EXPERIMENTAL STUDY ON PARTICLE DEPOSITION IN PIPELINES IN A FRESH AIR SYSTEM

by

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A semi-empirical formula was recommended to analyze the deposition law of atmospheric particles in pipelines in fresh air systems, where the sizes of particles, inlet velocity, and the air temperature, humidity on the deposition of particulate matters were considered. The results showed when the particle sizes were less than 1.0 μm, the deposition rate was decreased from the increased in particle sizes. When the particle sizes were larger than 1.0 μm, the deposition rate was increased from the increased in particle sizes. A higher inlet velocity resulted in a greater deposition rate. High humidity or low temperature would also lead to a high deposition rate of dust. The results given in this paper are helpful for optimization of the fresh air system.

Key words: *fresh air systems, particulate matters, fresh air pipeline, application, turbulent deposition*

Introduction

Sick building syndrome was outbreaked everywhere in recent years [1, 2]. People are paying more attention to indoor environmental sanitation, especially the indoor air quality and the content of fresh air [3]. The fresh air system is one of the most popular in residential buildings, and now it has been widely used and applied for buildings [4].

Many researchers focused on the filtration efficiency of filters [5, 6], energy consumption of fans [7] and indoor air quality [8, 9], and much achievement was obtained, but the particle deposition of pipelines in a fresh air system was studying rarely [10]. Fresh air systems were popularized only in recent years, the fresh air pipelines are less used than the traditional air-conditioned rectangular galvanized iron pipelines. There were also differences in sizes, materials and cross-sections [11]. As a result, it was difficult for theoretical analysis. On the other hand, the default for fresh air pipelines deposition was small, and they could be ignored. That would lead to the fresh air pipelines were selected only by experience. The research of the deposition of pipelines in practical systems was slightly not enough. With the outbreak of 2019-nCoV epidemic in China, the research on pipe deposition in fresh air systems will return to hot topics.

In this paper, it was based on the semi-empirical formula calculation method. The particles deposition law of pipelines in residential fresh air systems was analyzed. It was verified by experiments.

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Methods

Experimental system

Pipelines of PVC were selected which were popular used in residential fresh air systems in China, as shown in fig 1. The flat pipeline was 130 mm × 30 mm, and the length was 6 m. The coefficient of friction in the pipeline was 0.03. The velocity range was 2.5~4 m/s. The testing time was from December 22nd to 29th, 2018.

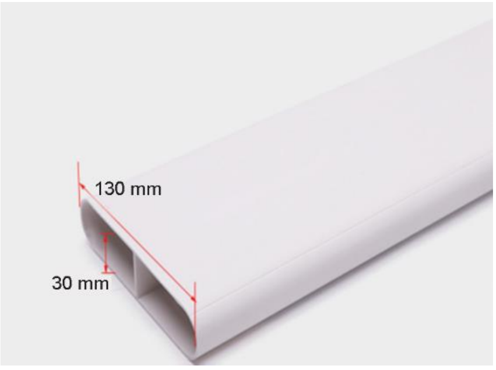

Figure 1. Experimental model

The GRIMM1.109 portable aerosol particle size spectrometer was used to measure the mass and counting concentration of particles before and after the fresh air pipelines. Measuring range was 0.1~100.000 μg/m^3. Counting range was 2000000 P/L, and 31 particle size channels were divided between 0.25~32 μm. The repeatability was 5%. The TESTO480 climate measuring instrument was used to measure the temperature and humidity. Measuring range was –100~+400 °C. Measurement accuracy was ± (0.3 °C~0.1% measured value). The humidity measuring range was 0~100% RH. Measurement accuracy was ± (1.4% RH~0.7% measured value).

Calculation model

The deposition rate of particles on the surfaces was V_d [12]:

$$V_\mathrm{d} = \frac{J}{C_\mathrm{ave}} \tag{1}$$

where J is the time averaged particle flow to the surfaces and C_ave – the time averaged concentration of the particles in the pipelines.

Definition of dimensionless deposition rate was V_d^+ [12]:

$$V_\mathrm{d}^+ = \frac{V_\mathrm{d}}{u^*} = \frac{J}{u^* C_\mathrm{ave}} \tag{2}$$

where $u*$ is the friction velocity.

$$u^* = U_\mathrm{ave}\sqrt{\frac{f}{2}} \tag{3}$$

where U_ave [ms^{-1}] is the inlet average velocity and f – the friction coefficient, for fully developed turbulence, f can be calculated by [12]:

$$f = \frac{\Delta P D_h}{\Delta L 2 \rho_a U_\mathrm{ave}^2} \tag{4}$$

where $\Delta P/\Delta L$ [Pam^{-1}] is the pressure drop per unit pipeline length.

$$D_h = \frac{4A}{P} \tag{5}$$

where A [m^2] is the cross-sectional area of the pipeline and P [m] – the circumference of pipeline.

