Energy and Buildings 128 (2016) 867–875

Contents lists available at ScienceDirect

Energy and Buildings

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

Numerical simulation of particle deposition in duct air flows with uniform, expanding or contracting cross-section

Hao Lu, Lin Lu*, Yu Jiang

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

ARTICLE INFO

Article history:
Received 9 March 2016
Received in revised form 25 April 2016
Accepted 25 July 2016
Available online 26 July 2016

Keywords:
Particle deposition
Expanding duct
Contracting duct
Numerical simulation

ABSTRACT

Particle deposition in two-dimensional turbulent duct air flows with uniform, expanding or contracting cross-section was studied by CFD simulation. The Reynolds stress turbulent model (RSM) with UDF correction and discrete particle model (DPM) were adopted to predict air flow fields and particle deposition rate. After numerical validation of air velocity profiles and particle deposition velocity in uniform duct, the air flow field structures, flow drag and particle deposition behaviors in expanding and contracting ducts with different air velocities and particle sizes were investigated and compared with uniform duct case. It was found that particle deposition velocity is overall reduced in expanding duct while enhanced in contracting duct. However, the modification magnitude of deposition velocity is significant discrepant for different particle sizes due to the role of near-wall turbulent eddies. For expanding duct cases, the particle deposition velocities are reduced about one or two orders of magnitude for large particles ($d_p > 3\mu m$) but less than 5 times for small particles ($d_p < 3\mu m$), compared with uniform duct cases. For contracting duct cases, the particle deposition velocities are increased less than 7 times for large particles while about 20–60 times for small particles. Besides, the deposition mechanisms of particles in expanding and contracting duct were also studied and discussed.

1. Introduction

Particle deposition and dispersion in duct air flow are significant for environment and energy engineering applications, such as indoor environment quality, pneumatic conveying and pulverized coal combustion [1–6]. Better understanding of particle deposition behaviors in duct is crucial for improving indoor air quality (IAQ) and related equipment efficiency [7–11]. So far, particle deposition in ducts with uniform section has been well investigated by many researchers. Nevertheless, few attentions have been paid on particle deposition in duct with variable cross-section, such as expanding section or contracting section. However, this issue may also be commonly encountered in a large number of energy and environment engineering applications, and need to be studied in details.

For particle deposition in duct air flows with uniform section, a large number of experimental studies were conducted to measure deposition velocity profile with particle relaxation time [12–15]. The results showed that deposition velocity profile in vertical duct flow can be divided into three regimes: turbulent particle diffusion regime, eddy diffusion-impaction regime and inertia-moderated regime. The particle deposition velocity profile would first decrease, and then greatly increase for several orders of magnitude, finally keeps constant or decreases slightly with the increase of particle relaxation time. Theoretical models [15–19] were also developed for fast predicting particle deposition rate in practical engineering application. Lai and Nazaroff [17] proposed the three-layer model to predict particle deposition velocity on smooth surface by considering gravitational settling, Brownian and turbulent diffusion. This model was further developed by Zhao and Wu [18,19] to successfully predict particle deposition velocity in ventilation duct with smooth and rough walls. In recent years, numerical simulation based on CFD method has become a powerful tool to investigate particle deposition process in various engineering problems [20–23]. Many numerical investigations have been carried out to successfully predict particle deposition in duct air flows with uniform section [24–28]. The Eulerian-Lagrangian approaches were usually applied to simulate particle deposition process in duct air flow [29]. Tian and Ahmadi [30] predicted particle deposition rate in duct air flows by different turbulent models. They found that Reynolds Stress model with turbulent fluctuation correction can simulate particle deposition velocity more accurately, compared with other RANS model. Zhang and Chen [31] proposed a modified Lagrangian method to predict particle deposition in turbulent

---

* Corresponding author.
E-mail address: vivien.lu@polyu.edu.hk (L. Lu).

http://dx.doi.org/10.1016/j.enbuild.2016.07.052
0378-7788/

Nomenclature

C_0	Mean particle concentration
D_1	Uniform duct width
D_2	Outlet width of expanding duct
D_3	Outlet width of contracting duct
F_S	Saffman's lift force
f	Fanning friction factor
h	Duct height
J	Number of particles deposited per unit time and unit area
k	Turbulent kinetic energy (T.K.E.)
$\bar{p}$	Time-averaged pressure
Re	Reynolds number
S	Ratio of particle-to-fluid density
U_{mean}	Mean velocity of air
U_{free}	Freestream velocity of air
u_g	Velocity of fluid
$\bar{u}_i$	Time-averaged velocity
u_p	Velocity of particle
u'_{rms}	Streamwise fluctuating velocity of air
V_d	Particle deposition velocity
V_d^+	Dimensionless particle deposition velocity
v'_{rms}	Wall-normal fluctuating velocity of air
w'_{rms}	Spanwise fluctuating velocity of air
u^*	Frictional velocity of air
y^+	Dimensionless distance from the wall

Greek symbols

ε	Dissipation rate of turbulent kinetic energy
ρ_g	Density of fluid
ρ_p	Density of particle
ζ	Normal distributed random number
μ	Dynamic viscosity of air
ν	Kinetic viscosity of air
τ_p^+	Dimensionless particle relaxation time

duct flow. The results showed that near-wall turbulence effect is important for particle deposition behaviors.

