Airborne Particulate Matter in HVAC Systems and its Influence on Indoor Air Quality

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Abstract: This paper first reviews the mechanisms governing movement of PMs in HVAC systems. Then, the basic equations governing PM deposition in ducts are introduced and investigations on airborne PMs distribution in HVAC systems are reviewed. The influence of PMs on indoor air quality and effectiveness of corresponding controlling measures is discussed extensively in the paper. Finally, recommendations for further research are given.

Key words: particulate matter; HVAC system; indoor air quality (IAQ)

1. INTRODUCTION

Airborne particulate matter (PM), including dust, mist, fog, microorganism, pollen and so on, is one of the most important pollutants in outdoor air and indoor air. Heating, ventilation, and air conditioning (HVAC) systems, mainly duct systems, are the key components combining outdoor air with indoor air, and one of their purposes is to prevent outdoor PMs from entering indoor air. Meanwhile, HVAC systems can remove indoor airborne PMs to ensure occupants' health. However, duct systems may become pollutant sources, like volatile organic compounds (VOCs) [1], microorganisms [2], in the case of abnormal maintenance.

Because there are all kinds of components in the duct systems, tapping the law of particle distribution in HVAC systems is not an easy work. Generally speaking, flow in the duct system is turbulent except those in some kind of components like filters. Particle movement, especially particle deposition, is strongly related to organized structures in near-wall turbulence [3]. The mechanisms governing particle transport in HVAC systems are even more compound, as eight of them are prominent in duct flows and will be discussed in this section. All of the mechanisms are applicable to turbulent flow, but only turbulent diffusion and turbophoresis are unique to turbulent flow.

The first mechanism, Brownian diffusion, is always present as a result of the random interactions between particles and air molecules. A net flux of particles generated by Brownian diffusion only exists in the presence of a nonzero particle concentration gradient. Brownian diffusion can be the dominant transport mechanism of very small particles over very small distances, but is a weak transport mechanism for particles larger than about 0.1 μm.

Whenever there is relative motion between a particle and the surrounding air, the particle experiences a drag force from the air that tends to reduce that relative motion. For particle whose Reynolds number less than 0.3, the drag coefficient is in reverse proportion to the particle Reynolds number, which is the famous Stokes law. Particles more dense than air will settle owing to the effects of gravitational acceleration. The importance of gravitational settling increases with particle size. It is generally an unimportant mechanism for particles smaller than 0.1μm. Similar to gravitational force, a charged particle in an electric field experiences an electrostatic force, with four components accounting for the Coulomb force, image force, dielectric force and dipole-dipole force. In the absence of an electric field, the only component of the electrostatic force that can influence particle motion is the image force. The image force is always directed towards a wall and is only appreciable extremely close to a wall. It only occurs near a conducting surface [4].

A particle entrained in a shear flow field like that in boundary layer may experience a lift force perpendicular to the main flow direction named by the finder as Saffman force [5]. The direction of the lift force depends on the relative velocity between the particle and the air in the streamwise direction, evaluated at the particle center. A particle in a positive velocity gradient near a wall with a streamwise velocity higher than the air velocity will experience a negative lift force towards the wall; conversely, a particle that lags the air stream in the streamwise direction has a lift force away from the wall. The Saffman force arises due to particle inertia and is most important for large particles. Analyses from Lagrangian simulations suggest that the lift force is most important very close to the wall, where the velocity gradient is largest and the differences between particle and fluid velocities are greatest [6]. If a temperature gradient exists in an air volume, a particle in that volume tends to migrate towards the cooler region. The motion is the result of gas molecules on the warm side striking the particle with a greater average momentum than those on the cooler side [7]. Thermal gradients are common in HVAC ducts because the delivered air is often heated or cooled and ducts are often outside of the thermal envelop of buildings.

