Atmospheric Environment 45 (2011) 275–288

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Review

Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor

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ARTICLE INFO

Article history:
Received 11 August 2010
Received in revised form
16 September 2010
Accepted 21 September 2010

Keywords:
Particle
Penetration
Infiltration
I/O ratio
Indoor environment
Outdoor environment

ABSTRACT

Epidemiologic evidence indicates a relationship between outdoor particle exposure and adverse health effects, while most people spend 85–90% of their time indoors, thus understanding the relationship between indoor and outdoor particles is quite important. This paper aims to provide an up-to-date revision for both experiment and modeling on relationship between indoor and outdoor particles. The use of three different parameters: indoor/outdoor (I/O) ratio, infiltration factor and penetration factor, to assess the relationship between indoor and outdoor particles were reviewed. The experimental data of the three parameters measured both in real houses and laboratories were summarized and analyzed. The I/O ratios vary considerably due to the difference in size-dependent indoor particle emission rates, the geometry of the cracks in building envelopes, and the air exchange rates. Thus, it is difficult to draw uniform conclusions as detailed information, which make I/O ratio hardly helpful for understanding the indoor/outdoor relationship. Infiltration factor represents the equilibrium fraction of ambient particles that penetrates indoors and remains suspended, which avoids the mixture with indoor particle sources. Penetration factor is the most relevant parameter for the particle penetration mechanism through cracks and leaks in the building envelope. We investigate the methods used in previously published studies to both measure and model the infiltration and penetration factors. We also discuss the application of the penetration factor models and provide recommendations for improvement.

1. Introduction

Epidemiologic evidence indicates a relationship between particle pollution exposure and adverse respiratory and cardiovascular health effects, including decreased lung function, asthma, myocardial infarction and all-cause mortality (Dockery et al., 1993; Pope et al., 1995; Schwartz et al., 1996; Gold et al., 1999; Klemm et al., 2000; Peters et al., 2000; Samet et al., 2000; Yu et al., 2000; Brunekreef and Holgate, 2002; EPA, 2005). Since most people spend 85–90% of their time indoors (Jenkins et al., 1992; Robinson and Nelson, 1995; EPA, 1996; Klepeis et al., 2001), assessing indoor particle pollution exposure is important for understanding the impact of particle pollution on human heath. Outdoor particle pollution concentrations are a major contributor to indoor concentrations. Many sources of outdoor particles including automobiles, industry and many combustion processes such as coal-burning (Peterson and Junge, 1971; Gartrell and Friedlander, 1975; Heicklein, 1976; Spengler et al., 1990; UNEP/WHO, 1993), can also result in indoor air pollution. The impact of outdoor particles on the indoor environment is particularly important in many developing countries where outdoor particle pollution is increasing (Lee et al., 1997).

Buildings are typically ventilated using three mechanisms: mechanical ventilation, natural ventilation and infiltration. All of these mechanisms can result in the transport of outdoor particles into the indoor environment, as shown in Fig. 1. Mechanical ventilation typically includes a supply of fresh (outdoor) air which contains outdoor-originated particles. Since filters in a mechanical ventilation system cannot completely remove all particles of outdoor origin, these particles enter into the indoor environment. Natural ventilation occurs by moving wind and buoyancy-induced flow through open windows or doors, thereby transporting outdoor particles into the indoors. There have been many studies dealing with the application of ventilation in both the indoor and outdoor environment. Ventilation concepts have been used for both indoor building ventilation (Kato et al., 2003; Huang et al., 2006; Niachou et al., 2008; Chen, 2009) and the urban environment (Baby et al., 2008; Bu et al., 2009; Buccolieri et al., 2010). Both indoor and urban air quality has been analyzed in terms of ventilation efficiency and breathability concepts. Infiltration refers to the

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doi:10.1016/j.atmosenv.2010.09.048

Nomenclature

a (s^{-1})	Air exchange rate
C ($mg\,m^{-3}$)	Particle concentration
C_{in} ($mg\,m^{-3}$)	Indoor particle concentration
C_{out} ($mg\,m^{-3}$)	Outdoor particle concentration
$C_{\dot{S}}$ ($mg\,m^{-3}$)	Indoor particle concentration that is contributed by indoor sources
C_i ($mg\,m^{-3}$)	$C_i = C_{in}(t = 0)$
C_f ($mg\,m^{-3}$)	$C_f = C_{in}(t = \infty)$
C_∞ ($mg\,m^{-3}$)	Particle concentration at the inlet of the cracks
d (mm)	Crack height
d_p (m)	Particle diameter
D ($m^2\,s^{-1}$)	Particle Brownian diffusivity
F_{in}	Infiltration factor
$\vec{F}_x$ ($m\,s^{-2}$)	An additional acceleration (force/unit particle mass) term
$\vec{g}_x$ ($m\,s^{-2}$)	Gravitational acceleration
K (s^{-1})	Particle deposition rate
n_b	The number of right-angle bends in the crack
N_{escape}	Number of the escaped particles at the outlet
N_{total}	Number of the total particles released at the crack inlet
P	Penetration factor
P_g	Particle deposition rate due to gravitational settling
P_d	Particle deposition rate due to Brownian diffusion
P_i	Particle deposition rate due to inertial impaction
ΔP (Pa)	Pressure difference between inlet and outlet of the crack
Q ($m^3\,s^{-1}$)	Airflow rate
$\dot{S}$ ($mg\,s^{-1}$)	Indoor particle emission rate
t (s)	Time
u ($m\,s^{-1}$)	Airflow velocity
u_y ($m\,s^{-1}$)	Airflow velocity at vertical axis
u_m ($m\,s^{-1}$)	Average velocity of air in the crack
$\vec{u}$ ($m\,s^{-1}$)	Fluid phase velocity
$\vec{u}_p$ ($m\,s^{-1}$)	Particle velocity
V (m^3)	Volume of the room
v_s ($m\,s^{-1}$)	Gravitational settling velocity of particles
w (mm)	Crack width
x (m)	Absolute horizontal axis
y (m)	Absolute vertical axis
z (mm)	Crack length
μ ($N\,s\,m^{-2}$)	Dynamic viscosity of air
ρ ($kg\,m^{-3}$)	Air density
ρ_p ($kg\,m^{-3}$)	Particle density
ε	Particle deposition ratio

uncontrolled flow of air through cracks and leaks in the building envelope, which can also result in the entry of outdoor particles. Residential building windows are frequently closed during times of the year when the air conditioning system or heating systems are in use. Comparing with natural ventilation, infiltration results in a relatively low air exchange rate. Yamamoto et al. (2010) reported a median air exchange rate of 0.71 ACH (Air Change per Hour) among approximately 500 residences). In this case, infiltration becomes the primary pathway for outdoor air and particles entering the residential spaces. Therefore, understanding the relationship between indoor and outdoor particles is quite important. This paper aims to provide an up-to-date review of both experiment and modeling on relationship between indoor and outdoor particles.

This paper summarized the experimental studies as well as modeling studies for the relationship between indoor and outdoor particle concentration. Three widely used parameters, i.e. indoor/outdoor (I/O) ratio, penetration factor and infiltration factor, were reviewed in this paper. In the section "2. Quantifying the relationship between indoor and outdoor particles", we review the definitions of the three parameters as well as the reasons why choosing them. In the section "3. Experimental study review", we review the measurement methods and investigate the results of experimental data for the three parameters. The applications of penetration factor measurement methods are also discussed. In the section "4. Modeling study review", we evaluate the models of the penetration factor only, since most studies on I/O ratio and infiltration factor are based on experimental data. We conclude by discussing the application of these penetration factor models and provide recommendations for improvement.

