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Numerical investigation on monodispersed particle deposition in turbulent duct flow with thermophoresis

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Abstract

The study presents thermophoretic deposition characteristics of particles in duct air flow. The *v2-f* turbulence model and discrete particle model were used to simulate particle-air flow. After numerical validation, particle thermophoretic deposition with different temperature gradient and particle diameters were investigated and analyzed. It was found that thermophoretic force has obvious effect on deposition velocity for small particles ($d_p < 10\mu m$), while almost no effect for large particles ($d_p > 10\mu m$). Thermophoresis effect is obviously enhanced when temperature gradient increases. Besides, thermophoretic deposition is mainly caused by the dramatic temperature difference in temperature boundary layer.

Keywords: Dust pollution; PV system; Building roof; Numerical simulation

1. Introduction

Thermophoretic deposition of particulate matter (PM) in turbulent flow fields is widely encountered in energy engineering, such as pulverized coal burner, heat exchanger and gas-solid reactor [1-2]. Understanding of

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thermophoresis of particles in turbulent flow is crucial for improving the efficiency and lifetime of many related devices. Thus more attention needs to be paid on thermophoretic deposition behaviors and mechanisms in turbulent flow fields.

Particle deposition in duct flow has attracted many studies including theoretical, experimental and numerical methods [3-4]. Particle deposition in duct flow can be divided into different regimes [5]. Brownian diffusion and flow vortex are main mechanisms for small particles. However, deposition motions are determined by flow vortex and particle inertia with increase of particle diameter. Finally, particle inertia is the dominated factor for particle deposition of large particles. Moreover, Lai et al [6] and Zhao et al. [7] developed a theoretical model to estimate deposition velocity by considering Fick diffusion, turbulent diffusion, gravitational settling, Brownian diffusion and turbophoresis. Furthermore, Tian and Ahmadi [8] established a solid CFD method to simulate particle deposition in duct air flow.

Effects of gravitational and Saffman's lift forces on particle deposition characteristics had been investigated by researchers, such as Jiang et al. [9]. However, thermophoretic deposition of particles has been seldom investigated. Thus the present study aims to examine particle thermophoresis in duct flow with different particle diameters and temperature differences.

2. Numerical Models

The governing equations for air flow are written by,

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0, \tag{1}$$

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

where $\overline{u}_i$ is air velocity and $\overline{p}$ is pressure. The *v2-f* turbulence model was used in the study. Moreover, discrete particle model (DPM) was used to predict deposition process by tracking particle trajectories. The governing equation of particle deposition can be described by,

$$\frac{du_p}{dt} = \frac{1}{\tau}\frac{C_D \operatorname{Re}_p}{24}(u_g - u_p) + \frac{g(\rho_p - \rho_g)}{\rho_p} + \zeta\sqrt{\frac{\pi S_0}{\Delta t}} + \frac{2\rho K_c v^{0.5}}{\rho_p d_p (S_{lk} S_{kl})} s_{ij}(u_g - u_p) + F_{th} \tag{3}$$

$$F_{th} = -\frac{6\pi d_p \mu^2 C_s \left(K + C_t Kn\right)}{\rho\left(1 + 3C_m Kn\right)\left(1 + 2K + 2C_t Kn\right)} \frac{1}{m_p T}\frac{\partial T}{\partial x} \tag{4}$$

In the Eq.(4), Kn is the Knudsen number. K is the thermal conductivity ratio of fluid and particle. T is local fluid temperature. It was assumed that particle will deposit on the duct wall if they touch the wall surface. The rebound and resuspension of particles were not considered in the study.

Finite volume method was adopted to resolve the Navier-Stokes equations. The particle motion equation was resolved by the Runge-Kutta method. No-slip boundary was applied on the duct walls. The symmetry condition was adopted at the upper boundary.

4. Computational Cases

Schematic of particle deposition in turbulent duct flow was shown in Fig.1. The duct size is 0.5 m × 0.01m. Hot air flows from the inlet. The lower wall is cooled wall and the temperature is 300K, as shown in the Fig.1.