In the same way that fluctuating turbulent velocity components contribute to momentum transport in turbulent flows, turbulent fluctuations contribute to the diffusive flux of particles. The instantaneous particle concentration in a turbulent flow can be expressed as the sum of an average and a fluctuating concentration, just as the instantaneous turbulent velocity components. As with Brownian diffusion, there is no net particle flux owing to turbulent diffusion in the absence of a concentration gradient.

The last particle transport mechanism, turbophoresis, is a particle transport mechanism only existing in inhomogeneous turbulence and caused by the gradient in turbulent fluctuating velocity components. Because turbulent velocity fluctuations decay to zero at surfaces, near-wall turbulence is highly inhomogeneous with a gradient in turbulence intensity as a function of near-wall distance. The velocity of a particle with sufficient inertia can be decoupled from the local air velocity because of the lag in particle response, as measured by its relaxation time. Where there is a gradient in turbulence intensity, the likelihood that an inertial particle is thrown to a region of lower turbulence intensity near a wall is greater than the likelihood that it will make the return journey away from the wall. This asymmetry leads to a net migration of particles in turbulent flows down a gradient in turbulence intensity and towards walls [8]. Turbophoresis has rarely been explicitly recognized in the literature, even though it proves to be a dominant transport mechanism in turbulent flows for some inertial particles near walls. In contrast to turbulent diffusion, turbophoresis gives rise to a flux of particles even in the absence of a concentration gradient.

2. PARTICLE DISTRIBUTION IN HVAC SYSTEMS

2.1 PM Deposition in Ducts

To decrease the diverse parameters affecting particle deposition in ducts, normalized parameters are often defined in the literatures.

Turbulent duct flows can be characterized in part by their turbulence intensity as measured by the friction velocity, u^*, which is defined as

$$u^* = U_{ave}\sqrt{f/2} \tag{1}$$

where U_{ave} is the bulk airflow velocity in the duct and f is the Fanning friction factor. For a fully developed turbulent flow, f is given by

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

where $\triangle P/\triangle L$ the pressure drop per unit duct length, and D_h is the hydraulic diameter of the duct.

The dimensionless particle deposition velocity is defined by normalizing the dimensional deposition velocity with the friction velocity:

$$V_d^+ = V_d / u^* \tag{3}$$

where V_d is the particle deposition velocity, directly measured by laser Doppler velocimetry (LDV) and particle image velocimetry (PIV) [9] or indirectly calculated by dividing the time-averaged particle flux to the surface (mass or number per area per time) by the time-averaged airborne particle concentration in the duct (mass or number per volume) [10].

In studies of particle deposition from turbulent flow, it is common to investigate the relationship between the dimensionless particle deposition velocity and the dimensionless particle relaxation time. The dimensional relaxation time of a particle, τ_p, is the characteristic time for a particle velocity to respond to a change in air velocity. It may be calculated for spherical particles in the Stokes flow regime as follows:

$$\tau_p = \frac{C_c \rho_p d_p^2}{18\mu} \tag{4}$$

where C_c is the Cunningham slip correction factor (necessary for particles whose diameter is less than 1~10 μm), ρ_p is the particle density, d_p is the particle diameter, and μ is the dynamic viscosity of air. Because deposition happens at walls, particle interactions with near-wall eddies are potentially important in determining deposition rates. A dimensionless particle relaxation time, τ^+, can be defined by comparing the particle relaxation time to the timescale associated with the near-wall turbulent eddies:

$$\tau^+ = \frac{\tau_p}{\tau_e} = \frac{\tau_p}{\nu / u^{*2}} = \frac{C_c \rho_p d_p^2 u^{*2}}{18\mu\nu} \tag{5}$$

where τ_e is the time scale of near-wall turbulent air eddies, ν is the kinematic viscosity of air.