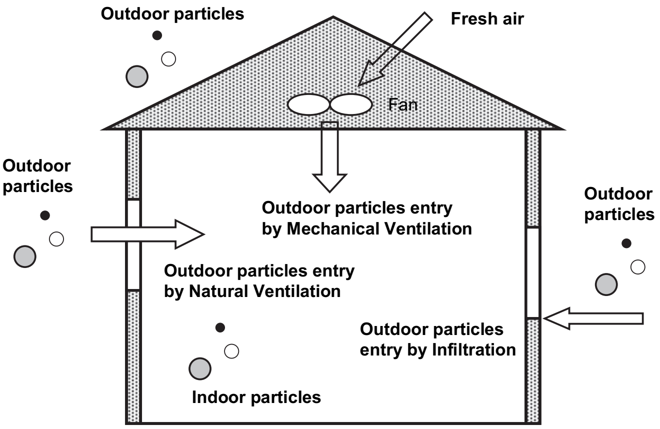

Fig. 1. The pathways of outdoor particles entering into indoor environment.

2. Quantifying the relationship between indoor and outdoor particles

2.1. Indoor/outdoor (I/O) ratio

I/O ratio directly represents the relationship between indoor and outdoor particle concentrations, which is very easy to understand and widely used. Thus, I/O ratio data were summarized in order to provide a general impression on the relationship between indoor and outdoor particles. I/O ratio is defined as:

$$\text{I/O ratio} = \frac{C_{in}}{C_{out}}, \tag{1}$$

where C_{in} and C_{out} are the indoor and outdoor particle concentration, respectively.

2.2. Infiltration factor

Infiltration factor represents the equilibrium fraction of ambient particles that penetrates indoors and remains suspended. It avoids the mixture with indoor particle sources, thus, it is worthy to summarize. Infiltration factor (F_{in}) is obtained by applying a mass balance to derive an equation connecting the ambient and indoor concentrations:

$$V\frac{\mathrm{d}C_{\mathrm{in}}}{\mathrm{d}t} = aPVC_{\mathrm{out}} - aVC_{\mathrm{in}} - KVC_{\mathrm{in}} + \dot{S}, \tag{2}$$

where V is the volume of the room, t is time, a is the air exchange rate due to infiltration, P is the particle penetration factor, K is the particle deposition rate, and $\dot{S}$ is the indoor particle emission rate. It should be noted that the resuspension of particles is neglected in this equation. All the parameters except V and a are a function of both time and particle size (Li and Chen, 2003).

Infiltration factor is defined based on the steady-state and zero indoor particle emission rate case of Eq. (2):

$$F_{\mathrm{in}} = \frac{aP}{a+K}, \tag{3}$$

when the mechanical ventilation system is used, the filter efficiency can affect Eq. (2). Thus the generalized definition of infiltration factor can be expressed as:

$$C_{\mathrm{in}} = F_{\mathrm{in}}C_{\mathrm{out}} + C_{\dot{S}}, \tag{4}$$

where $C_{\dot{S}}$ is the indoor particle concentration which is contributed by indoor sources.

2.3. Penetration factor

Penetration factor, P, is defined as the fraction of particles in the infiltration air that passes through the building shell. Since it is the most relevant parameter for the particle penetration mechanism through cracks and leaks in the building envelope, studies about penetration factor were also reviewed.

3. Experimental study review

3.1. I/O ratio

3.1.1. Measurement methods

Since I/O ratio directly represents the relationship between indoor and outdoor particle concentrations, there have been many studies concerning measurements and data analysis for I/O ratio. The measurement method for I/O ratio is relatively simple. The most common used method is installing two particle sample monitors inside and outside the testing building, and then the I/O ratio can be obtained. The most important part of an experiment on I/O ratio is the study design. According to different research objectives, researchers choose specific sample buildings to measure I/O ratio under different conditions for comparison.

3.1.2. Data analysis

The experimental data of I/O ratio and corresponding conditions were tabulated (see supporting information: Table S1 and S3). Fig. 2 shows the distribution of measured I/O ratios in the studies. The RSP (Respirable Suspended Particle) in Table S1 were classified to the group of PM2.5. The TSP (Total Suspended Particle) in Table S1 were classified to the group of PM10. The data were separated into 4 groups: PM2.5, PM10, 0.001–0.5 μm, 0.5–15 μm. As shown in Fig. 2, I/O ratios in these studies vary in a large range (from 0.02 to 31) due to differing measurement conditions. The largest I/O ratio happened in homes in Nepal where the owners presumably cooked and smoked in homes without chimneys, while the smallest I/O ratio happened in an uninhabited telephone switching building with excellent filtration. The differences among the buildings including indoor particle sources, geometry of the cracks in buildings, outdoor wind environments, ventilation patterns and the use of filtration result in the enormous range of I/O ratio.

Since there are many I/O ratio studies (77 studies reviewed in this paper including over 4000 homes), we distilled out the large-scale studies (larger than 20 homes) as shown in Fig. 3 (PM2.5) and 4 (PM10). The detailed information of other references can be seen in Table S1 (Abt et al., 2000; Adgate et al., 2002; Adgate et al., 2003; Anderson, 1972; Arhami et al., 2010; Baek and Kim, 1997; Blondeau et al., 2005; Brickus et al., 1998; Brunekreef et al., 2005; Cao et al., 2005; Chan, 2002; Clayton et al., 1999; Davidson et al., 1986; Fischer et al., 2000; Gotschi et al., 2002; Janssen et al., 1998, 2000; Kado et al., 1994; Kinney et al., 2002; Letz et al., 1984; Lioy et al., 1990; Long and Sarnat, 2004; Lunden et al., 2008; Molnar et al., 2005; Menetrez et al., 2009; Monn et al., 1997; Meng et al., 2005;

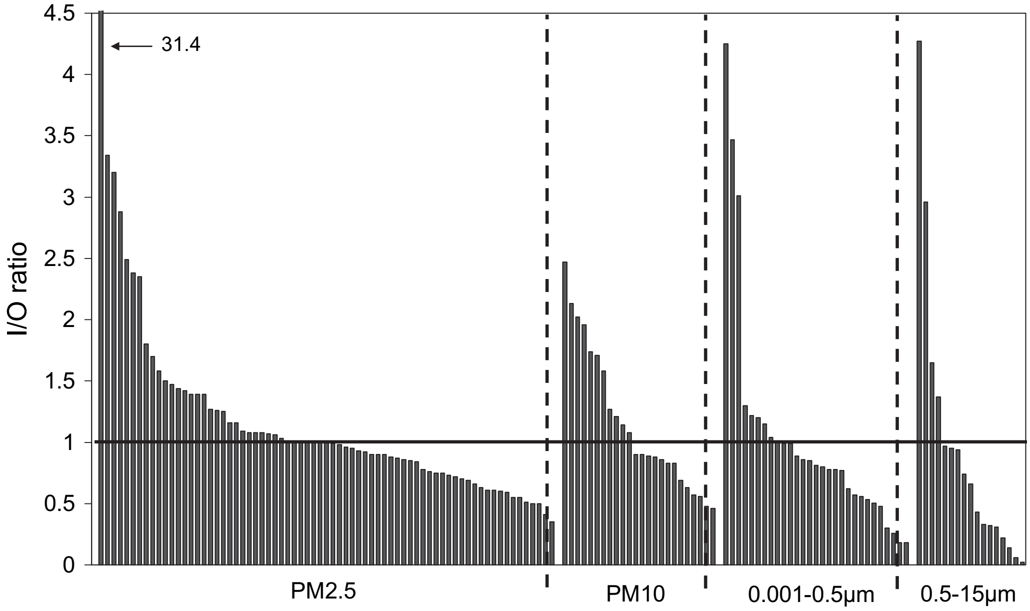

Fig. 2. Experimental data distribution of particle I/O ratios in the studies tabulated in Table S1. The RSP in Table S1 were classified to the group of PM2.5.The TSP in Table S1 were classified to the group of PM10. The data in Matson (2005), Guo et al. (2008), Morawska et al. (2001) (ultrafine particle data) and the data of PM1 were classified to the group of 0.001–0.5 μm. (Abscissa represents the experimental studies reviewed in this paper.)