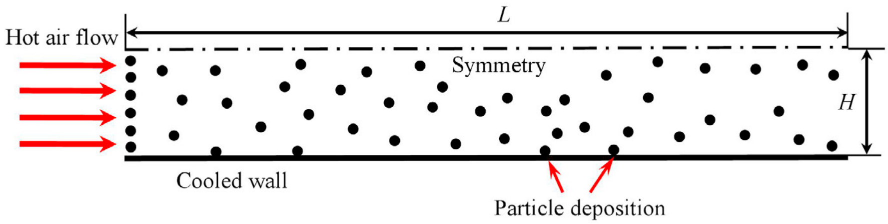


Fig. 1. Schematic of particle deposition in turbulent channel flow with thermophoresis

Air velocity is 5m/s. Air dynamic viscosity μ is 1.789×10^{-5} kg s/m. 15,000 spherical particles were released from the duct inlet. The particle density is 2800 kg/m^3 and particle sizes are from 1 to 50 μm. The first mesh spacing was 0.05mm and increasing factor of mesh spacing was 1.1. The total grid numbers are 40,000 in the simulation.

3. Results and Discussions

3.1. Numerical validation

Turbulent mean flow velocity profile in the duct was validated with DNS data [10], as shown in Fig. 2. Present air flow velocity profile agrees well with the literature results. This indicated that the present turbulence model can resolve air flow fields accurately. Besides, deposition velocity profile in turbulent flow was obtained and compared with previous experimental and numerical results, as shown in Fig. 3. Particle deposition velocity significantly increases and then keeps constant when particle relaxation time increases. Present deposition velocities agree well with related literature results [11-16]. Therefore, the present Eulerian-Lagrangian method could accurately model particle deposition behaviours in turbulent flow fields.

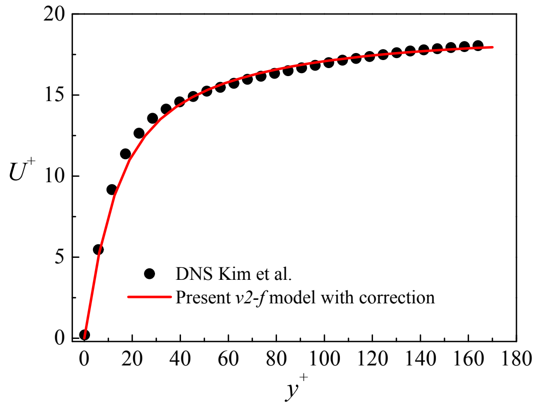


Fig. 2. Numerical validation of turbulent mean velocity profile with DNS data

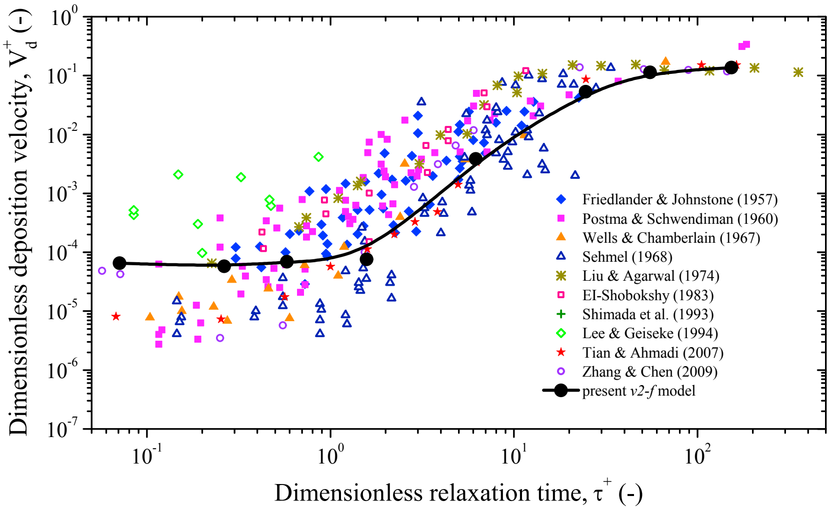


Fig. 3. Numerical validation of particle deposition velocity profile in vertical duct flow

3.2. Thermophoretic deposition of particles

Particle deposition velocity profiles in turbulent flow fields with different temperature gradient were obtained and illustrated in Fig.4. The initial temperatures of inlet hot air were 300K, 350K and 400K respectively. The wall temperature was 300K. From the Fig.4, it can be clearly observed that the effect of thermophoretic force on deposition velocity is different in different particle regime. As thermophoretic force towards to low temperature, particle deposition velocity is increased by thermophoresis effect in the present study. In particle diffusion-impaction regime ($d_p < 10\mu m$), particle deposition velocities are obviously increased when temperature difference between inlet air and wall increases. Moreover, smaller particles have more obvious deposition enhancement. For example, particle deposition velocity of 1μm particles was increased from 6.5×10^{-5} to 1.9×10^{-3} when temperature difference increases for 100K. However, particle deposition velocities are almost not modified by thermophoresis effect in inertia-moderated regime ($d_p > 10\mu m$). This is because particle inertia is quite large in the regime. Therefore, thermophoretic force has significant effect on particle deposition behaviors of small particles ($d_p < 10\mu m$). However, very limited influence can be found by thermophoresis for large particles ($d_p > 10\mu m$).

