Building and Environment 107 (2016) 79–89

Contents lists available at ScienceDirect

Building and Environment

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

Modeling particle deposition on the surfaces around a multi-slot diffuser

Chun Chen [a, b], Chao-Hsin Lin [c], Daniel Wei [d], Qingyan Chen [a, e, *]

[a] School of Mechanical Engineering, Purdue University, West Lafayette, IN, 47907, USA
[b] Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, N.T. 999077, Hong Kong SAR, China
[c] Environmental Control Systems, Boeing Commercial Airplanes, Everett, WA, 98203, USA
[d] Boeing Research & Technology, Beijing, 100027, China
[e] Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin, 300072, China

ARTICLE INFO

Article history:
Received 17 May 2016
Received in revised form
11 July 2016
Accepted 15 July 2016
Available online 19 July 2016

Keywords:
Indoor environment
Computational fluid dynamics (CFD)
Aerosol
Lagrangian tracking
Black magic dust
Soiling

ABSTRACT

Enhanced soiling on the wall/ceiling around a diffuser due to particle deposition is very unsightly and reduces our quality of life. This study aimed to model the particle deposition on the surfaces around multi-slot diffusers, which are widely used in transportation vehicles. An SST k-ω model with a modified Lagrangian method was proposed and validated with experimental data on particle deposition rate from the literature. This investigation then conducted chamber tests to qualitatively validate model's ability to predict the deposition distribution around a multi-slot diffuser. Using the validated model, this study numerically investigated the effects of slot setting, supply air angle, and temperature differential on particle deposition around a multi-slot diffuser. The results indicated that, with the same supply airflow rate, increasing the area ratio of openings to bars in a multi-slot diffuser can reduce the particle deposition. When the angle between the supply air jet and the wall was increased to more than 45°, the particle deposition was significantly reduced. Furthermore, the impact of thermophoresis on particle deposition around a multi-slot diffuser was negligible.

1. Introduction

There is strong evidence of a relationship between exposure to ambient particles and adverse health effects, such as lung cancer [1], asthma [2], and mortality [3]. However, a large amount of ambient particles can penetrate through cracks in building envelopes into indoor spaces [4], where people spend roughly 90% of their time [5]. Thus, exposure to indoor particles has become a major threat to public health [6]. These particles deposit onto indoor surfaces, with mixed effects on our daily lives. On one hand, particle deposition reduces indoor exposure to airborne particles [7,8]. On the other hand, particle deposition can cause discoloration of and damage to indoor surfaces [9,10]. Such significant impacts on our health and environment have driven the rapid development of research on indoor particle deposition.

Numerous experimental and modeling studies have focused on quantifying particle deposition indoors. A comprehensive review by Lai [7] systematically summarized the experimental data on particle deposition rates that was published before 2002. Generally speaking, higher deposition rates were observed for both ultrafine (<0.1 μm) and coarse (>1 μm) particles than for accumulation mode particles (0.1–1 μm). This difference occurred because Brownian and turbulent diffusion were dominant for ultrafine particles, and gravitational settling for coarse particles, whereas neither of these mechanisms was dominant for accumulation mode particles. Most of the measured particle deposition rates published after 2002 have shown a similar "V-shape" trend [11–17].

In addition to experimental studies, many efforts have been made to model indoor particle deposition. Eulerian and Lagrangian modeling are the most popular methods to be adopted for indoor environments. The Eulerian method solves the equation that describes the particle flux through the boundary layer to a certain surface. Lai and Nazaroff [18] developed a semi-empirical Eulerian deposition model by considering the effects of Brownian and turbulent diffusion and gravitational settling. Building on Lai and

---

* Corresponding author. School of Mechanical Engineering, Purdue University, West Lafayette, IN, 47907, USA.

E-mail address: yanchen@purdue.edu (Q. Chen).

http://dx.doi.org/10.1016/j.buildenv.2016.07.016

Nazaroff's model, Zhao and Wu [19] considered the effect of thermophoresis. To account for the effects of airflow and turbulence distribution indoors, a number of researchers have implemented the Eulerian deposition models into computational fluid dynamics (CFD) codes [20–23]. Other influencing factors, such as the thermophoretic, lift, and electrostatic forces, have also been investigated using the Eulerian method [24,25]. On the other hand, many studies have calculated indoor particle deposition by means of the Lagrangian method [26–29]. The Lagrangian method tracks the trajectory of each particle, usually on the basis of the airflow distribution calculated from CFD. When particle resuspension is negligible, the trajectory calculations are terminated as a particle deposits onto a surface. Integrating CFD into the calculation allows the distribution of particle deposition to be obtained. For instance, Wang et al. [29] quantified the deposition of exhaled infectious particles onto passengers, floor, ceiling, walls, seat backs, and tray tables in an aircraft cabin. This information is essential for assessing the risk of infection through indirect contact.

