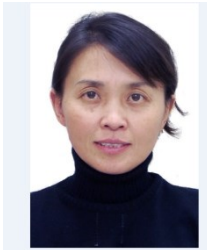


A methodology for predicting $PM_{2.5}$ penetration and deposition based on the air infiltration through the window gaps



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Abstract

Purpose / Context - During the process of ventilation, outdoor fine particulate matter enters indoor space through gaps in the external window of building and pollutes the indoor environment. Penetration factor (P), deposition loss rate (k), and air exchange rate (a) are important parameters to evaluate the number of outdoor fine particles infiltrate into indoor space and the exposed quantity of indoor personal fine particulate matter. At present, these parameters are mainly obtained through the methods of laboratory actual measurement or theoretical derivation.

Methodology / Approach - In this study, according to the law of indoor-outdoor particle mass balance and statistical theory, a novel method for estimating the above three parameters was developed, which dependent on a large number of indoor and outdoor $PM_{2.5}$ mass concentrations field monitored data.

Results -The results of the method application in three typical office buildings showed that the value of penetration factor (P) was influenced by the external window air-tightness level obviously, it was about 0.965 when external window air-tightness in level-4 and it was 0.920 when external window air-tightness The influence factors of penetration factor (P) and deposition loss rate (k) are different by analyzing in the last section

Key Findings / Implications -The value of P , k can be treated as be as a fixed value. The window with different structure has different value of P .

Originality - A new method of Reference can be provided to study the windows crack permeability, predict the impact outdoor $PM_{2.5}$ on indoor environmental and analyze the $PM_{2.5}$ exposure of indoor.

Keywords - Airborne fine particulate matter ($PM_{2.5}$) pollution; Infiltration characteristic; Penetration factor; Deposition rate; evaluation model



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1. Introduction

Epidemiological studies have shown that many serious human diseases, such as cardiovascular disease and lung function impairment, can be caused by long-time exposure to fine particulate matter ($PM_{2.5}$). A large number of experiment has also proven that when the external windows are closed, outdoor $PM_{2.5}$ can also go into the indoor environment through the cracks around external windows, mainly through infiltration (Chan, 2002; Chen et al., 2016; Massey et al., 2012; Massey et al., 2009). Actually, the process of $PM_{2.5}$ going into indoors through infiltration is very complicated. In this research area, researchers preferably focus on two important parameters, i.e. penetration factor (P) and deposition rate (k), due to their direct reflection of the characteristic of outdoor particles going into indoors, as well as their attenuation characteristic.

Many researchers have adopted mathematical approaches to determine the two parameters: Liu and Nazaroff (2001) investigated the influence of pressure difference and crack size on particle penetration characteristic using a theory model that calculates the penetration factor using the crack size and the pressure difference between the two sides of the crack. Based on this study, Tian et al. (2009) established a penetration factor mathematical model with crack roughness correction, and Chen et al. (2012) proposed a method calculating the penetration factor based on real window structure. Bennett and Koutrakis (2006) tried to use dynamic indoor-outdoor $PM_{2.5}$ mass concentration balance equations to compute the values of both P and k for various air exchange rate, but the result showed that it was really hard to reach a solution because there were more than one values of P and k obtained from this method. The infiltration factor ($F_{in}=aP/(a+K)$) can then be obtained with the minimum error as the constraint. Based on the study carried out by Bennett and Koutrakis, Mleczkowska et al. (2016) took less than 5% of the minimum error to calculate the mean penetration factor and deposition rate. However, the air exchange rate in the sampling sites also need to be measured, and it can only give the mean air exchange rate during the measurement period but cannot provide dynamic values. To solve this problem, this paper introduces a novel method that can calculate penetration factor, deposition rate and dynamic air exchange rate based on field measured indoor-outdoor $PM_{2.5}$ mass concentrations. The method is very useful when analyzing outdoor particle penetration characteristic, indoor particle deposition characteristic and building infiltration performance.