Relaxation time of particles [12]:

$$\tau_\mathrm{p} = \frac{C_\mathrm{C}\rho_\mathrm{p} d_\mathrm{p}^2}{18\mu} \tag{6}$$

where C_C is the cunningham sliding correction coefficient, ρ_P [kgm^{-3}] – the density of particles, μ [kgms^{-1}] – the dynamic viscosity coefficient of air, and d_p [m] – the particle size:

$$C_\mathrm{C} = 1 + K_n\left[1.257 + 0.4\exp\left(-\frac{1.1}{K_n}\right)\right] \tag{7}$$

Dimensionless relaxation time is [12]:

$$\tau^+ = \frac{\tau_\mathrm{p}}{\tau_e} = \frac{C_\mathrm{C}\rho_\mathrm{P} d_\mathrm{p}^2 u^{*2}}{18\mu\nu} \tag{8}$$

The Smith number is defined [12]:

$$\mathrm{Sc} = \frac{\nu}{D_B} \tag{9}$$

where

$$D_B = \frac{C_\mathrm{C} K_B T}{3\pi d_\mathrm{p}\mu}, \text{ and } K_B = 1.38\cdot 10^{-23}\ \mathrm{J/K}$$

The dimensionless deposition rate [13, 14] was taken as shown in eq. (10), and it was good consistent with the experimental data:

$$V_\mathrm{d}^+ = 0.084\mathrm{Sc}^{-2/3} + \frac{1}{2}\left[\frac{\left(0.64k^+ + \dfrac{d^+}{2}\right)^2 + \dfrac{\tau^{+2}g^+L^+}{0.01085(1+\tau^{+2}L^+)}}{3.42 + \dfrac{\tau^{+2}g^+L^+}{0.01085(1+\tau^{+2}L^+)}}\right]^{1/(1+\tau^{+2}L^+)} \cdot \left[1 + \frac{8e^{-(\tau^+-10)^2}}{32}\right]\frac{0.037}{1-\tau^{+2}L^+\left(1+\dfrac{g^+}{0.037}\right)} \tag{10}$$

According to conserving mass, the flat pipeline was ab, the length was dL.

Since change of the particles number in gas, $uabdN$, is equal to the deposition amount per unit time was $2(a + b)JdL$, then from $uabdN = 2(a + b)JdL$, we obtain eq. (11) [13, 14]:

$$N = N_0 \exp\left[-\frac{2(a+b)V_\mathrm{d}^+ u^*}{abu}L\right] \tag{11}$$

and the deposition rate as it is shown in eq. (12) [13, 14]:

$$\eta = 1 - \exp\left[-\frac{2(a+b)V_d^+ u^*}{abu} L \right] \tag{12}$$

Results and discussion

The outdoor atmospheric dust was directly selected as the experimental dust source. Figure 2 showed that with a particle size of 0-0.3 μm accounted for 75.9% of the total particles. With a particle size of 0.3-0.5 μm accounted for 21.8% of the total particles. With a particle size of 0.5-1.0 μm accounted for 1.9% of the total particles. With a particle size of 1.0 to 2.5 μm accounted for 0.35% of the total particles. With a particle size of 2.5 to 5.0 μm accounted for 0.11% of the total particles. With a particle size of 5.0-10 μm accounted for the total particles were almost zero.

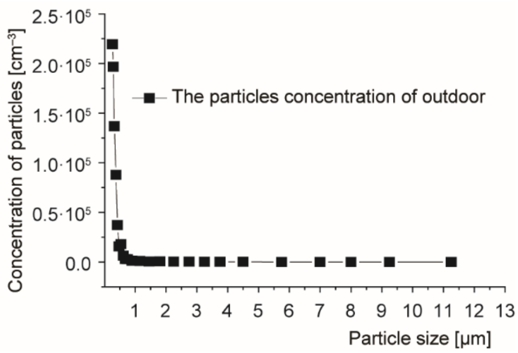

Figure 2. Distributing outdoor atmospheric particles

The particle sizes of 0-2.5 μm accounted for most of the atmosphere during the testing, accounting for 99.9%. The particle sizes of 0-1.0 μm accounted for more than 99.5%, which were easy to enter the human respiratory tract and lungs. They were seriously harmful to human health [15].