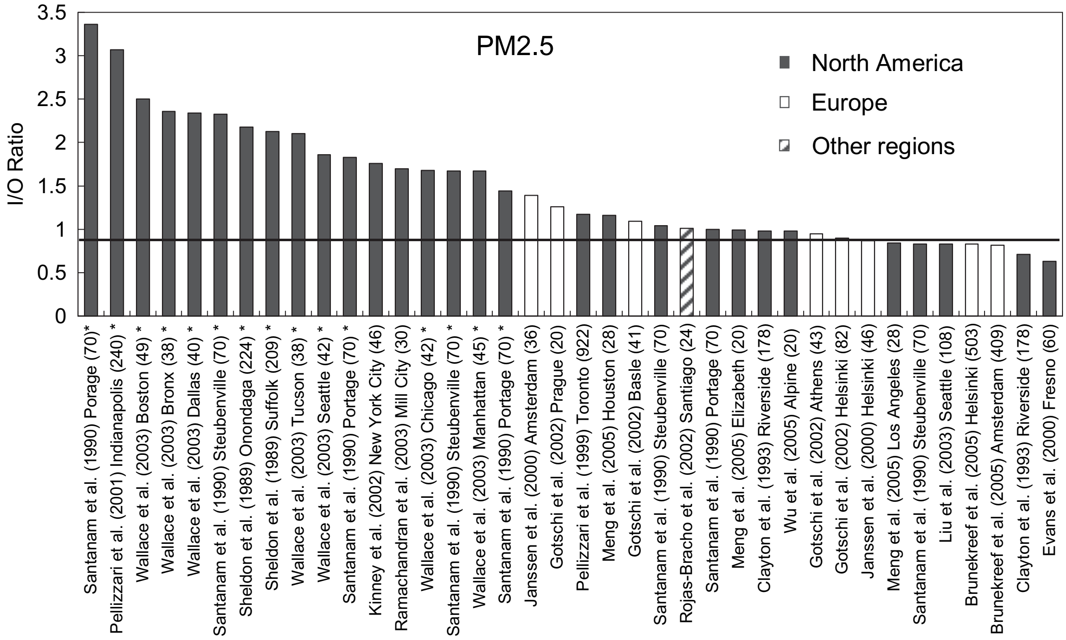

Fig. 3. Experimental data distribution of PM2.5 I/O ratios in the large-scale studies (larger than 20 homes) in different cites. The RSP were classified to the group of PM2.5. The numbers in ( ) represent the number of the sample homes. *Indoor smoking that was definitely mentioned in the studies.

Monkkonen et al., 2005; Mouratidou and Samara, 2004; Pekey et al., 2010; Pellizzari et al., 1999; Polidori et al., 2007; Ramachandran et al., 2003; Sexton et al., 1984; Sinclair et al., 1990; Spengler and Thurston, 1983; Spengler et al., 1981; Tovalin-Ahumada et al., 2007; Wu et al., 2005).The summary of the major studies also shows an enormous range of I/O ratio for both PM2.5 and PM10. As shown in Figs. 3 and 4, the huge I/O ratio is highly due to the presence of indoor smoking, such as 3.36 in Portage and 2.33 in Steubenville (Santanam et al., 1990), 3.07 in Indianapolis (Pellizzari et al., 2001), 1.67–2.5 in seven U.S. cites (Wallace et al., 2003), 2.13 and 2.18 in Onondaga and Suffolk (Sheldon et al., 1989) for PM2.5 and 2.3 in Indianapolis (Pellizzari et al., 2001) for PM10. Besides, other indoor combustion process such as the use of fireplace can also lead to high I/O ratio. The low I/O ratio is strongly related to few indoor sources, the use of filtration and the tightness of the buildings, such as 0.71 for PM2.5 in Riverside which is measured at night with few indoor sources (Clayton et al., 1993) and 0.48 for PM10 in Daegu which is measured in winter with the use of filtration (Jo and Lee, 2006).

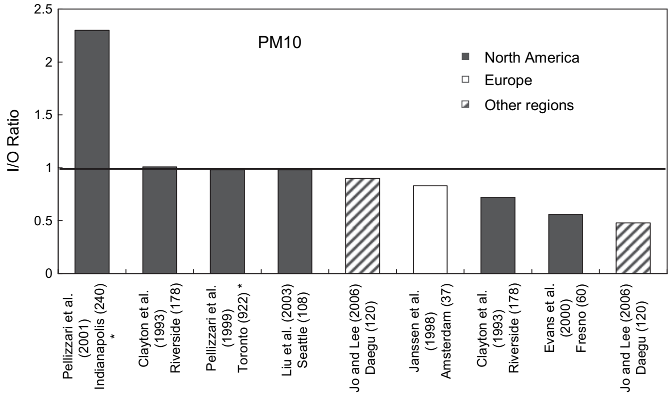

Fig. 4. Experimental data distribution of PM10 I/O ratios in the large-scale studies (larger than 20 homes). The TSP were classified to the group of PM10. The numbers in ( ) represent the number of the sample homes. *Indoor smoking that was definitely mentioned in the studies.

Many researchers focus on one of the influencing factors of I/O ratio in order to find some conclusive information. However, the conclusions by different researchers are inconsistent. The following sections focus on the comparison of different researchers' conclusions on specific issues such as particle size, ventilation mode, season variety and so on. For convenience, the I/O ratio was rewritten as according to Eq. (1) and the steady-state case of Eq. (2) when a building is naturally ventilated:

$$\mathrm{I/O\ ratio} = \frac{aP}{a+K} + \frac{\dot{S}}{(a+K)VC_{\mathrm{out}}}, \tag{5}$$

For particle size, many researchers chose to compare PM2.5 and PM10. As shown in Table S1, the results by Rojas-Bracho et al. (2000), Monn et al. (1995), Jones et al. (2000), Liu et al. (2003) show that the I/O ratios of PM2.5 are lower than those of PM10. The results by Morawska et al. (2001) and Poupard et al. (2005) also indicated that the I/O ratios of fine particles are lower than that of coarse particles. However, the results by Li (1994), Evans et al. (2000), Pellizzari et al. (2001), Colbeck et al. (2010), Wang et al. (2006) and Rojas-Bracho et al. (2002) show that the I/O ratios of PM2.5 are higher than that of PM10, which is different from the previous opinion. The results by Thatcher and Layton (1995), Weschler (1984) and Geller et al. (2002) also indicate that the I/O ratios of fine particles are higher than that of coarse particles. Additionally, the results by Clayton et al. (1993), Li and Lin (2003) and Riain et al. (2003) show that the I/O ratios of PM2.5 almost equate to that of PM10. Some researchers measured the size-dependent I/O ratios for ultrafine particles (0.002–0.5 μm) (Zhu et al., 2005; Koponen et al., 2001), while other researchers measured the size-dependent I/O ratios for fine and coarse particles (Gupta and Cheong, 2007; Tippayawong et al., 2009). However, they also did not obtain a uniform conclusion of the impact of particle size on I/O ratio. The most probable reason for the inconsistency among these studies is that the measurement conditions are different. In each study, the deposition rate for PM10 should be larger than that of PM2.5, while penetration factor for PM10 should be smaller than that of PM2.5. The characteristics of penetration factor and deposition rate may cause the higher I/O ratio of PM2.5

than that of PM10. However, the indoor particle source emission rates may be quite different between PM10 and PM2.5, which depends on the characteristics of the indoor sources. It is possible that the indoor sources emit more coarse particles than fine particles, while outdoor coarse particle concentration is lower than fine particles, which may cause the lower I/O ratio of PM2.5 than that of PM10. However, most of the studies only provide the general information of the indoor sources, since the size-dependent indoor particle source emission rates are difficult to measure in most of the cases.