2. Materials and methods

2.1 Model development

Under the condition of infiltration, indoor $PM_{2.5}$ mass concentration is dependent on the rate of outdoor $PM_{2.5}$ going into indoors and then some other processes happening indoors such as coagulation, chemical reaction and resuspension. However, researchers (Branis et al., 2005; Hahn et al., 2009; Lopez-Aparicio et al., 2011) have proven that the impact of indoor coagulation, chemical reaction and resuspension on indoor $PM_{2.5}$ mass concentration is ignorable. Therefore, the indoor-outdoor $PM_{2.5}$ mass concentration dynamic equation can be expressed as (Li and Chen, 2003)

$$V \underbrace{\frac{dC_{in}}{dt}}_{\text{Transient}} = \underbrace{aPVC_{out,t}}_{\text{Indoor sources}} + \underbrace{v_{sources}}_{\text{Indoor sources}} + \underbrace{RL_f A_f}_{\text{Indoor sources}} - \underbrace{aVC}_{\text{Air flow removal}} - \underbrace{kVC_{in,t}}_{\text{Air flow removal}} \quad (1)$$

where V is the room volume, (in m^3); $C_{in,t}$, $C_{out,t}$ are indoor and outdoor $PM_{2.5}$ mass concentrations at time t , respectively, (in $\mu g/m^3$); a is air exchange rate, (in h^{-1}); P is penetration factor, (dimensionless); $v_{sources}$ is hourly indoor $PM_{2.5}$ pollutant source (in $\mu g/h$); k is deposition rate, (in h^{-1}); R is indoor $PM_{2.5}$ resuspension rate, (in h^{-1}); L_f is $PM_{2.5}$ mass per unit area, (in $\mu g/m^2$); A_f is inner surface area of room, (in m^2).

When there is no indoor $PM_{2.5}$ pollutant source and also ignoring any coagulation and phase change process, Equation (1) can be simplified as Equation (2),

$$\frac{dC_{in}}{dt} = aPC_{out,t} - (k + a)C_{in,t} \quad (2)$$

Equation (2) can be solved when using discrete time steps, expressed as Equation (3) (Bennett and Koutrakis, 2006),

$$C_{in,t} = \frac{a_i P_i C_{out,t-\Delta t}}{(k + a_i)} (1 - e^{-(k_i + a_i)\Delta t}) + C_{in,t-\Delta t} \cdot e^{-(k_i + a_i)\Delta t} \quad (3)$$

where Δt is time step, in this study $\Delta t=1h$; a_i , P_i , k_i are hourly air exchange rate, penetration factor and deposition rate, respectively. Therefore, Equation (4) can be obtained when $C_{in,i}$, $C_{out,i}$ ($i=1, 2, \dots, n$) are known for a period of time:

$$\left\{ \begin{array}{l} C_{in,2} = \frac{a_1 P_1 C_{out,1}}{(k_1 + a_1)} (1 - e^{-(k_1 + a_1)}) + C_{in,1} \cdot e^{-(k_1 + a_1)} \\ C_{in,3} = \frac{a_2 P_2 C_{out,2}}{(k_2 + a_2)} (1 - e^{-(k_2 + a_2)}) + C_{in,2} \cdot e^{-(k_2 + a_2)} \\ \vdots \\ C_{in,i} = \frac{a_{i-1} P_{i-1} C_{out,i-1}}{(k_{i-1} + a_{i-1})} (1 - e^{-(k_{i-1} + a_{i-1})}) + C_{in,i-1} \cdot e^{-(k_{i-1} + a_{i-1})} \\ \vdots \\ C_{in,n} = \frac{a_{n-1} P_{n-1} C_{out,n-1}}{(k_{n-1} + a_{n-1})} (1 - e^{-(k_{n-1} + a_{n-1})}) + C_{in,n-1} \cdot e^{-(k_{n-1} + a_{n-1})} \end{array} \right. \quad (4)$$

where hourly indoor and outdoor $PM_{2.5}$ mass concentrations could be determined by field measured data, so the unknowns are air exchange rate (a_i), penetration factor (P_i) and deposition rate (k_i). Since the number of equations is $(n-1)$ and the unknowns were $3(n-1)$ in equation (4) (there were $n-1$ a_i , P_i , k_i).

2.2 Model solution

There are two main factors influencing penetration factor; one is window crack structure, including the crack width, length, depth and the number of the right-angle bends, and another is the airflow characteristic in the window crack. However, relevant studies have confirmed an insignificant influence of air exchange rate on penetration factor (Chen et al., 2012; Liu and Nazaroff, 2001; Tian et al., 2009), so the penetration factor can be regarded as constant for a certain building, namely $P_i \approx P$ (P is mainly ranging from 0.8 to 1.0 under normal conditions according to Bennett and Koutrakis (2006) and Mleczkowska et al. (2016)). On the other hand, the deposition rate is mainly dependent on particle size, internal surface roughness and indoor airflow velocity near the wall. With a certain room structure and closed doors and windows, the indoor airflow is nearly to zero, so the deposition rate can also be considered to be a constant, with a k mainly ranging between 0 and 0.4.

