Particuology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Particuology

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

Effect of heat-source geometry on distribution and deposition of particulates in a ventilated chamber

Xi Chen [a,b,*]

[a] School of Civil Engineering and Architecture, Henan University of Technology, Zhengzhou 450001, Henan, China
[b] Key Laboratory of Heating and Air Conditioning, The Education Department of Henan Province, Zhengzhou 450007, Henan, China

ARTICLE INFO

Article history:
Received 4 August 2016
Received in revised form 11 March 2017
Accepted 16 March 2017
Available online xxx

Keywords:
Particle deposition
Particle distribution
Near-wall heat source
Computational fluid dynamics
Lagrangian method

ABSTRACT

To investigate the effect of near-wall heat-source shape on particulate motion, the particulate distribution and deposition in a ventilated chamber with different heat-source configurations were numerically modeled. Using the discrete random walk model of the Lagrangian method, the trajectories of 3200 mono-disperse particulates ranging from 1 to 10 μm with a density of 1400 kg/m^3 were tracked. Airflow pattern, temperature fields, the distribution of particulate concentrations, and deposition patterns are calculated and presented. The results show that the shape of a near-wall heat source has an influence on the airflow as well as the temperature field in the chamber and hence affects the particulate distribution and deposition.

Introduction

Exposure to airborne particulate matter has been found to be widely associated with health outcomes (Pope et al., 2004). Several studies indicate that exposure to particulates correlates strongly with morbidity and mortality (Zanobetti, Austin, Coull, Schwartz, & Koutrakis, 2014). Particulates deposited in the human respiratory tract cause many diseases, such as chronic pharyngitis, bronchitis, pneumonia, asthma, and pneumoconiosis (Morawska & Salthammer, 2003). People are spending a considerable amount of their time indoors (USEPA, 1997). Therefore, it is critical to understand particulate distributions and related features in buildings to reduce adverse health effects from particulates.

Several studies concerned with particulate diffusion and deposition in indoor environments indicate various influencing factors. In investigating the thermophoretic force, Abdolzadeh and Mehrabian (2011) found that the electrostatic force, surface roughness, and tilt angle had insignificant effect on particulate deposition rate when temperature differences exceeded a threshold. In modeling particulate dispersion in a displacement ventilated room, Kang, Wang, and Zhong (2011) found that the temperature and vertical location of a supply inlet of air could significantly affect the indoor air quality with contaminant sources located at lower levels. Also, using the Eulerian Reynolds-averaged Navier–Stokes (RANS) model, the distribution of bacteria-carrying particulates resulting from the movements of a surgeon in the operating theatre has been studied (Chow & Wang, 2012). Results showed that periodic leaning over of personnel around the critical surgical site could cause build-up of bacteria-carrying particulates with concentrations exceeding the recommended 10 cfu/m^3. Shi, Li, and Zhao (2014) analyzed the effect of surface air speed in indoor environments on particulate deposition velocity onto skin. They found that the change in surface air speed had a stronger effect on particulates that were smaller. The efficiency of particulate removal by radiators and floor heating systems was investigated numerically in Golkarfard and Talebizadeh (2014), indicating that radiator heating systems had larger particulate deposition ratios. Jurelionis et al. (2015) explored the influence of air distribution methods on the behavior of aerosols in a ventilated room, noting that displacement air distribution was inefficient in removing particulates compared with the mixing ventilation.

In brief, many influencing factors such as indoor airflow patterns, surface roughness, temperature differences, and human behavior have been extensively studied. The effect of the near-wall heat sources on particulate distribution and deposition indoors has received scant attention with insufficient available data.

Widely found in indoor environments, near-wall heat sources often produced sudden discoloration, called “black magic dust”, on surfaces to the side and above. Some researchers suggested

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* Correspondence to: School of Civil Engineering and Architecture, Henan University of Technology, Zhengzhou 450001, Henan, China.
E-mail address: chenxi2014013@haut.edu.cn

http://dx.doi.org/10.1016/j.partic.2017.03.004

Please cite this article in press as: Chen, X. Effect of heat-source geometry on distribution and deposition of particulates in a ventilated chamber. *Particuology* (2017), http://dx.doi.org/10.1016/j.partic.2017.03.004

that near-wall heat sources contributed significantly to particulate deposition (Morawska & Salthammer, 2003; Salthammer et al., 2011). Questionnaires initiated by the German Federal Environment Agency showed that “black magic dust” in dwellings almost exclusively occurred on walls above near-wall heat sources. Morawska and Salthammer (2003) found that dust particulates were causing the discoloration. In our previous studies (Chen & Li, 2014, 2015) of cuboid near-wall heat sources, the temperature, relative humidity, and air velocities above such heat sources were closely correlated with particulate deposition. Moreover whereas deposition above near-wall heat source has been considered, few studies have looked at particulate conditions in ventilated chambers with different planar near-wall heat sources. Because indoor near-wall heat sources may come in various shapes, this study takes shape as an influencing factor in particulate deposition.