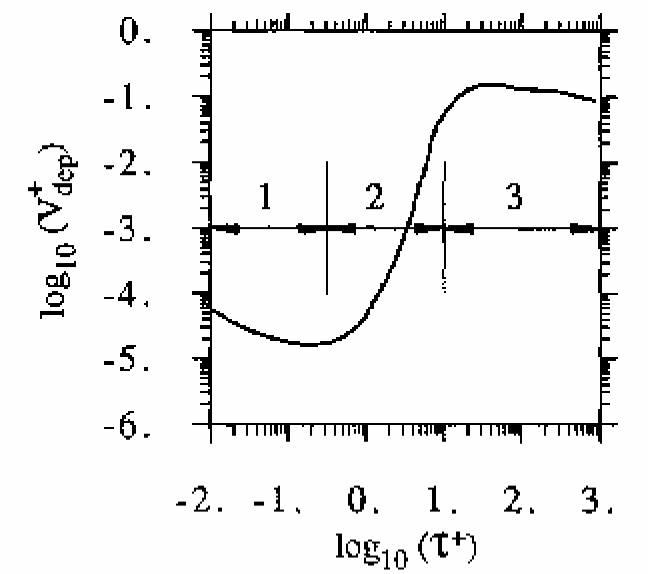

Fig.1 A typical variation of deposition velocities with relaxation time

Fig.1 is a typical variation of deposition velocities with relaxation times, illustrating the profile of relationship between dimensionless deposition velocity and relaxation time. However, ventilation ducts are generally rectangular and horizontal, so there are horizontal planes like floor and ceiling, which make it necessary to account for the gravitational force. Furthermore, bends, valves, internal insulation or sound-absorption materials, and so on make the turbulent flow often not fully developed and the vortices more complex (e.g. secondary flows). What makes the situation more complex is resuspension, which has been the subject of some investigations, but has long defied simple explanation and will almost continue to do so.

Using empirical equations calibrated by experimental data, Sippola modeled and predicted losses of 0.01-100 μm particles in a typical HVAC system serving mid-sized office buildings, including the effects of surface roughness, bends and local geometry variation in duct junctions [11]. Results suggest that duct losses are negligible for particle sizes less than 1 μm and complete for particle sizes greater than 50 μm. The 50th percentile cut-point diameters were 15.2 μm in supply duct runs and 24.9 μm in return duct runs. Losses in supply duct runs were higher than in return duct runs, mostly because of the presence of internal insulation in supply ducts. In the absence of insulation, losses of particles larger than 1 μm were controlled by deposition to the floors of horizontal ducts and to duct bends. The presence or absence of a significant amount of insulation appears to be the most important factor for determining particle losses in a duct run.

2.2 Particle Fates in Buildings

There are two general sources of particles in buildings: outdoor sources and indoor sources. Outdoor sources include volcanic eruption, wind-blown dust, pollen, industrial air pollution, vehicle effluent air and so on. A bi-modal size distribution is very common in ambient urban aerosols [12]. Indoor sources such as tend to elevate ultrafine and fine particle concentrations whereas mechanically generated sources (sweeping, dusting, resuspension from clothes and carpets) tend to elevate concentrations in the coarse fraction.

During the process outdoor PMs penetrating indoor space with infiltrated outdoor air, building fabrics, door gap, window louver, ventilation duct components may act as ‘sinks’ and reduce the amount of outdoor PMs brought into residential buildings. Then, the penetrated outdoor PMs will distribute indoors and contribute to PMs in indoor air or on indoor surfaces. Substantial uncertainty in the parameter P exists in the literature. Gravitational settling and inertial impaction govern the deposition behavior for micron-sized particles, while Brownian diffusion becomes the major deposition mechanism for sub-micron particles. Particle in the accumulation mode are expected to penetrate most effectively, with P approaching 1. Particle penetration diminished for larger and smaller particles and for cracks with significant surface roughness and irregular geometry [13].

Following the generation of particles indoors, concentration levels may be reduced through several mechanisms including exfiltration through air exchange, filtration using portable or in-duct air cleaners, and deposition. Of these mechanisms, exfiltration losses are relatively easy to quantify for a given space, based on the air exchange rate, and these losses apply equally to all particle sizes. The other loss rates, however, are dependent on several factors including particle size, shape, composition, concentration, room air velocity, room surface characteristics, and volume flow of air through filters and duct work [14].