For air exchange rate, some researchers studied the influence of ventilation mode, i.e. natural ventilation, mechanical ventilation and infiltration. The mass balance equation of a sample room with mechanical ventilation is slightly different from Eq. (2), which has been described in Thornburg et al. (2001). For mechanical ventilated homes, the filter efficiency can strongly affect I/O ratio (Partti-Pellinen et al., 2000). The results in Zhu et al. (2005) and Chao and Tung (2001) show that the I/O ratio with windows open is higher than the ratio with windows closed. However, the results by Guo et al. (2008) show the opposite conclusion. Also, the I/O ratios under natural ventilation were compared with ratios under mechanical ventilation by Baker et al. (1987), Ho et al. (2004), Poupard et al. (2005) and Gupta and Cheong (2007). However, there is no uniform conclusion on this issue. The possible reason may also be due to different measurement conditions. The first term of the right side of Eq. (5) will increase with the increase of air exchange rate, while the second term of the right side of Eq. (5) will decrease with the increase of air exchange rate. In other words, the impact of the air exchange rate depends on other influencing factors, such as penetration factor, deposition rate, indoor particle source emission rate and outdoor particle concentration. For instance, if there is no indoor particle source, the I/O ratio will increase with the increase of air exchange rate. However, if the indoor particle source emission rate is very large and the outdoor particle concentration is very low, the I/O ratio will decrease with the increase of the air exchange rate.

Particle penetration factor is another important factor deciding the I/O ratio. If the building is naturally ventilated by opening windows, the particle penetration factor should be approximately equal to 1. However, if the building is ventilated by infiltration, the particle penetration factor is a strong function of air exchange rate, particle size and the geometry of cracks in the building envelope (Liu and Nazaroff, 2001, 2003). The detailed information on the geometry of cracks in building envelopes is difficult to quantify, thus most of these studies cannot provide the information.

Deposition rate, which is size-dependent, can also affect the I/O ratio. There are a number of studies focusing on measuring or modeling the deposition rate. Lai (2002) reviewed the particle deposition studies before 2002. Then, there are many studies focus on the deposition of aerosol particles in chambers under controlled conditions and in real-life conditions such as apartments and office buildings (Thatcher et al., 2002; Chao et al., 2003; Wallace et al., 2004; Bouilly et al., 2005; He et al., 2005; Hussein et al., 2005, 2006, 2009; Lai and Nazaroff, 2005; Chen et al., 2006; Hamdani et al., 2008). Also, there are some modeling studies on indoor particle deposition (Zhao et al., 2004; Lai and Nazaroff, 2005; Tian and Ahmadi, 2007; Lai and Chen, 2007). These studies show that not only particle size but also other influencing factors such as airflow pattern, turbulence level, and properties of indoor surfaces can affect indoor particle deposition. Generally speaking, Brownian diffusion is an important mechanism for ultrafine particles. Gravitational settling is the most important for coarse particles. And accumulation mode particles deposit least effectively.

Based on experimental data in the literature, simulation results also show that indoor particle sources, penetration factor, air exchange rate and outdoor particle concentration can strongly affect the I/O ratio (Li and Chen, 2003; Kulmala et al., 1999). The influence of different seasons on I/O ratio was analyzed in some studies (Santanam et al., 1990; Lachenmyer and Hidy, 2000; Schneider et al., 2004; Jo and Lee, 2006; Martuzevicius et al., 2008). Nevertheless, since the conditions including air exchange rate, size-dependent outdoor particle concentration are different in different seasons, there is also no uniform conclusion on this issue.

Generally speaking, the I/O ratio can provide a general idea on the relationship between indoor and outdoor particle concentration, nevertheless, it is affected by many influencing factors especially indoor particle sources, which results in an enormous range of measured values (from far below 1 to far above 1). Through comparing different studies, it can be found that all the issues discussed above have no uniform conclusions. These evidences strongly demonstrate that the I/O relation is not useful in understanding indoor/outdoor particle relationships.

3.2. Infiltration factor

3.2.1. Measurement methods

According to Eq. (4), the linear approach can be used to measure the infiltration factor. After measuring the indoor and outdoor particle concentrations under different conditions, the parameters F_{in} and $C_{\dot{S}}$ can be solved from the regression of indoor concentration against the outdoor concentration as demonstrated by Ott et al. (2000). The slope of the regression estimates the F_{in}, and the intercept estimates the average concentration of indoor generated particles ($C_{\dot{S}}$). This method allows for both steady and non-steady conditions. The idea for non-steady conditions is that over many measurements there will be about as many with positive as negative residuals. This method is very simple and was applied by many researchers (Dockery and Spengler, 1981; Ozkaynak et al., 1996; Lee et al., 1997; Lachenmyer and Hidy, 2000; Landis et al., 2001; Long et al., 2001; Wallace et al., 2003; Allen et al., 2003; Williams et al., 2003; Reff et al., 2005; Wallace and William, 2005; Hanninen et al., 2004; Lazaridis et al., 2006; Sarnat et al., 2006; Meng et al., 2007; Hoek et al., 2008; Meng et al., 2009).

Bennett and Koutrakis (2006) developed an alternative method for calculating the infiltration factor using time-dependent indoor and outdoor particle concentrations and air exchange rate. Assuming there are no indoor particle sources, Eq. (2) can be rewritten as follows:

$$C_{\text{in},t} = \frac{aP}{a+K} C_{\text{out}} \left(1 - e^{-(a+K)\Delta t}\right) + C_{\text{in},t-\Delta t} e^{-(a+K)\Delta t}. \qquad (6)$$

Since there are two unknowns P and K in Eq. (6), it was not possible to obtain two independent solutions for these two unknown parameters. To determine P and K, they were allowed to vary independently over the likely ranges of values, $0 < K$ and $0 < P < 1$, respectively. For each pair of P and K values, they examined the error between the calculated and measured data. The pair of P and K values that fits best was determined as the final values. Then the infiltration factor can be obtained using Eq. (3).

3.2.2. Data analysis

The experimental data of infiltration factors and their measurement conditions in different studies were tabulated (see supporting information, Table S2 and S3). Fig. 5 shows the distribution of measured infiltration factor in the large-scale studies (larger than 20 homes). The infiltration factors measured by different researchers vary in the large range of 0.3–0.82 for PM2.5, 0.17–0.52 for PM10, since their measurement conditions are quite different. Generally speaking, the infiltration factors of PM2.5 are