With the availability of high performance computers, computational fluid dynamics (CFD) is a powerful tool for particulate research offering several advantages. Many numerical results obtained using CFD methods abound for particulate distribution and deposition. For example, on particulate transport in enclosed spaces, results using the Eulerian and Lagrangian methods were compared in Zhang and Chen (2007). Both methods reproduced well the steady-state particulate concentration distributions, although the Lagrangian method was computationally more demanding. Using a Lagrangian discrete-random-walk (DRW) model and two Eulerian models (drift flux model and mixture model), simulation results of indoor particulate dispersion was conducted (Zhao, Yang, Yang, & Liu, 2008). The results established that both the DRW model and drift flux model yielded satisfactory estimations in contrast to the unsatisfactory mixture model. In addition, a multi-zone airflow and contaminant transport model was adopted in Rim, Persily, Emmerich, Dols, and Wallace (2013) to analyze the flow of outdoor ultrafine particulates into a building under three different ventilation patterns. A comparison between estimations and measurements suggested that this model could provide insight into the particulate entry into buildings. Makhoul, Ghali, Ghaddar, and Chakroun (2013) developed a numerical model to simulate the flow, temperature, and particulate concentration. The validation against experimental measurements and the published experimental data showed that this numerical model was suitable for modeling indoor particulate distribution with sufficient accuracy. Also, Rai, Lin, and Chen (2015) established a numerical model based on particulate generation measured in a chamber as well as physical formulations of particulate nucleation, condensational growth, and deposition, to investigate the particulate generation from ozone reactions with clothing worn by humans in indoor environments. This model was able to estimate particulate size distributions reasonably well. Following this work, Sajjadi et al. (2016) conducted a series of numerical simulations to estimate the particulate deposition on a newly designed passive dry deposition sampler. The k–ε turbulence model was adopted and turbulent fluctuating velocities were generated using the DRW model. The results revealed that the modeled deposition velocities were in general agreement with the experimental data. Recently, particulate penetration, dispersion, and deposition in a historic house were simulated (Grau-Bové, Mazzei, Malkii-Ephstein, Thickett, & Strlič, 2016). The computational model used was based on the drift-flux approach and provided accurate estimations of the spatial distribution of the deposition. These studies have demonstrated the accuracy of CFD as a predictive tool enabling the particulate distribution and deposition in indoor environments. Thus, the CFD method is introduced in this research to calculate the particulate behavior in the chamber with the near-wall heat source.

The purpose of this study is to analyze the effect of planar geometry of near-wall heat source on distributions of particulates (ranging from 1 to 10 μm) and the deposition in a ventilated chamber. The renormalization group (RNG) k–ε model is used to simulate the three-dimensional airflow field and the DRW model of Lagrangian approach is employed to track the trajectories of 3200 particulates. Using a CFD program, the airflow field, temperature field, particulate concentration, particle deposition fraction, and particle deposition number in four cases are estimated.

Model description

Fluid phase

Airflow fields in a ventilated chamber with different heat source geometries were simulated using the RNG k–ε turbulence model with the enhanced wall treatment. Derived using the renormalization group theory (Fluent, 2006), the RNG k–ε turbulence model provides accuracy and reliability for indoor airflow simulations (Posner, Buchanan, & Dunn-Rankin, 2003) with results that reproduce measured data (Kang et al., 2011; Sadrizadeh, Tammelin, Ekolind, & Holmberg, 2014).

The RNG k–ε model is a refinement of the standard k–ε model specified by transport equations given as (Fluent, 2006)

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_i}(\alpha_{\mathrm{k}}\mu_{\mathrm{eff}}\frac{\partial k}{\partial x_j}) +G_{\mathrm{k}}+G_{\mathrm{b}}-\rho\varepsilon-Y_{\mathrm{M}}+S_{\mathrm{k}}, \tag{1}$$

and

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_i}(\alpha_{\varepsilon}\mu_{\mathrm{eff}}\frac{\partial \varepsilon}{\partial x_j})+C_{1\varepsilon}\frac{\varepsilon}{k}(G_{\mathrm{k}}+C_{3\varepsilon}G_{\mathrm{b}}) -C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_{\varepsilon}+S_{\varepsilon}, \tag{2}$$

where G_{k} and G_{b} describe the generation of turbulence kinetic energy associated with mean velocity gradients and buoyancy, respectively, Y_{M} represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, S_{k} and S_{ε} are user-defined source terms, α_{k} and α_{ε} represent the inverse effective Prandtl numbers for k and ε, respectively, and $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are constants. More details are given in FLUENT user’s guide (Fluent, 2006).

Particle phase

The DRW model implements the Lagrangian particulate-tracking algorithm to compute particle trajectories by integrating the force balance equation for each particle. For this study, the Saffman lift force, Brownian force, particulate inertia by gravity, drag, thermophoretic force, and turbulent diffusions are taken into account in the force balance equation. The fluctuating velocity components are regarded as discrete piecewise-constant functions of time. The DRW model calculates the interaction of a particle with a succession of discrete stylized fluid phase turbulent eddies (Fluent, 2006). To simplify our simulation, some assumptions about particulates are introduced: (i) they are all spherical, (ii) they do not rebound from solid surfaces, and (iii) they do not coagulate. Although Lagrangian trajectories are calculated, particle concentrations are not directly calculated. To analyze distributions in the chamber, the particulate phase is coupled (exchanges mass, momentum and energy) with the continuous phase; that is, the “interaction with continuous phase” mode is selected (Fluent, 2006), and the concentration data mentioned below is the total concentration of the discrete phase reported by FLUENT.

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