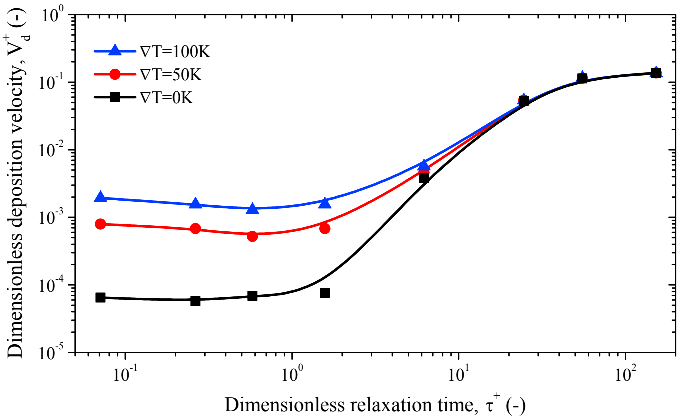
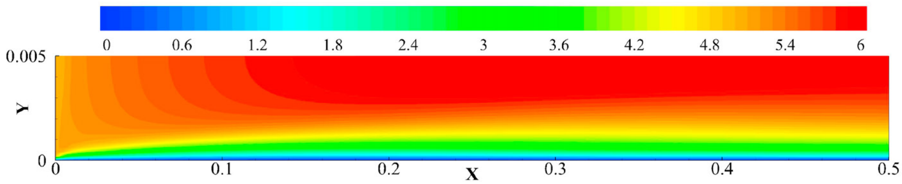


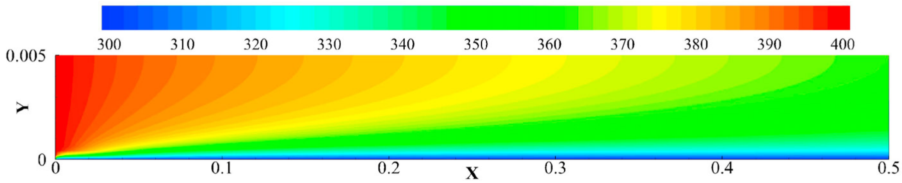
Fig. 4. Particle deposition velocity profiles in turbulent channel flow with different temperature gradient

3.3. Turbulent air flow fields

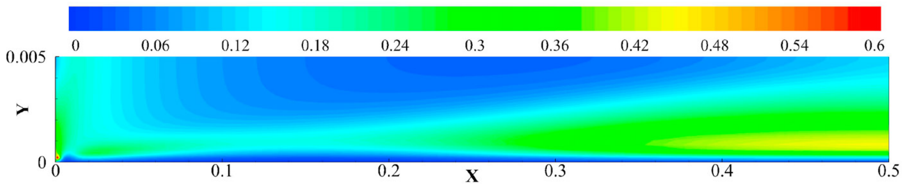
Air velocity fields, air temperature fields and air turbulent kinetic energy (TKE) fields were displayed in Fig.5. It can be found that turbulent boundary layer and temperature boundary layer are both well resolved from Fig. 5 (a) and (b). The dramatic temperature gradient in the temperature boundary layer causes thermophoresis effect of particles. Moreover, TKE values are large in near-wall region, which is important for particle deposition behaviours of small particles.



(a) Turbulent air velocity fields



(b) Turbulent air temperature fields



(c) Turbulent air TKE fields

Fig. 5. Air thermo-fluid fields in turbulent duct flow

4. Conclusions

Thermophoretic deposition of fine particles in duct air flow was investigated by CFD simulation. Air flow fields were solved by *v2-f* turbulence model. Particle deposition motions were resolved by Lagrangian DPM model considering turbulent dispersion of particles. The effects of different temperature gradient and particle sizes on thermophoretic deposition of particles were investigated and analyzed. It was found that thermophoresis effect has great influence on particle deposition velocity for small particles ($d_p < 10\mu m$). Thermophoretic deposition is increased with the increase of temperature difference between inlet air and duct wall. However, particle deposition behaviors almost are not affected by thermophoretic force for large particles ($d_p > 10\mu m$). Moreover, dramatic temperature difference in temperature boundary layer causes thermophoretic deposition in turbulent duct flow. More detailed mechanics of thermophoretic deposition will be further investigated in future experimental and numerical studies.

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