The deposition rate of PM

Figure 3(a) showed that with the increased in inlet velocity, the deposition rates of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ were showed a decreasing trend. The change of $PM_{1.0}$ was the smallest, which was only 0.3%. The change of PM_{10} was the largest, which was 6.4%. The main reasons were that with the inlet velocity increased, the particle sizes of the small particles continually spread with the inlet velocity, the diffusion effect was weakened. With the increased in inlet velocity, the deposition rates of large particles increased continuously from inertia effect, which would lead to the decrease of the deposition rate.

Figure 3(b) showed the theoretical value calculated from the integral of the deposition rates formula was higher than the value. The theoretical value of $PM_{1.0}$ was 0.07 greater than the value. The value of the error was 6.08%, which is not much different. The theoretical value of $PM_{2.5}$ was 0.18 smaller than the value. The value of the error was 17.84%. The theoretical value of PM_{10} was 4.79 larger than the value. The value of the error was 34.09%. The main reasons were that they were related to the local aerosol composition type and concentration distribution [3]. The spreading above 3 μm particles was unstable, and it might relate to the materials of pipelines. The error of PM_{10} was large. The formula has a good practicability for the particle size of small, which was consistent with the conclusions given in [16].

The influence of particle sizes

Figure 4 showed the particle sizes were less than 1 μm, and the turbulent deposition rates decreased from the increase in particle sizes. The particle sizes were larger than 1 μm, and the turbulent deposition rates had an opposite trend. The particle sizes were increased, and the deposition rates were kept growing. Therefore, the particle sizes of larger particulates had a larger turbulent deposition rate. The deposition rates of particle sizes of less than 1μm

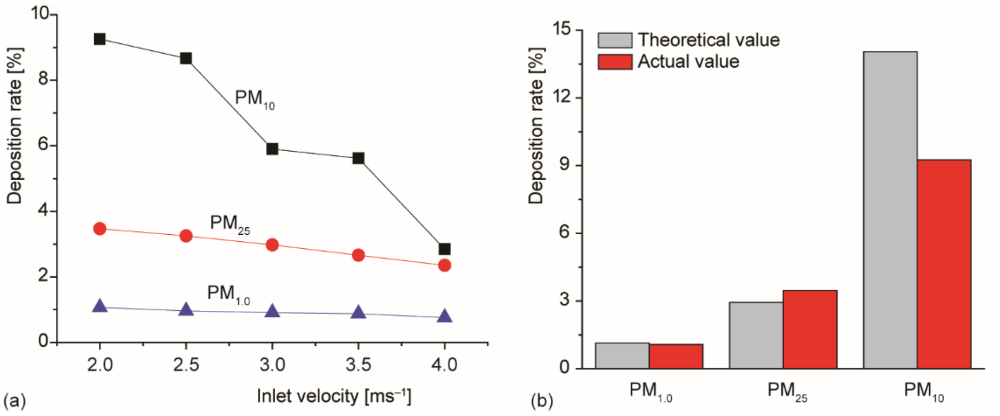

Figure 3. Deposition rates of PM; (a) deposition rates vary with inlet velocity and (b) differences of deposition rates

were small. They were at the boundary of the diffusion area and diffusion-collision area. Diffusion played a decisive role in the deposition of particulate matters. With the increase in particle sizes, the inertia played an incisive role. The deposition rates were increased [16].

The figure also showed the deposition rates of the dust particles we large. The main reasons were the sizes of fresh air pipelines were small. The relative area contacted with the airflow was larger under the same velocity condition, which increased the chance of dust particles contacting the surfaces. However, fine dust particles would clot in the ventilation ducts [17]. They would increase intensively from dust deposited in the ventilation ducts.

