5 shows the variation of air exchange rate (a) with the outdoor relative humidity, and a is calculated by equation (3). As shown in figure 5, a of both sample sites is negatively correlated with the outdoor wind speed, but the influence of outdoor relative humidity on a of sample site 1 is not as obvious as the effects of sample site 2. Additionally, a of sample site 2 is always higher than a of sample site 1 and the difference value of a between the two sample sites becomes less and less along with the outdoor relative humidity, which is similar to the variation of I/O ratio in figure 6. When the outdoor relative humidity is less than 40%, the a of sample site 1 is 0.16/h, while the sample site 2 is 0.57/h. When the outdoor relative humidity is higher than 90%, the a of sample site 1 is about 0.05/h, and the sample site 2 is as high as 0.06/h.

**Fig. 6. Influence of outdoor air relative humidity**

**Fig. 7. Air exchange rate of infiltration ventilation and outdoor air relative humidity**

### 4. Conclusion

In order to evaluate the influence of windows with different airtightness levels on infiltration characteristic of PM$_{2.5}$, a longitudinal monitoring regarding PM$_{2.5}$ mass concentration and meteorological parameters (outdoor wind speed, relative humidity, etc) have been carried out in two offices located in Beijing, China from 1st July to 2nd November, 2014. Research results showed that the indoor PM$_{2.5}$ mass concentration, the I/O ratio and the air...
exchange rate of the sample site with lower window airtightness were always higher than the one with higher window airtightness when windows and mechanical ventilation were closed and there were no obvious indoor particle sources. Furthermore, the I/O ratio and air exchange rate were both positively correlated with outdoor wind speed, while negatively correlated with outdoor relative humidity. The I/O ratio and air exchange rate of sample site 2 (level 4 for the window airtightness) were always higher than that of sample site 1 (level 6 for the window airtightness). Additionally, the variation of the I/O ratio and air exchange rate at sample site 1 was not as obvious as sample site 2 with the increasing of outdoor wind speed and relative humidity. The findings can provide meaningful reference to further research on influence of atmospheric PM$_{2.5}$ on indoor environment and help further develop approaches to control outdoor originated indoor PM$_{2.5}$.

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