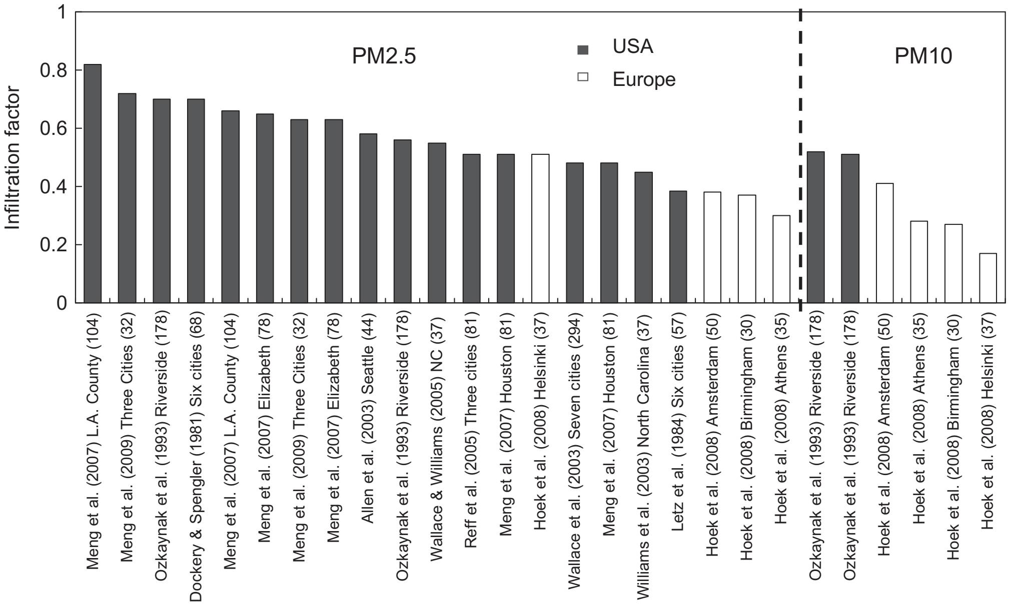

Fig. 5. Experimental data distribution of particle infiltration factor in the large-scale studies (larger than 20 homes) tabulated in Table S2. The RSP were classified to the group of PM2.5. The numbers in ( ) represent the number of the sample homes.

higher than that of PM10, since the strength of deposition of PM2.5 is much weaker than that of PM10. According to Eq. (3), the infiltration factor can be affected by the penetration factor, air exchange rate and deposition rate. When a building is ventilated by infiltration, the penetration factor is a function of particle size, indoor/outdoor pressure difference, air exchange rate and geometry of cracks in the building envelopes. Wind direction and speed can affect the indoor/outdoor pressure difference and air exchange rate, thus they are also influencing factors. Again, since the detailed information on these influencing factors is difficult to quantify, most of these studies cannot provide it. Besides, the use of mechanical ventilation with air filter can also strongly affect the infiltration factor. Higher filter efficiency can reduce the infiltration factor. For instance, the infiltration factors measured by Hoek et al. (2008) were relatively smaller than others, since the measured houses include some using mechanical ventilation system with air filter.

Infiltration factor represents the equilibrium fraction of ambient particles that penetrates indoors and remains suspended, which avoids the influence of indoor sources. Thus it is quite useful for qualifying the fraction of the total indoor particles coming from the outdoor environment. However, since it contains the process of indoor particle deposition, infiltration factor is difficult to reflect the process of outdoor particles entering to indoors through buildings.

3.3. *Penetration factor*

Among the three parameters, the most relevant parameter for the penetration mechanism through cracks is the penetration factor.

3.3.1. *Measurement methods*

There are two kinds of experimental studies on penetration factor: one is in real buildings, the other is in laboratories.

3.3.1.1. Real buildings. Tung et al. (1999) measured the penetration factor in an office building for PM10 using the following equation:

$$C_{\mathrm{in}}(t) = \left[C_i - \frac{\dot{S} + aPVC_{\mathrm{out}}}{(a+K)V}\right]e^{-(a+K)t} + \frac{\dot{S} + aPVC_{\mathrm{out}}}{(a+K)V} = \left[C_{\mathrm{i}} - C_{\mathrm{f}}\right]e^{-(a+K)t} + C_{\mathrm{f}}, \tag{7}$$

where $C_{\mathrm{i}} = C_{\mathrm{in}}(t=0)$ and $C_{\mathrm{f}} = C_{\mathrm{in}}(t=\infty)$. The authors assumed that there are no particle sources $(\dot{S} = 0)$ in the sample room since they conducted the measurements at night. After measuring the particle decay curve and air exchange rate, the penetration factor can be calculated by:

$$P = \frac{(a+K)C_{\mathrm{f}}}{aC_{\mathrm{out}}}. \tag{8}$$

The same approach was applied by Chao et al. (2003) to measure particle size-dependent penetration factors in non-smoking residences. The authors also assumed that there are no particle sources in non-smoking residences. Different from measuring particle decay curve (Tung et al., 1999; Chao et al., 2003), Thatcher et al. (2003) developed a concentration rebound method to measure particle penetration factor and deposition rate. First the authors measured the particle loss rate following artificial elevation of indoor particle concentrations to obtain the deposition rate, then rapidly reduced particle concentration through induced ventilation by pressurization of the houses with HEPA-filtered air. Finally they measured the particle concentration rebound to obtain the penetration factor. In the authors' opinion, during the particle concentration decay period, when indoor concentrations are very high, losses due to deposition are large compared to gains due to particle infiltration. During the concentration rebound period, the opposite is true. Therefore, the effects of penetration and deposition losses can be separated.

The methods applied by Tung et al. (1999), Chao et al. (2003) and Thatcher et al. (2003) that are based on measuring the particle decay or rebound curve all assume that there are no particle sources indoors. However, when indoor particle emissions cannot be avoided, the method developed by Long et al. (2001) which is based on the linear regression approach can be used.

After measuring the indoor and outdoor particle concentrations under different conditions, $C_{\hat{S}}$, i.e. the intercept of the linear regression Eq. (5), can be obtained. Then, according to Eq. (5), a linear expression can be rewritten as:

$$\frac{C_{\text{out}}}{C_{\text{in}} - C_{\hat{S}}} = \frac{K}{P}\left(\frac{1}{a}\right) + \frac{1}{P}. \tag{9}$$

After measuring air exchange rates under different conditions, the linear expression (Eq. (5)) can be regressed. Then the penetration factor can be easily obtained.

Based on Eq. (3) and the measured data of the infiltration factor, Williams et al. (2003) and Zhu et al. (2005) used error analysis that is similar to the error analysis approach applied by Bennett and Koutrakis (2006) to obtain the particle penetration factor. According to Eq. (3), Vette et al. (2001) used the measurement data of the infiltration factor, air exchange rate and deposition rate to calculate the particle penetration factor.

3.3.1.2. Laboratory. While measurements in real buildings cannot control the indoor/outdoor pressure difference, measurements in laboratories can maintain the pressure differences between the inlet and outlet of the cracks. Therefore, to understand the factors influencing particle penetration, some researchers measured the particle penetration factors in laboratories. Mosley et al. (2001) conducted an experiment in a chamber which consists of two compartments of the same size. Compartment 1 of the chamber simulates the outdoors, while compartment 2 simulates the indoor space. After cleaning the chamber, particles were injected into compartment 1 until a certain concentration was reached. Then the particle decay curve in compartment 1, raise curve in compartment 2, and the flow rate were measured. According to the mass conservation equations, the following equation can be obtained:

$$\frac{C_{\text{in}}(t)}{C_{\text{out}}(t)} \approx \frac{PQ}{V}t \equiv mt, \tag{10}$$

where Q is the flow rate. According to Eq. (10), the slope, m, can be obtained. Thus, the particle penetration factor can be calculated:

$$P = \frac{mV}{Q}. \tag{11}$$

Liu and Nazaroff (2003) directly measured the particle concentrations upstream and downstream of a crack in a laboratory setting. The penetration factor was evaluated as the ratio of the downstream to upstream concentration. Jeng et al. (2006, 2007) also measured the particle concentration at crack entrances and exits in a chamber to evaluate the penetration factors. These authors fee that their experimental setup enables particle measurement without interfering with infiltration flow field, and avoids experimental variation that may have occurred in the Mosley et al. (2001) study.