Most of the studies mentioned above quantified particle deposition in order to accurately evaluate indoor exposure to airborne particles. However, particle deposition can also increase the soiling of indoor surfaces, a phenomenon which has not been thoroughly investigated. This enhanced soiling has been referred as “black magic dust” in several other studies [10,30]. The soiling usually appears on the wall above a heater, the wall/ceiling around a diffuser, the ceiling above a lamp, and/or the corners of walls/ceiling in a few weeks to a few months after the system is in operation. Many factors have been found to be correlated with this phenomenon, including elevated concentrations of particulate matter ($PM_{2.5}$ and PM_{10}) and semi-volatile organic compounds (SVOCs), a large temperature differential, local airflow characteristics, and a low air exchange rate [10,30]. A possible pathway for the deposition of the stains is that the gaseous SVOCs condense on airborne particles, and they deposit together onto the surfaces [30]. Elevated particle and SVOC concentrations, which are frequently correlated with a low air exchange rate [31], would lead to an increased amount of deposited particles [30]. Chen and colleagues investigated particle deposition above a heater next to a wall, both experimentally [32] and numerically [33]. It was found that a larger temperature differential between the wall and the heater increased the amount of deposited particles. Timmer and Zeller [34] performed CFD simulation with a Lagrangian method to calculate the particle deposition around a ceiling induction outlet. They found that local airflow characteristics were the decisive factors in particle deposition.

Although these studies have provided great insight into enhanced soiling indoors, the understanding of this phenomenon is still far from complete. One case is that of soiling on the wall/ceiling around a diffuser, which is frequently observed in indoor environments [35,36]. Although the soiling around a diffuser is very unsightly and reduces our quality of life, there is a lack of scientific literature on this issue. Multi-slot diffusers are widely used in transportation vehicles, such as aircraft cabins, in order to meet air distribution specifications [37–39]. The enhanced soiling on the wall/ceiling around these diffusers could be a problem. To increase the body of knowledge in this field, the present study aimed to model the particle deposition around a multi-slot diffuser using a CFD technique with Lagrangian tracking. The proposed model was validated by experimental deposition-rate data from the literature. This investigation also conducted chamber tests to qualitatively validate the model's ability to predict particle deposition distribution around a slot diffuser. Finally, the effects of slot setting, supply air angle, and temperature differential on particle deposition were numerically evaluated. The results could be used in the design of multi-slot diffusers in order to prevent enhanced soiling.

2. Methods

2.1. Airflow and turbulence model

This investigation used the shear stress transport (SST) k-ω model [40] to calculate the indoor airflow field. The SST k-ω model uses a transformed standard k-ε model in the free shear region and the standard k-ω model in the near-wall region. This model not only directly resolves the airflow in the near-wall region, but also enhances the robustness in predicting the mean velocity of free shear flows in the wake region [40]. Previous comparative studies concluded that the SST k-ω model was the most effective model for predicting a jet flow [41,42]. Since the airflow from a diffuser slot is a jet in nature, the SST model was utilized in the present study to calculate the airflow field.

2.2. Particle motion and deposition model

This study followed the Lagrangian method to calculate the trajectory of each particle, using the momentum equation based on Newton's law:

$$\frac{d\vec{u}_p}{dt} = F_D(\vec{u}_a - \vec{u}_p) + \frac{\vec{g}\left(\rho_p - \rho_a\right)}{\rho_p} + \vec{F} \tag{1}$$

where t is the time, $\vec{u}_p$ the particle velocity, $\vec{u}_a$ the air velocity, $\vec{g}$ the gravitational acceleration, ρ_p and ρ_a the particle and air density, respectively, and $\vec{F}$ the Brownian motion and thermophoretic force. The drag force, $F_D(\vec{u}_a - \vec{u}_p)$, can be calculated by:

$$F_D(\vec{u}_a - \vec{u}_p) = \frac{18\mu_a}{\rho_p d_p^2 C_c}(\vec{u}_a - \vec{u}_p) \tag{2}$$

where μ_α is the air viscosity, d_p the particle diameter, Re the Reynolds number, and C_c the Cunningham correction to Stokes' drag law, which can be calculated by:

$$C_c = 1 + \frac{\lambda}{d_p}\left(2.514 + 0.8\exp\left(-0.55\frac{d_p}{\lambda}\right)\right) \tag{3}$$

where λ is the mean free path of air molecules. This investigation used the discrete random walk (DRW) model to calculate the turbulence dispersion:

$$u_i^{u} = \zeta_i\sqrt{2k/3} \tag{4}$$

where u'_i is turbulent fluctuating air velocity, ζ_i a standard normal random number, and k the turbulence kinetic energy. This study assumed the particle resuspension to be negligible, since the particles usually cannot accumulate enough rebound energy to overcome the adhesion force [43,44]. Thus, when a particle reaches a surface, the calculation of particle trajectory is terminated, and the particle is considered to have deposited onto the surface. This study also assumed that all the surfaces were smooth.

For turbulent dispersion within a turbulent boundary layer, particles are driven to the wall by the turbulent fluctuating velocity component in the direction normal to the wall. In the near-wall region, the turbulent fluctuating velocity in the wall-normal direction is smaller than that parallel to the wall. However, the SST k-ω model assumes the turbulence to be isotropic, which over-predicts the fluctuating velocity in the wall-normal direction. Consequently, the particle deposition will also be over-predicted [45]. Many studies have adopted near-wall corrections to the fluctuating velocity component in the direction normal to the wall,