Based on the above analysis, P and k can both be considered as a constant for a certain building, so Equation (4) can be transferred into Equation (5), which has $(n-1)$ equations and $(n+1)$ unknowns (there were $n-1$ a_i , and only one P_i , k_i).

$$\left\{ \begin{array}{l} C_{in,2} = \frac{a_1 PC_{out,1}}{(k+a_1)} (1 - e^{-(k+a_1)}) + C_{in,1} \cdot e^{-(k+a_1)} \\ C_{in,3} = \frac{a_2 PC_{out,2}}{(k+a_2)} (1 - e^{-(k+a_2)}) + C_{in,2} \cdot e^{-(k+a_2)} \\ \vdots \\ C_{in,i} = \frac{a_{i-1} PC_{out,i-1}}{(k+a_{i-1})} (1 - e^{-(k+a_{i-1})}) + C_{in,i-1} \cdot e^{-(k+a_{i-1})} \\ \vdots \\ C_{in,n} = \frac{a_{n-1} PC_{out,n-1}}{(k+a_{n-1})} (1 - e^{-(k+a_{n-1})}) + C_{in,n-1} \cdot e^{-(k+a_{n-1})} \end{array} \right. \quad (5)$$

In this study, the penetration factor was assumed to be ranging from 0.8 to 1.0 and the deposition rate was from 0 to 0.4, and the change of step size was 0.01. So combinations between P_i and k_j (referred as $[P_i, k_j]$) could be established. Among them, $P_{i+1}=P_i+\Delta$ ($P_1=0.8, i=1-20$); $k_{j+1}=k_j+\Delta$, ($k_1=0.01, j=1-40$), so the total number of matrix $[P_i, k_j]$ was 840, as expressed in Equation (6):

$$\left[\begin{array}{cccccc} (0.80, 0.01) & (0.80, 0.02) & \dots & & & \\ (0.81, 0.01) & (0.81, 0.02) & \dots & & & \\ \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ (P_i, 0.01) & (P_i, 0.02) & \dots & & & \\ \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ (1, 0.01) & (1, 0.02) & \dots & & & \end{array} \right] \quad (6)$$

To selected out the reasonable values $[P_i, k_j, a_{ij}^1, a_{ij}^2, \dots, a_{ij}^{n-1}]$ from the eight hundred forty numbers of ventilators, the air exchanges rate almost stable when outdoor meteorological parameters in a steady state. Therefore, standard deviation (δ_{ij}) was adopted to evaluating the stability of air exchange rate $\{a_{ij}^{n-1}\}$. All values of δ_{ij} were sorted from lowest to highest (the values within $1 < a_{ij} < 0$ were removed) and the former 5% were the solutions of Equation (5), and also regarded the mean value of corresponding penetration factor and deposition rate were the solutions

$$\delta_{i,j} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n-1} (a_{i,j} - u)^2} \quad (7)$$

where u is the arithmetic mean value of $\{a_{ij}^{n-1}\}$.

3. Case study

In order to evaluate the reasonable of the proposed method, which depends on a large number of indoor-outdoor PM_{2.5} mass concentrations monitoring data, three typical office buildings have been monitored for a long-term. Among them, sampling site 1 located in Dongcheng District, of Dongzhimen Avenue, adjacent to the East Second Ring Road, and sampling site 2 located in Peace West Bridge of Chaoyang District, adjacent to North Third Ring Road, sampling site 1 and 2 were both in Beijing.



Fig. 1 Location of the monitored office in Beijing

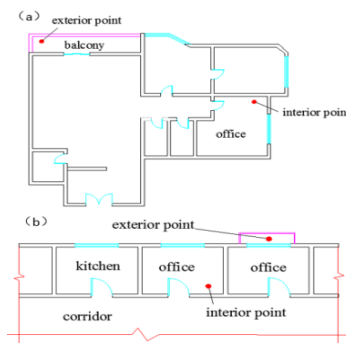


Figure 2 Floor plans of the monitored office in SP1 (a) and SP2 (b)

Indoor and outdoor PM_{2.5} mass concentrations were monitored using LD-5C(R) line laser particle monitors. The monitor sensitivity was 1µg/m³. The counting interval was 5 minutes, and the monitoring data was uploaded to the server through a wireless network. Indoor temperature and humidity were automatically collected using the Testo 175-H2 temperature and humidity logger. Meteorological parameters were obtained from the local meteorological observatory (update hourly), which was located approximately 2km east from the monitoring office. The parameters included real-time data of outdoor dry bulb temperature, relative humidity, atmospheric pressure, wind speed and direction. The exterior windows of the office building were closed during the measurement time.