3.3.2. Data analysis

The experimental data of penetration factor measured in both real buildings and laboratories and their conditions were tabulated (see supporting information, Tables S4 and S5). Figs. 6 and 7 present the size-dependent experimental data of particle penetration factor for real buildings and laboratories, respectively. Fig. 6 shows that in real buildings the penetration factors are in the range of 0.6–1.0 for particles with diameters greater than about 0.05 μm and less than 2 μm. When the diameter is larger, the penetration factor decreases due to the stronger gravitational setting. The penetration factor of PM2.5 measured by Williams et al. (2003) is 0.72, while that of PM10 measured by Tung et al. (1999) is in the range of 0.69–0.86. As shown in Fig. 7, particle penetration through cracks is a strong function of particle size, indoor/outdoor pressure difference, geometry and surface roughness of the cracks. For large particles, penetration factors are relatively small due to the effect of gravitational settling, while for ultrafine particles, the penetration factors are also small due to the effect of Brownian diffusion. Penetration factors increase with the larger pressure difference and crack height, which agrees with the finding by Jeng et al. (2006). Additionally, roughness can decrease the particle penetration factors (Liu and Nazaroff, 2003).

Comparing the experimental data in real buildings with that in laboratories (Fig. 8), we see that for particles with diameters in the range of 0.1–0.4 μm, the experimental data measured in real buildings are close to that measured in laboratories. However, for particles with diameters larger than 0.4 μm, it seems that the influence of gravity is not that strong in real buildings. These large particle data measured in real buildings only match the data which was taken under the conditions of higher pressure difference or larger crack height in laboratories. Results measured by Thatcher

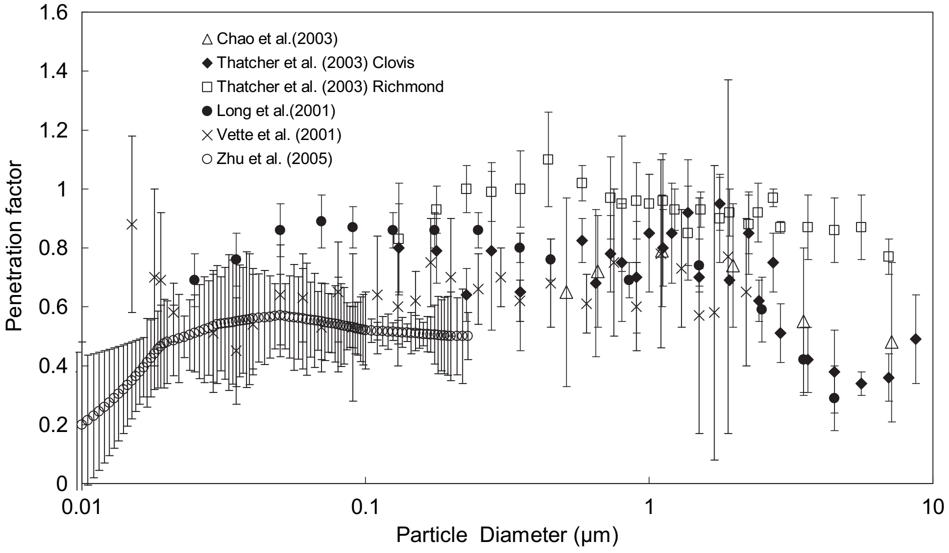

Fig. 6. Data of particle penetration factors obtained from experiments in real buildings.

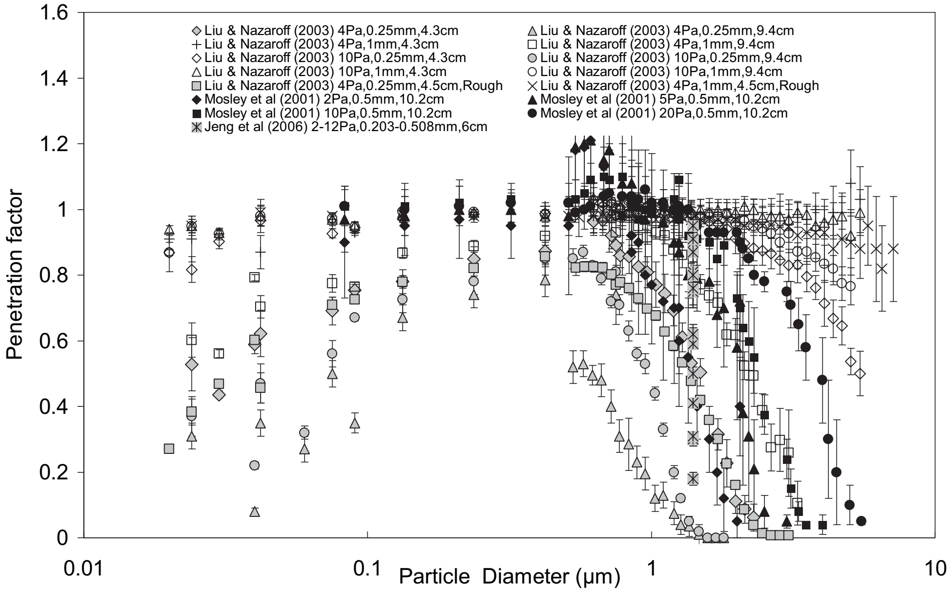

Fig. 7. Data of particle penetration factors obtained from experiments in laboratories. Legend example: Liu and Nazaroff (2003) 4 Pa (pressure difference between inlet and outlet of the crack), 0.25 mm (crack height), 4.3 cm (crack length). "Rough" means the crack is a strand board with rough innerfaces.

and Layton (1995) show that the penetration factors are near 1 for particles with diameters in the range of 1–25 μm. Wallace (1996) also calculated penetration factors very close to 1 for PM2.5 and PM 10, based on the particle mass data from an EPA study for a large number of households in the Los Angeles area. These may indicate that the crack heights are relatively large in these real buildings. Furthermore, the penetration factors for particles with diameter smaller than 0.1 μm seem match better than that for particles with diameter larger than 0.4 μm. A possible explanation is that in current laboratory-based experimental studies, only particle penetrations through straight cracks were measured. However, vertical cracks widely exist in real buildings. For ultrafine particles, the penetration factor through vertical cracks is similar to that through straight ones, since the dominating influencing factor is Brownian effect. While for coarse particles, the penetration factor through vertical cracks may be larger than that through straight ones, since the gravitational settling onto the inner surfaces is much weaker in vertical cracks. This may be another explanation for the inconsistence between experimental data in real buildings and that in laboratories. Additionally, the geometry of cracks in real building envelopes may be quite different. L-shaped or double-bend cracks are common in real building envelopes. Therefore cracks with different geometries should be further measured in laboratories to understand the characteristics of particle penetration through differing types of cracks.

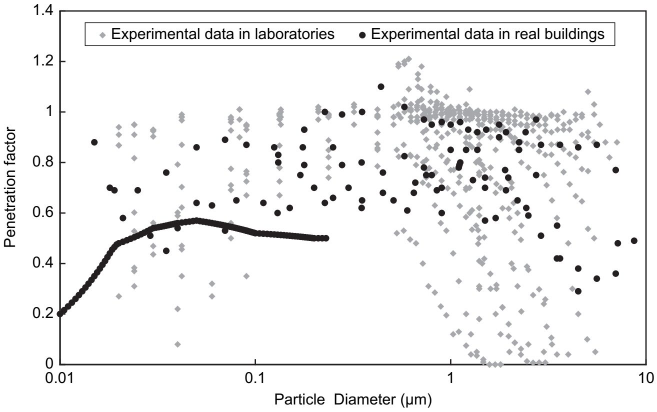

Fig. 8. Comparison of data of particle penetration factors obtained from experiments in real buildings and laboratories.

3.3.3. *Discussion on application of measurement methods*

Since the different measurement methods reviewed above have both advantages and disadvantages, the application of these methods is worthy of discussion. For a real house which has been built, if someone wants to know the particle penetration factors, the methods applied by Tung et al. (1999), Chao et al. (2003) and Thatcher et al. (2003) can be used. However, the use of these methods requires meeting the condition that there are no particle sources indoors. If the indoor particle emission cannot be avoided, the method developed by Long et al. (2001) can be used.