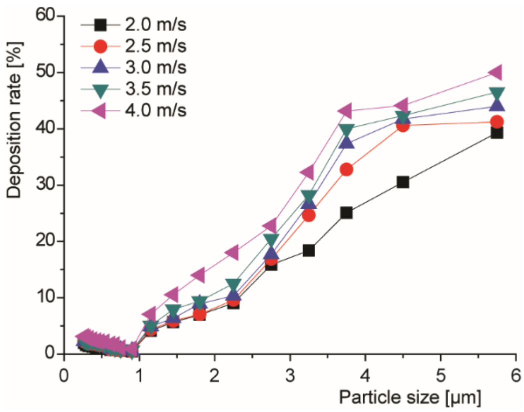

Figure 4. Variation of deposition rates at different particle sizes

The influence of inlet velocity

Figure 5 showed that with the increased in inlet velocity, the turbulent deposition rates at different velocities gradually showed a large difference. When inlet velocity was 4.0 m/s, the turbulent deposition rates were the highest, deposition rates of different particle sizes were 3.1%, 7.1%, 18%, 32.3%, and 50%, respectively. While inlet velocity was 2.0 m/s, the turbulent deposition rates were the smallest, and the differences would become more and more obvious as the particle sizes increased. The main reasons were that with the inlet velocity increased, the dif-

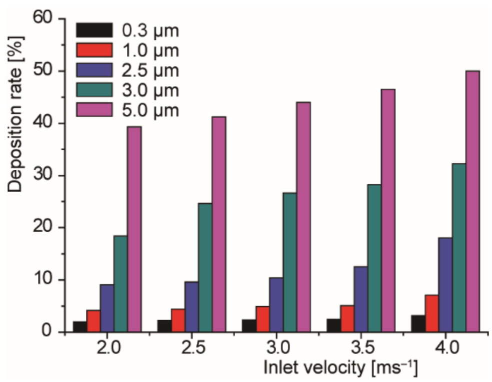

Figure 5. Variation of deposition rates at different inlet velocity

fusion effect was decreased, the inertia effect was increased, and the turbulent deposition rates of the particles increased sharply. The results were consistent with the conclusions of the [18].

The influence of air temperature and air humidity

Figure 6(a) showed with the temperatures of the air were getting higher, the turbulent deposition rates of the dust were reduced. The turbulent deposition rates of the large particle sizes were more obvious. As the temperature increased, the viscosity of the air was increased, the Reynolds number of the gas flow was decreased, and the turbulent diffusion of particles was weakened [19]. Figure 6(b) showed with the humidity of air was higher, and the viscosity of air was also larger. The turbulent deposition rates of the dust increased, the turbulent deposition rates of the larger particle size were more obvious. The humid environment and suitable temperature of pipelines would provide good growth and breeding environment for bacteria and fungi, which were seriously affecting people's life and health [19].

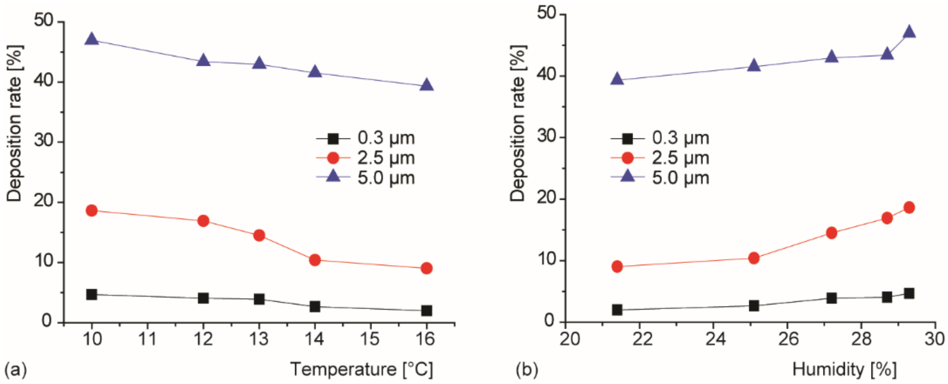

Figure 6. Variation of deposition rates at an inlet velocity of 2.0 m/s; (a) deposition rates vary with temperature and (b) deposition rates vary with humidity

Conclusion

Through the study on the deposition law of particulate matters in the pipelines of residential fresh air system, the following conclusions were as followed. The particle sizes were less than 1 μm, the turbulent deposition rate was decreased form the increased in particle sizes. The particle sizes were larger than 1 μm, the turbulent deposition rate was increased from the increased in particle sizes. The greater the inlet velocity was, the greater the dust deposition rates had. Increasing the air humidity or lowering the air temperature would increase the turbulent deposition rates of the dust particles in the pipelines. The soft connection and direct pipeline were used would have a certain impact on the pipeline deposition. So, reducing to use the elbow and local units, and selecting the applicable layout of the pipelines would be more useful in residential fresh air systems.

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