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The experimental study on indoor and outdoor penetration coefficient of atmospheric fine particles

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ABSTRACT

In recent years, haze pollution of China has become increasingly serious. Outdoor particles can enter the room through the building crack. Therefore, it is of great significance to study the indoor and outdoor penetrating and transport characteristics of fine particles. In this paper, the main factors affecting the penetration coefficient are quantitatively analyzed by combining theoretical and experimental research. The results indicate that there is no obvious function between the pressure difference and the penetration coefficient when the crack height 1 mm, but they can be unified with a linear function when the crack height 0.25 mm. The effect of the crack height and length on penetration coefficient is related to the maximum net displacement of particles. The smaller the crack height (H), the longer the crack length (L) and the smaller the pressure difference (ΔP) would cause the greater the decrease of the penetration coefficient as the particle size increases. Temperature and relative humidity have no significant correlation with the penetration coefficient. The semi-empirical formula of penetration coefficient is established based on the correlation analysis and the theory of penetrating coefficient, which has the advantages of high accuracy, simple form and easy to measurement.

1. Introduction

In recent years, China's air pollution situation has become increasingly serious, and several regions of the country suffer from fog and haze violations in different degrees, in which fine particles become the primary pollutant in many cities, especially for large and medium-sized cities [1–3]. Fine particles refer to particles that the aerodynamic diameter is less than 2.5 μm, known as $PM_{2.5}$. Compared with larger particles, $PM_{2.5}$ is easier to enter the body through the respiratory tract, endangering human health [4–9]. Outdoor particulate penetration is the main source of indoor particulate pollution under the premise of no obvious indoor source [10], therefore, it is of great significance to study the penetration and transport characteristics indoor and outdoor fine particles.

Outdoor particles usually take the wind into the indoor environment, and common air exchange modes in the building contains: natural ventilation, mechanical ventilation, and infiltration. With the increasing air pollution, doors and windows are often in a closed state to avoid the outdoor fine particulate matter into the room. Even if the outside window of building is closed, the outdoor fine particles can still enter indoor through outer window gap or opening of building (such as wall embedded parts, pipe hole, building new vents and exhaust vents, etc.) [11]. The air tightness of the outer window is not only related to the performance and installation form of the sealing strip, but also the installation quality. When the outer window is used for a long time, the sealant strip will have the condition of aging and breakage, which also reduces the air tightness. Moreover, as the building time increases and the pipeline vibrates, the sealing strips at the pipe hole may also show aging or leakage. These holes will also increase the penetration coefficient of particles, leading to more outdoor particles entering the indoor [12,13]. Jiang and Chen et al. indicated that China's building air tightness is poor compared with developed countries such as the United States, Germany, Finland and Denmark, which would result in more atmospheric fine particles penetrating into indoor through the building gap structure [14,15]. Penetration coefficient (P) refers to the concentration ratio of particles through the building gap following air infiltration, and it is also the most important parameter and index for the study of indoor and outdoor penetration characteristics of particles [16]. Current research methods of penetrating coefficients include field test [17–20], experimental cabin tests [21–24] and theoretical analysis [25–28]. As the experimental compartment can be controlled to adjust the test conditions, researchers often explored the penetration

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coefficient through establishing the experimental cabin. Leweis et al. established the experimental cabin to study the penetration coefficient of 0.1–10 μm particles under a specific pressure difference and gap size [21]. Mosely et al. measured the penetration properties of a single particle in the range of 0.05–5 μm under different pressure conditions by the experimental cabin, which found that the particle penetration rate was correlated with the pressure difference [22]. Liu et al. tested the penetration coefficients of different particles size under different pressure and gap structure, and analyzed the influence of different parameters on the penetration coefficient [23]. However, there are few researchers to study the penetration coefficient of the cabin in China. Sun et al. discussed the indoor and outdoor penetrating characteristics and influencing factors of ultrafine particles using the method of experimental cabin and CFD simulation [24]. In the experimental cabins' studies, previous studies have qualitatively analyzed the influence of a certain factor on the penetration coefficient, but the disadvantage was that there was no quantitative analysis of the influence of pressure, particle size and other factors. Although the theoretical model used can solve the penetration coefficients in various cases, it is too complex and involves many parameters to apply to actual buildings.

In view of the current problems, an experimental cabin experiment was conducted to achieve quantitative analysis of penetration mechanism. The goal of this paper is to establish a simple semi-empirical formula to solve the shortcomings of the measurement model time-consuming and the theoretical model complexity.