However, very few studies have been conducted for particle deposition in duct air flows with variable cross-section. Sippola and Nazaroff [32–34] detailedly measured particle deposition in straight duct, S-connector and duct bend. They found that particle deposition rate in S-connector and duct bend are greater than that in straight ducts. Particle transport and deposition in expanding and contracting alveolus were numerically investigated by Haber et al. and Lee et al. [35,36]. It was found that near-wall motion is crucial for the enhancement of aerosol deposition inside the alveoli. Nevertheless, the alveolus configuration and flow structure are greatly different with duct flows. In the authors' previous studies, particle deposition in ribbed duct air flow with different rib heights, spacing and shapes were investigated by CFD simulation [2,20,22]. The results showed that particle deposition behavior and velocity are significantly modified because of the variation of duct section configuration. In this study, the particle deposition in expanding and contracting duct air flows were investigated by CFD method and compared with uniform section duct case. The Reynolds stress model (RSM) with turbulent fluctuation correction and discrete particle model (DPM) were employed to predict air flow fields and particle deposition behaviors. Particle deposition velocity with different sizes, flow field structures, flow drag and deposition mechanisms in expanding and contracting ducts were analyzed and discussed.

2. Numerical models and solution methods

In this study, Eulerian-Lagrangian approaches were adopted to simulate particle deposition process in turbulent duct air flows. The Reynolds stress model (RSM) with near-wall correction and discrete particle model (DPM) were employed to predict air flow fields and particle deposition behaviors, respectively. The simulation was conducted based on the commercial software ANSYS FLUENT with UDF codes.

2.1. Turbulent air flow model with near-wall correction

To resolve the turbulent duct air flow fields, the mass conservation governing equation is described by,

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \tag{1}$$

The momentum conservation governing equation is demonstrated as follow,

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \overline{u'_i u'_j}\right), \tag{2}$$

In Eqs. (1) and (2), $\bar{u}_i$is the time-averaged velocity. $\bar{p}$is the time-averaged pressure. $\rho \overline{u'_i u'_j}$is the Reynolds stress tensor.

The RSM model was adopted to close the above Reynolds-Averaged Navier-Stokes equations. The Reynolds stress transport equation can be described by,

$$\frac{\partial}{\partial t}(\overline{u'_i u'_j}) + \bar{u}_k \frac{\partial}{\partial x_k}(\overline{u'_i u'_j}) = \underbrace{\frac{\partial}{\partial x_k}\left(\frac{\nu_t}{\sigma_k}\frac{\partial \overline{u'_i u'_j}}{\partial x_k}\right)}_{D_{T,ij}=TurbulentDiffusion}$$

$$\underbrace{-\left(\overline{u'_i u'_k}\frac{\partial \bar{u}_j}{\partial x_k} + \overline{u'_j u'_k}\frac{\partial \bar{u}_i}{\partial x_k}\right)}_{P_{ij}=StressProduction} \underbrace{-C_1 \frac{\varepsilon}{k}\left[\overline{u'_i u'_j} - \frac{2}{3}\delta_{ij}k\right] - C_2\left[P_{ij} - \frac{2}{3}\delta_{ij}P\right]}_{\phi_{ij}=PressureStrain} - \underbrace{\frac{2}{3}\delta_{ij}\varepsilon}_{\varepsilon_{ij}=Dissipation} \tag{3}$$

The two-layer zonal model with enhanced wall function was employed to deal with near-wall turbulent flow fields in the simulation [30]. The previous studies [29–31] showed that the wall-normal turbulent velocity fluctuation has great influence on particle deposition behaviors. The RSM model without near-wall turbulent fluctuation correction would over-predict the deposition velocity in the diffusion-impaction regime. In this study, RSM model with wall-normal turbulent velocity fluctuation correction was adopted to predict particle deposition in uniform, expanding and contracting duct air flows. To correct the near-wall turbulent velocity fluctuation in the wall-normal direction, the direct numerical simulation (DNS) data by Kim et al. [37] in uniform duct flow was employed and imposed in FLUENT by UDF codes, as follows,

$$\frac{v'_{rms}}{u^*} = C(y^+)^2, \text{ for } y^+ < 4 \tag{4}$$

For expanding and contracting duct cases, the correction Eq. (5) was adopted in the near-wall region. This correction was successfully applied in predicting aerosol deposition in a human mouth geometry by Dehbi [38] and ribbed duct by Lecrivain et al. [39]. It can be described by,

$$\frac{v'_{rms}}{u^*} = \frac{a_1 y^{+2}}{1 + b_1 y^+ + c_1 y^{+2.41}}, \text{ for } y^+ < 30 \tag{5}$$

In Eq. (4) and (5), $C = 0.008$,$a_1 = 0.0116$,$b_1 = 0.203$ and $c_1 = 0.0014$. $u^*$is the friction velocity. $y^+$is the non-dimensional distance from the wall, which can be defined by,

$$y^+ = \frac{yu^*}{\nu} \tag{6}$$