Sippola modeled the fates of indoor and outdoor particles in an archetypal mechanically ventilated building [11]. For 1-30 μm particles generated in a building with no filtration, a significant fraction may deposit in both supply and return ducts. When released within a building with ASHRAE 40% HVAC filters, a larger fraction of particles larger than 1 μm are predicted to deposit in ventilation ducts compared to particles drawn in from outdoors. Deposition in return ducts is a more important fate of particles released indoors than for outdoor particles. A significant percentage (up to 25%) of 1-30 μm particles generated indoors may deposit in ventilation ducts, even when relatively efficient ASHRAE 85% filters are installed.

3 INFLUENCE OF PM ON IAQ AND EFFECTIVENESS OF CONTROLLING MEASURES

3.1 Influence of PM in HVAC Systems on IAQ

According to the above modeling by Sippola and on-site investigation by the authors [15], depositon in duct system is an important fate of PMs in buildings without filters or with low-efficiency filers (it is the case in most residential or public buildings). Because microbe such as fungi, bacteria, virus transport in the air by attaching on PMs, large numbers of microbe will deposit with their attached particles. When air temperature and relative humidity in the 'dirt' duct system are favorable, microbe may reproduce to cause sick building syndrome (SBS) or even building-related illness, using settled dust as nourishment. Such growth produces microbial VOCs (MVOCs) and may amplify the concentration of bioaerosols in the air stream. Chemical interactions can occur between pollutants and HVAC surfaces, and particle deposits may alter the nature of these surface interactions. Deposited materials may also become nutrient sources for microorganisms that release MVOCs. These sorts of transformations might be of great importance in overall HVAC hygiene.

Ventilation ducts can act as sinks, and in some cases as sources, for a variety of pollutants including particulate matter, microorganisms and volatile organic compounds (VOCs). Particles may deposit to and resuspend from duct surfaces. Particle deposits sorb and desorb VOCs in the passing air stream. Bacteria and fungi deposit on HVAC surfaces and grow if sufficient water is present. In addition to these pollutant interactions, ventilation duct materials like sealants, fibrous insulation and residual manufacturing oils may directly pollute the ventilation air [2]. In summary, particle deposition in HVAC systems alters the exposure of building occupants to particles of outdoor and indoor origin and is linked to a host of indoor air quality concerns.

3.2 Effectiveness of Controlling Measures

Filtration, including in-duct filters, portable air cleaners and so on, and dilution by outdoor air are the two crucial controlling measure on IAQ. In the case of proper operation and maintenance, these measures are effective to control PM indoors and its influence on indoor air quality. But their effectiveness is also influenced by outdoor air quality, source strength and distribution, indoor airflow structure, efficiency of filtration, indoor and in-duct air temperature and relative humidity, etc [16].

4 RECOMMENDATIONS FOR FURTHER RESEARCH

Deposition to ducts with rough surfaces (different insulation types, flexible duct) and deposition within duct component like bends are two cases where deposition rates are known to be high enough to lead to significant particle losses, but still have relatively large associated uncertainties. High quality experiments including high quality deposition measurements and high quality measurements of the near-surface turbulent flow characteristics are crucial to understand the mechanisms governing particle movement in HVAC systems. However, field measurement of size resolved particle deposition rates is also necessary to establish an important connection between particle behaviors in real ventilation ducts and those observed in laboratory experiments and models. Because experimental methods are expensive and time-consuming, numerical method (also called computational fluid dynamics, CFD) is a nice alternative [17].

Airborne PM is a diverse pollutant class, consist of dust, radiotoxin, microbe, and so on. Therefore, the chemical characteristics of PM and interactions between different species are important to fully understand indoor particle dynamics [18]. Beside the above dynamic processes, transport and transformation processes including mixing, interzonal transport, resuspension, coagulation, and phase change within indoor environments may also play an important role in influencing particle concentrations and consequences.

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