To detect the penetration characteristics of a certain envelope such as a window or a door, the envelope can be tested in laboratory and the measurements taken under controllable conditions. In this case, the methods applied by Mosley et al. (2001), Jeng et al. (2006, 2007) can be used.

The methods applied by Liu and Nazaroff (2003), Jeng et al. (2006, 2007) are more suitable for studying the influence of factors on particle penetration such as particle size, pressure difference, and geometry and surface roughness of the cracks, since they involve direct measurements of particle concentrations at the crack entrances and exits without interfering with airflow field and the measurement of flow rate. However, laboratory experiments are constrained to study systems that are more idealized than the reality (Nazaroff, 2004).

4. Modeling study review

4.1. *Modeling methods*

In this section we evaluate the models of the penetration factor only since most studies on I/O ratio and infiltration factor are based on experimental data.

4.1.1. Airflow through cracks

Because the motion of particles depends on air flow through cracks, all models are based on the relationship between pressure difference and air velocity distribution. Airflow in cracks can be assumed as laminar due to the small size of cracks and low air flow speed in the cracks. Baker et al. (1987) developed a quadratic expression to approximate the relationship between pressure difference and flow rate:

$$\Delta P = \frac{12\mu z}{d^2}u_\mathrm{m} + \frac{\rho(1.5+n_\mathrm{b})}{2}u_\mathrm{m}^2, \tag{12}$$

where z is the crack length, d is the crack height, w is the crack width, u_m is the average velocity of air in the crack, μ is the dynamic viscosity of air, ρ is the air density and n_b is the number of right-angle bends in the crack. The air velocity along the cracks can be calculated from an analytical solution of laminar airflow (Taubee and Yu, 1975).

$$\frac{u_\mathrm{y}}{u_\mathrm{m}} = \frac{3}{2}\left[1 - 4\left(\frac{y}{d}\right)^2\right], \tag{13}$$

where y is absolute vertical distance from the ceiling or floor surface of the crack. An alternative approach for obtaining the relationship between pressure difference and air velocity distribution is the computational fluid dynamics (CFD) approach (Zhao et al., 2010).

4.1.2. Particle penetration through cracks

There are three major deposition mechanisms controlling particle deposition for particles penetrating through cracks: gravitational setting, Brownian diffusion, and inertial impaction. Based on the particle deposition mechanisms of gravitational settling, Fuchs (1964) applied a flow equation to derive the penetration factor for a channel flow:

$$P = 1 - \frac{z}{d}\frac{v_\mathrm{s}}{u_\mathrm{m}}, \tag{14}$$

where v_s is the gravitational settling velocity of particles. Some researchers adopted this same model in their studies (Walton, 1954; Pich, 1972; Wang, 1975).

Licht (1980) proposed a similar method that calculated penetration factor by:

$$3\varepsilon^2 - 2\varepsilon^3 = \frac{z}{d}\frac{v_\mathrm{s}}{u_\mathrm{m}}, \tag{15}$$

$$P = 1 - \varepsilon, \tag{16}$$

where ε is the deposition ratio.

Based on the particle deposition mechanisms of gravitational setting and Brownian diffusion, Taubee and Yu (1975) solved the particle transport equation for steady-state laminar flow in cracks to calculate the particle penetration factor:

$$u\frac{\partial C}{\partial x} + v_\mathrm{s}\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2}, \tag{17}$$

where C is the particle concentration, u is the airflow velocity, D is the particle Brownian diffusivity, and x and y denote the horizontal and vertical axis respectively. These three models have been reviewed and compared by Jeng et al. (2003).

Based on all the three deposition mechanisms, Liu and Nazaroff (2001) developed a mathematical model to calculate the particle penetration factor through building cracks, which has been applied by Riley et al. (2002) as shown below:

$$P = P_\mathrm{g} \times P_\mathrm{d} \times P_\mathrm{i}. \tag{18}$$

P_g, P_d and P_i represent the particle deposition rate due to mechanisms of gravitational settling, Brownian diffusion and inertial impaction respectively. P_g can be calculated according to Eq. (14), and P_d can be obtained through the following equation (De Marcus and Thomas, 1952):

$$P_\mathrm{d} = 0.915\exp(-1.885\phi) + 0.0592\exp(-22.3\phi) + 0.026\exp(-152\phi) + \cdots, \tag{19}$$

$$\phi = \frac{4Dz}{d^2 u_\mathrm{m}}, \tag{20}$$

It was found that inertial impaction was not an important deposition mechanism for particle penetration through cracks (Liu and Nazaroff, 2001). A similar model was applied by Mosley et al. (2001), whose P_d was calculated by the following expression (Lee and Gieseke, 1980):

$$P_\mathrm{d} = \exp\left(-\frac{1.967Dz}{h^2 u_\mathrm{m}}\right), \tag{21}$$

The study by Tian et al. (2009) presented a similar model to calculate particle penetration factor incorporating the influence of surface roughness.

Zhao et al. (2010) developed three different models to predict the particle penetration through a crack. The first one is an analytical model that is based on solving an ordinary differential equation of particle concentration in the boundary layer which can be described as:

$$P = \exp\left(-\frac{v_\mathrm{d} z}{u_\mathrm{m} d}\right), \tag{22}$$

$$v_\mathrm{d} = \frac{i1.5v_\mathrm{s}}{1 - \exp\left[\frac{v_\mathrm{s}}{D}\left(\frac{d_\mathrm{p}-d}{2}\right)\right]} \begin{cases} i = 1 & \text{for floor surface} \\ i = -1 & \text{for ceiling surface} \end{cases}, \tag{23}$$

The second model developed by Zhao et al. (2010) is a Eulerian model that solves the particle mass conservation/transport equation numerically. Then the particle penetration factor can be calculated by:

$$P = \frac{\dfrac{\int u(y)C(x_z, y)\mathrm{d}A}{\int u(y)\mathrm{d}A}}{C_\infty}, \tag{24}$$

where $C(x_z, y)$ is the particle concentration distribution at the outlet of the cracks and C_∞ is particle concentration at the inlet of the cracks.

The third model by Zhao et al. (2010) is a Lagrangian model that calculates the trajectory of each particle by integrating the force balance on each particle, which is written as:

$$\frac{\mathrm{d}\vec{u}_\mathrm{p}}{\mathrm{d}t} = F_\mathrm{D}(\vec{u} - \vec{u}_\mathrm{p}) + \frac{\vec{g}_x(\rho_\mathrm{p} - \rho)}{\rho_\mathrm{p}} + \vec{F}_x, \tag{25}$$

where $\vec{u}$ is the fluid phase velocity, $\vec{u}_\mathrm{p}$ is the particle velocity, ρ is the fluid density, ρ_p is the particle density, $\vec{g}_x$ is the gravitational acceleration and $\vec{F}_x$ is an additional acceleration (force/unit particle mass) term. Then particle penetration factor can be obtained by:

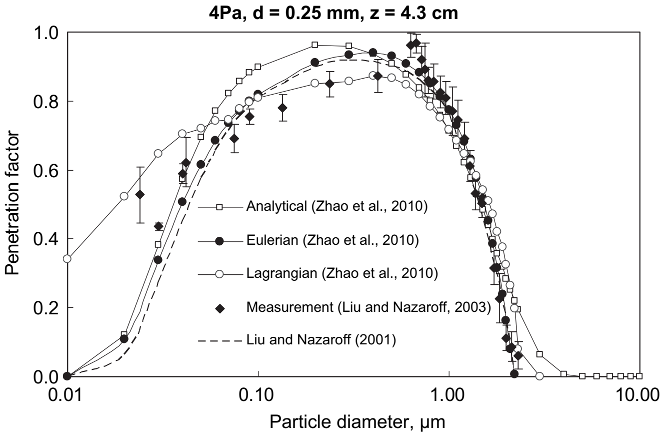

Fig. 9. Comparison of model predictions with experimental data for aluminum cracks (Fig. 2 in Zhao et al., 2010).

$$P = \frac{N_{\text{escape}}}{N_{\text{total}}}, \tag{26}$$

where N_{escape} is the escaped particles at the outlet, and N_{total} is the total particles released at the crack inlet.