Air-exchange is mainly determined by the grade of window air tightness. Table 1 shows the tightness scale of the window under internal-external pressure difference of 10 Pa referred to the classified standard of Graduations and test methods of air permeability, water tightness, wind load resistance performance for building external windows and doors(GB/T 7106-2008). Obviously, the higher grade of window, the more it can prevent.

Table 1: Air permeability performance level of window.

level	1	2	3	4	5	6	7	8
q_l^*	3.5~4.0	3.0~3.5	2.5~3.0	2.0~2.5	1.5~2.0	1.0~1.5	0.5~1.0	≤0.5

* q_l is volume of air flow through per length of crack, m³/(m·h)

Table 2: Basic condition of the sampling site.

sampling point	Room size ($D \times W \times H$, m ³)	airtightness	Window size ($H \times D$ m ²)	crack width (m)	crack depth (mm)	crack height (mm)
1	2.8×4.5×4.4	4	1.15×0.7	3.7	50	0.82
2	3×6×4	8	1.2×0.9	8.4	70	0.56

The method of estimate the height of window crack base on the airtightness of external windows (Chen et al. under reviewing).

3.1 Analysis of measured buildings in site 1

3.1.1 Data collection

Data for six consecutive hours during stable meteorological parameters is chosen to compute P and K . Time interval is 1 hour and the measured data is divided into a set of 6 hours. So we could get a pair of the $[P, k]$ value by using the method in Model Solution. At last, 43 sets of data respective in winter and spring are selected to compute the $[P, k]$.

3.1.2 Values of the P and k

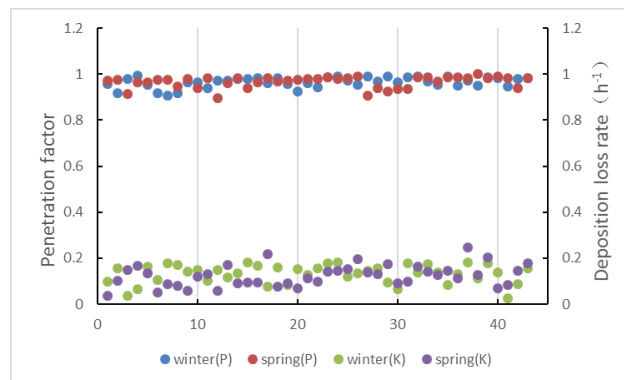
Figure 3 The P and k calculated by 2x43 groups measured data

Fig.3 shows the calculated value of P and k in winter and spring by using the method in Model Solution. As is shown here, the value of P in winter and spring are nearly equal, and the value is 0.965 ± 0.022 and 0.965 ± 0.024 respectively. The value of k in winter approximately is same as the spring, and the figure is 0.123 ± 0.046 and 0.131 ± 0.041 separately. The result shows the values of P and k are stable. It also proved that the values of P and k have little relationship with the air change rate, and the major factors are structural characteristics of the building.

3.1.3 Model validation

In order to validate the rationality of *AER*, this study used drikold as the tracer gas (CO₂) source to measure the air exchange rate. Drikold releases CO₂ until the concentration becomes stable. Then the indoor CO₂ concentration would gradually decrease to the original level because of existence of air infiltration, and based on this process the corresponding air exchange rate could be calculated. In this study, Lutron MCH-383SD was used for measuring both indoor and outdoor CO₂ concentrations, with a monitoring range between 0 and 4000ppm; an error of ±40ppm when CO₂ concentration is less than 1000ppm, an error of ± 5% rdg (rdg means tester reading) when the CO₂ concentration exceeds 1000ppm, and an error of ± 250ppm when the CO₂ concentration rises beyond 3000ppm.

The monitored curves of both outdoor and indoor CO₂ concentrations are shown in Figure 4. Drikold released CO₂ until the concentration rose to about 3800ppm when both doors and windows were closed. Then the Drikold was stopped and the indoor CO₂ concentration gradually decreased to the original level.