2. Theoretical basis of experimental cabin construction

Research indicates that gravity deposition, Brownian diffusion and inertial intercept play a decisive role in the particles penetration through the crack. Under the action of gravity subsidence, Fuchs developed a formula as Equation (1) [29,30],

$$P_g = 1 - \frac{Lu_{pt}}{Hu} \tag{1}$$

u_{pt}, u, C_c can be expressed in the following form [31,32]:

$$u_{pt} = \frac{C_c \rho_p d_p^2 g}{18\mu} \tag{2}$$

$$u = \sqrt{\Delta P + \left(\frac{1.208 \times 10^{-4}}{H^2} L\right)^2} - \frac{1.208 \times 10^{-4}}{H^2} L \tag{3}$$

$$C_c = 1 + \frac{2\lambda_g}{d_p}\left[1.246 + 0.42 \exp\left(-0.87 \frac{d_p}{2\lambda_g}\right)\right] \tag{4}$$

where P_g is penetration coefficient caused by gravity sedimentation; L is the crack length, m; H is the crack height, m; u_{pt} is the particle deposition velocity, m/s; u is the average flow rate of airflow in the crack, m/s; d_p is particle size, m; C_c is Cummingham slip correction factor; λ_g is the average free path of air, m; ρ_p is particle density, kg/m^3; μ is the aerodynamic viscosity coefficient, kPa·s; ΔP is the pressure difference between two sides of the crack, Pa.

In the Brownian sedimentation, the penetration coefficient can be expressed as [33]:

$$P_d = \exp\left(-\frac{1.967 D_{AB} L}{uH^2}\right) \tag{5}$$

where P_d is penetration coefficient caused by Brownian sedimentation; D_{AB} is the molecular diffusion coefficient of A in B, which can be expressed as:

$$D_{AB} = \frac{kTC_c}{3\pi d_p \mu} \tag{6}$$

T is air temperature, K; k is Boltzmann constant, 1.38×10^{-16} g cm^2/(s^2·K)。

Generally, the inertial subsidence effect is negligible under the experimental conditions, and the total penetration coefficient could be expressed as [34]:

$$P = P_g \times P_d \tag{7}$$

According to Equations (2)–(4) and (6), Equation (7) can be obtained:

$$\begin{aligned} P = {} & \Bigg(1 - \Bigg(1 + \frac{2\lambda_g}{\mathrm{d}}\Bigg(1.246 + 0.42\exp\Bigg(\\ & -0.87\frac{\mathrm{d}}{2\lambda_g}\Bigg)\Bigg)\Bigg)\frac{L\rho_p {d_p}^2 gH}{18\mu(\sqrt{\Delta PH^4 + 1.459 \times 10^{-8}L^2} - 1.208 \times 10^{-4}L)}\Bigg) \\ & \times \exp\Bigg(-\Bigg(1 + \frac{2\lambda_g}{\mathrm{d}}\Bigg(1.246 + 0.42\exp\Bigg(\\ & -0.87\frac{\mathrm{d}}{2\lambda_g}\Bigg)\Bigg)\Bigg)\frac{0.656kTL}{\pi d_p \mu(\sqrt{\Delta PH^4 + 1.459 \times 10^{-8}L^2} - 1.208 \times 10^{-4}L)}\Bigg) \end{aligned} \tag{8}$$

It could be concluded that the main influencing factors of penetration factor are pressure difference, crack length and crack height, particle size and temperature.

3. Experiments

3.1. Experimental platform and equipment

Experimental platform are composed of large cabin, small cabin, crack device, air flow mixing device, pressure difference control system, particle test device, temperature and humidity control device and filter device, as shown in Fig. 1. The large cabin (0.8 m × 0.8 m × 0.8 m) simulates the outdoor atmospheric environment, and the small cabin (0.6 m × 0.05 m × 0.03 m) simulates the indoor environment, both of which are connected by the crack device, forming the flow of particles from the large cabin - the crack - the small cabin. Large cabin and crack devices are made of acrylic plate to reduce error charged particles characteristics on the experimental result. This material has no adsorptive effect on the particles, and the light transmittance is good and easy to clean.

The air flow mixing device are installed at the top center of the large cabin. Pressure difference control system consists of vacuum pump (JP-100H), flowmeter (MF5712-N-200), flow control valve (SA10) and micro-pressure meter (TE-2000), and is connected with the small cabin, which could dominate air flow through the two cabin. Generally, the pressure difference on both sides of the crack in actual building is 4–15Pa [35]. The temperature and relative humidity controller (TR-72

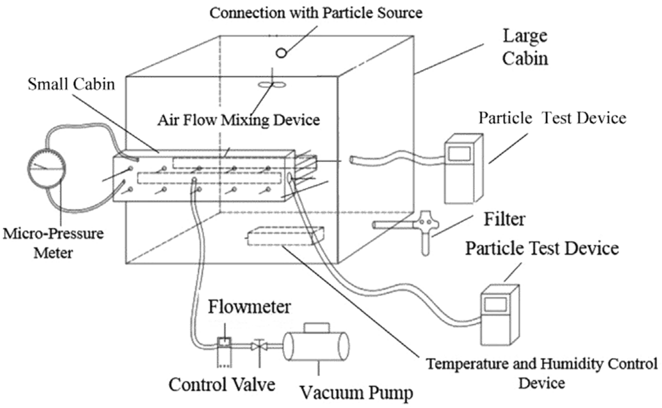

Fig. 1. Schematic diagram of experimental cabin.