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ScienceDirect
Journal of Hazardous Materials 147 (2007) 439–448
Journal of Hazardous Materials
www.elsevier.com/locate/jhazmat

Particle deposition in indoor environments: Analysis of influencing factors

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Received 10 September 2006; received in revised form 30 October 2006; accepted 5 January 2007
Available online 13 January 2007

Abstract

In this paper, several factors influencing particle deposition in indoor environments are analyzed with an analytical model and a three-dimensional drift flux model combined with the particle deposition boundary conditions for wall surfaces. The influences of flow conditions near the wall surfaces, surface roughness and particle concentration distribution on particle deposition indoors are studied. By modeling particle deposition onto surfaces with the analytical model, it is found that larger friction velocity near the wall surfaces and rougher surface may lead to larger particle deposition velocity when the particle size is small, but when particle size is large enough (the range is up to the actual friction velocity and in this study it is about 1–5 μm), the influence of the friction velocity and roughness could be neglected. Furthermore, the three-dimensional numerical simulations indicate that particle concentration distribution may be very different even for the same particle source and air change rate, which cause a different deposited particle flux. As the particle concentration distribution may not be uniform in most cases, especially for the ventilated rooms, it is important to incorporate particle concentration distribution when analyzing particle deposition in indoor environments. Some suggestions or rules for particle deposition controlling are also presented based on the analysis.

Keywords: Aerosol; Particle; Deposition; Indoor air quality (IAQ); Indoor environment; Ventilation

1. Introduction

Modern people spend most of their lives in the indoor environment which implies that indoor air quality (IAQ) has become more important than ever before. Particulate matter (PM) is a ubiquitous pollutant indoor and outdoor around the world and aerosol particles are regarded as significant pollutant sources in the indoor environment. One fate of aerosol particles in indoor air is deposition onto surfaces. This process is very important because deposited particles may damage the electronic equipment and artworks. Besides, particles deposited onto indoor surfaces might be re-suspended and pollute indoor environment. One should ensure as little as possible particles deposited if such hazardous material is released/generated indoor. Knowledge of particle deposition indoors is therefore important for indoor air quality study.

Previous studies of particle deposition indoors is mainly focused on mean deposition velocity and mean deposition rate of particles, by both experimental methods (for example, [1–15]) and theoretical methods (for example, [7,16–19]) which are useful and suitable for a lumped parameter study and analysis of indoor deposited particles as a whole. Studies on particle deposition together with particle distribution indoors with numerical methods have also been reported [20–24]. Reviewing these work shows that particle deposition velocity may differ much for different indoor environments. Lai has summarized published measured data of particle deposition and related experimental conditions [25]. He found that scattering of the data among different studies is quite significant and he pointed out that these discrepancies may attribute to different particle generation or incomplete measuring parameters. Zhao et al. further found that even for the same particle source and ventilation rate, the average particle deposition velocity may differ significantly in different ventilation rooms [22]. As the complexity and importance of particle deposition in indoor environments, the influencing factors of particle deposition deserve more attention and study. The main purpose of this paper is therefore to analyze several main

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doi:10.1016/j.jhazmat.2007.01.032

factors influencing particle deposition in indoor environments, which could be air flow near wall surfaces (represented by friction velocity), wall surface characteristics (roughness) and particle spatial distribution according to previous studies. As measurement of some important parameters is hard to perform, for example, the flow conditions near wall surfaces, surface roughness and particle spatial distribution (specially for larger particles), this study tends to adopt an analytical and numerical model for the analysis, with the assistance of measured data for validation.