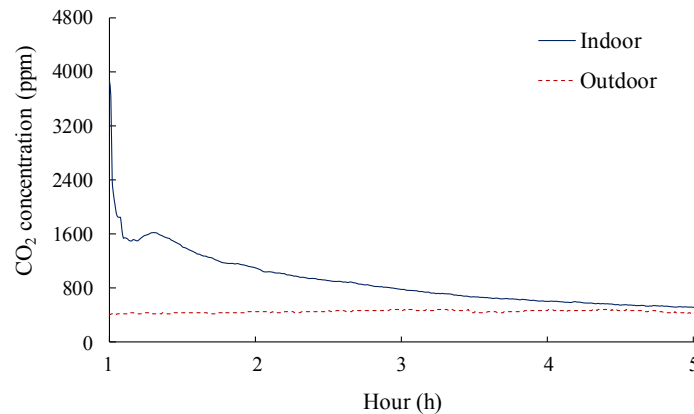


Figure 4 The monitored curves of both outdoor and indoor CO₂ concentrations

According to Equation (9)(You et al., 2012), the calculated air exchange rate was 0.24 h⁻¹ during the monitoring period. It showed a good agreement with the model calculation result (0.22 h⁻¹). Therefore, there is confidence to the proposed model about its prediction accuracy.

$$AER = \frac{\ln C_o - \ln C_t}{\Delta T} \quad (9)$$

where the *AER* is the air exchange rate, (in h⁻¹); *C_o* and *C_t* are the initial concentration and the concentration in *t* time, (in ppm). *ΔT* is the monitoring time, (in s).

3.2 Analysis of measured buildings in site 2

3.2.1 Data collection

Data for six consecutive hours during table meteorological parameters is chosen to compute *P* and *k*. Time interval is 1 hour and the measured data is divided into a set of 6 hours. So we could get a pair of the [*P*, *k*] value by using the method in Model Solution. At last, 48 sets of date are selected to compute the [*P*, *k*].

3.2.2 Values of the P and k

Fig.5 shows the calculated value of P and k by using the method in Model Solution. The value of P is 0.92 ± 0.11 . The value of k is 0.12 ± 0.076 . Trapping efficiency of the window in site 2 is 1 times higher than site 1. The value of k is the same in the two sites.

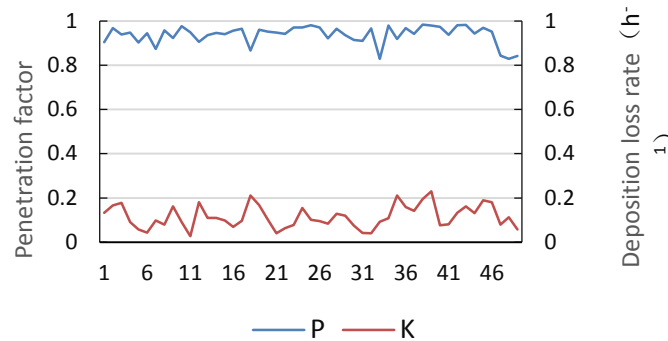


Figure 5 The P and k calculated by 48 groups measured data

3.3 Analysis of the differences P and K

The value of P in sampling site 1 and sampling site 2 are 0.96 and 0.92 respectively. The major factor that influences the P is the structural characteristics window, including crack height, crack depth, and crack width. There has been a positive correlation between crack depth and the value of P , and the crack height is negatively correlated with the value of P . Crack depth of site 1 and 2 is 0.05m and 0.07m respectively. The value of P in site 1 is 40 percent higher than site 2. Crack height of site 1 and 2 are 0.82mm and 0.56mm respectively. So, the value of P in site 2 is smaller. The wall roughness, the ratio of volume to room surfaces (V/S) can influence the deposition loss rate (k), k is positively correlated with roughness and V/S . The figure in site 1 and 2 are both 0.12. The differences of roughness need to be further studied.

4. Conclusion

Based on field measured indoor-outdoor $PM_{2.5}$ mass concentrations, a novel method that can be used to calculate penetration factor, deposition rate and dynamic air exchange rate has been proposed and validated. It is very useful when analyzing outdoor particle penetration characteristic, indoor particle deposition characteristic and building infiltration performance. Main conclusions that could be obtained from this study include:

- 1) The penetration factor and deposition rate were nearly constant for a given building structure;
- 2) The Penetration factor decreases when the window air-tightness level is promoted;
- 3) There was no conspicuous evidence for that the deposition rate is influenced by room dimension and internal surface roughness.
- 4) The indoor $PM_{2.5}$ mass concentration could be reduced when replacing low air-tightness windows by high ones.

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