Zhao et al. (2010) compared four recent penetration models, i.e. Liu and Nazaroff (2001) model, Analytical, Eulerian and Lagranian model by Zhao et al. (2010). Fig. 9 shows the comparison results of penetration factor through a single straight aluminum (smooth) crack using these four models. The pressure difference was set at 4 Pa. The crack length, the dimension parallel to the airflow direction, was 4.3 mm. The crack heights, perpendicular to the flow direction, were set at 0.25 mm. Particles were assumed to be spherical with a density of 1 g cm^{-3} and with a broad range of particle diameters, 0.01–10 μm. Inferring from the results, it could be found that the results predicted by Liu and Nazaroff (2001) model, Analytical and Eulerian model by Zhao et al. (2010) generally agree well with the experimental results. Nevertheless, the predicted results by the Lagrangian model agree worst for ultrafine particles ($d_p < 0.1$ μm). The most plausible reason for the poor performance is that the Lagrangian approach models a weaker effect of the Brownian diffusion (Zhao et al., 2010). Holding the same view, Robinson et al. (1997) suggested that the Lagranian model was unable to model molecular diffusion. More comparisons of the models for predicting penetration factor could be found in Zhao et al. (2010).

4.2. Discussion on application of modeling methods

These models can be used for studying particle penetration through cracks in building envelopes in certain suitable conditions. The models developed by Fuchs (1964) and Licht (1980) only consider the gravitational setting mechanism, thus they are only suitable for modeling large particles. The models developed by Taubee and Yu (1975), Liu and Nazaroff (2001) and the analytical model developed by Zhao et al. (2010) are suitable for modeling both large and ultrafine particles. These models, which assume that particles are homogeneously and uniformly distributed at the crack entrance, are quite simple, but they are only suitable for straight cracks. When the studied geometry of cracks is more complicated, the numerical modeling approach is always preferred to study the particle penetration factor. Therefore, the Eulerian model and Lagragian model developed by Zhao et al. (2010) are more suitable for complicated cases. Additionally, these two models are more flexible as they can incorporate different deposition mechanisms in cracks under different conditions.

Table 1
Comparison of gravitational settling velocity and deposition velocity caused by thermophoresis (crack height: 0.25 mm, temperature difference between wall and air: 10 °C).

Particle diameter (μm)	Gravitational settling velocity (m s^{-1})	Deposition velocity casued by thermophoresis (m s^{-1})
0.01	6.75E−08	1.78E−03
0.1	8.69E−07	1.66E−03
1	3.51E−05	1.12E−03
10	3.06E−03	2.64E−04

Another possible application of these particle penetration factor models is to assist in indoor environment design. When designers want to know how much ventilation or what kind of air cleaner a building should use for removing contaminated particles, they need to know how many outdoor contaminated particles penetrate through the cracks in the envelope into the indoor environment, which may be done by modeling investigation. However, cracks in real buildings are extremely complex and vary from one building to the next. It is difficult to measure the exact geometry of the cracks in real buildings in most cases, which is significant for the penetration prediction. Therefore, the value of models for particle penetration through cracks is to explain dependencies of influencing factors, rather than to predict penetration accurately in practical situations.

4.3. Discussion on model improvement

In many areas, the temperature difference between the outdoors and indoors can be very substantial, especially in winter or summer. When a temperature gradient exists, particles may be influenced by an additional drift force caused by thermophoresis (Hinds, 1982). For fine or ultrafine particles, this thermophoresis force may affect the penetration through cracks in building envelopes. Table 1 shows the comparison of gravitational settling velocity and deposition velocity caused by thermophoresis (calculated according to the equation suggested by Talbot et al., 1980) for particles with diameter in the range of 0.01–10 μm. The crack height was set as 0.25 mm and the temperature difference between wall and air was set as 10 °C, which may be typical for a real building/house. In this case, the gravitational settling velocity for 10 μm particles is in the order of 10^{-3} m s^{-1}, which can strongly affect the penetration process. On the other hand, the deposition velocities caused by thermophoresis for 0.01–1 μm particles are also in the order of 10^{-3} m s^{-1}, which means that the influence of thermophoresis force may be significant in this case. However, existing models do not incorporate the influence of the thermophoresis force, so this is an area which can be improved.

Since the outdoor wind environment is highly unstable, airflow infiltration is unsteady with a wide range of fluctuation frequencies, which may result in unsteady indoor air concentrations. The impact of airflow fluctuation on particle penetration may be quite influential. However, the way in which airflow fluctuation in cracks in building envelopes affects particle penetration cannot be modeled by existing models. Therefore, incorporating airflow fluctuation into existing models is another improvement point.

5. Discussion

In addition to transmission by ventilation and infiltration, outdoor airborne particles can be also brought into indoor environments by humans. Outdoor particles can migrate to indoor environments via soil adhering to footwear and then undergoing resuspension into the air (Layton and Beamer, 2009), which can affect human health. However, the amount of outdoor particles entering into indoor environments in this way is unclear and is also an area of further study.

Except for deposition and filtration, other processes can influence the behavior of the entry of outdoor particles to indoors. For instance, phase change processes (e.g., with aerosol nitrate) and coagulation in some cases can influence the extent to which outdoor particles influence indoor levels, which should be further studied.

6. Conclusions

This paper provides an up-to-date revision for both experiment and modeling on relationship between indoor and outdoor particles. The use of three different parameters: I/O ratio, infiltration factor and penetration factor, to assess the relationship between indoor and outdoor particles were reviewed. From this work, several conclusions were achieved:

1) The I/O ratio can provide a general impression on the relationship between indoor and outdoor particle concentration, nevertheless, it varies in an enormous range as it is affected by many influencing factors. Through comparing different studies, no uniform conclusions can be draw, which strongly demonstrates that the I/O relation is not useful in understanding indoor/outdoor particle relationships.
2) Infiltration factor, which avoids the influence of indoor sources, is quite useful for qualifying the amount of indoor particles that contributed by outdoor environment. However, it is difficult to reflect the process of outdoor particles entering to indoors through buildings.
3) Among the three parameters, the most relevant parameter for the penetration mechanism through cracks is the penetration factor. The experimental results of penetration factor show that the coarse particle data measured in the real buildings only match the ones which are under the condition of higher pressure difference or larger crack height measured in the laboratories, whose definite reason is unclear. The existence of vertical cracks in real buildings may be an explanation for that.
4) For penetration factor models, the results predicted by Liu and Nazaroff (2001) model, Analytical and Eulerian model by Zhao et al. (2010) generally agree well with the experimental results. Nevertheless, the predicted results by the Lagrangian model agree worst for ultrafine particles ($d_p < 0.1\ \mu m$). Furthermore, we feel that the influence of thermophoresis force and airflow fluctuation should be incorporated into the existing models and then further studied.

Acknowledgement

This study was sponsored by the National Natural Science Foundation of China (Grant No. 51078216) supported by Tsinghua University Initiative Scientific Research Program and also supported by Program for New Century Excellent Talents in University (NCET-07-0502), China.

Appendix. Supplementary information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.atmosenv.2010.09.048.

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