2. Method

2.1. Three-layer analytical model

The authors have developed a three-layer analytical model based on the one by Lai and Nazaroff [26] to incorporate turbophoresis (Zhao and Wu [27]). Using the correlation by Caporaloni et al. [28] to model the turbophoretic velocity, the relationship of particle and air wall normal fluctuating velocity intensity by Johansen [29], and relation to express the particle eddy (turbulent) diffusivity ε_p by Hinze [30], dimensionless particle deposition velocity could be deduced as:

$$v_d^+ = [Sc^{-1} + (\frac{\tau_L}{\tau_p + \tau_L})v_t^+]\frac{dC^+}{dy^+} + \{iv_s^+ + \tau^+ \frac{d[(\frac{\tau_L}{\tau_p + \tau_L})\overline{v_y'^2}^+]}{dy^+}\}C^+, \quad (1)$$

where v_d^+ is dimensionless particle deposition velocity, Sc is Schmidt number (ratio of fluid molecular viscosity υ to particle Brownian diffusivity D), τ_p and τ^+ is the particle relaxation time and its dimensionless format respectively, τ_L is the Lagrangian timescale of the fluid (air), v_t^+ is dimensionless fluid turbulent viscosity, C^+ is dimensionless particle concentration, y^+ is dimensionless normal distance to the surface, v_s^+ is the dimensionless settling velocity, and i is used to characterize the orientation of the surface, i.e., for an upward facing horizontal surface (floor), $i=1$; for a downward facing horizontal surface (ceiling), $i=-1$; for a vertical surface, $i=0$, $\bar{v}'^{2+}_y$ is dimensionless air wall normal fluctuating velocity intensity. All these variables could be found in the earlier paper [27] and thus not repeated here. With the expression of the Lagrangian timescale of the fluid (air) τ_L given by Johansen [29] and expression of the dimensionless air wall normal fluctuating velocity intensity $\overline{v_y'^2}^+$ given by Guha [31], which related these two parameters as function of the dimensionless normal distance to the wall (y^+), Eq. (1) is an ordinary partial equation (ODE) with the assistance of the fitted equation of υ_t. Thus an analytical three-layer model incorporating turbophoresis is built up and the particle deposition onto smooth walls could be modeled with corresponding boundary conditions.

When predicting particle deposition onto rough walls, the shift of turbulent boundary layer due to wall roughness should be considered, that is, the virtual origin of the velocity profile is shifted by a distance, e, away from the walls. Thus the effect of "interception" was accounted for by assuming that a particle is captured when it reaches the effective roughness height. Traditional treatment is to shift the velocity boundary layer a distance that is a constant ratio of the effective roughness height (for example, $0.55k$ is widely used by [31–35]) away from the walls. However, the turbulent flow over rough walls could be classified as three different regimes according to the value of roughness Reynolds number (or called dimensionless roughness), k^+, that is, hydraulically smooth, transition and completely rough regime of turbulent boundary layer. For each regime, the thickness of separated free shear layer behind the roughness is different and thus the shifted distance of turbulent boundary layer should not be a constant ratio of roughness (Zhao and Wu [36]). Based on the measured data by Wan [37] and Grass [38], the shifted distance of the virtual origin of the velocity profile, e, could be fitted as:

$$\begin{aligned}
\frac{e^+}{k^+} &= 0 && k^+ < 3 && \text{Hydraulically smooth}\\
\frac{e^+}{k^+} &= 0.3219\ln(k^+) - 0.3456, && 3 < k^+ < 30 && \text{Transition}\\
\frac{e^+}{k^+} &= 0.0835\ln(k^+) + 0.4652, && 30 < k^+ < 70 && \\
\frac{e^+}{k^+} &= 0.82 && k^+ > 70 && \text{Completely rough}
\end{aligned} \quad (2)$$

where:

$$e^+ = \frac{eu^*}{\upsilon}, \quad k^+ = \frac{ku^*}{\upsilon}$$

To solve the above model for both smooth and rough walls, the fluid (air) turbulent viscosity, υ_t, is calculated by the correlation of Johansen [29] in this study:

$$\begin{aligned}
\upsilon_t &= \left(\frac{y^+}{11.15}\right)^3, && y^+ < 3\\
\upsilon_t &= \left(\frac{y^+}{11.4}\right)^2 - 0.049774, && y^+ \in [3,\ 52.108]\\
\upsilon_t &= 0.4y^+, && y^+ > 52.108
\end{aligned} \quad (3)$$