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Original Research Paper

Numerical study to predict the particle deposition under the influence of operating forces on a tilted surface in the turbulent flow

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ABSTRACT

This study uses a v2-f turbulence model with a two-phase Eulerian approach. The v2-f model can accurately calculate the near wall fluctuations in *y*-direction, which mainly represent the anisotropic nature of turbulent flow. The model performance is examined by comparing the rate of particle deposition on a vertical surface with the experimental and numerical data in a turbulent channel flow available in the literature. The effects of lift, turbophoretic, electrostatic and Brownian forces together with turbulent diffusion are examined on the particle deposition rate. The influence of the tilt angle and surface roughness on the particle deposition rate were investigated. The results show that, using the v2-f model predicts the rate of deposition with reasonable accuracy. It is observed that in high relaxation time the effect of lift force on the particle deposition is very important. It is also indicated that decreasing the tilt angle from 90° to 0° enhances the deposition rate especially for large size particles. Furthermore, the results show that increasing the Reynolds number at a specific tilt angle decreases the rate of particle deposition and the tilt angle has insignificant impact on the particle deposition rate in high shear velocity or high Reynolds number.

1. Introduction

The deposition of suspended particles from turbulent gas flow on adjacent surfaces has been extensively investigated during the last 30 years. The understanding and prediction of deposition mass flux is of great interest in areas like pollution control, gas cleaning, design of industrial reactors or transport of particles in two-phase flow systems. Many publications explain calculations of the inertial deposition of particles in 2D flow fields while the effect of turbulent flow has not been considered. Most researchers used a Lagrangian approach in which the particle equations of motion were integrated along the particle pathlines. In such deterministic flows, a few pathline calculations give a good representation of the particle velocity field. Gosman and Ioannides [1] obtained the flow field using the random sampling of a crude turbulence model at each time-step. A similar method was reported by Kallio and Reeks [2] but problems remained in coping with very small particles when Brownian diffusion was important. Li and Ahmadi [3] developed a near-wall model using DNS analysis to capture the near wall fluctioatins. Ounis et al. [4] and, Brooke et al. [5] predicted the motion of particles where the fluid motion was predicted by direct numerical simulation (DNS). Using large eddy simulation [6] or direct numerical simulation methods [7] improved representations of the turbulence but consumed larger computational time. Healy and Young [8] showed that the particle concentration field can also be predicated accurately and efficiently if the so-called full-Lagrangian approach is used, but complications arise when the particles respond to the turbulence flow regime because Lagrangian approach includes a stochastic element in the governing equations. Tian and Ahmadi [9] successfully applied the near-wall model with a Reynolds stress model (RSM) to predict particle deposition in channel flows. Lai and Chen [10] adopted the RNG k-ε turbulence model to predict indoor particle dispersion, and deposition rate was used to quantify the wall-normal turbulent fluctuation within the viscous layer near the wall. Marchioli et al. [11] reported detailed statistics for velocity and deposition rates of heavy particles dispersed in turbulent boundary layers using DNS. However, Lagrangian approach typically involves the determination of trajectories of a very large number of particles (to establish statistically meaningful average quantities) and may be too time consuming to be effective as a practical calculation method, especially for small particles. Therefore, the two-phase Eulerian approach which is computationally more efficient was adopted for the present work. The air flow properties which can be obtained analytically or experimentally are used as the input parameters

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Nomenclatures

C_c	Cunningham coefficient
C_D	drag coefficient
d_p	particle diameter
D_B	Brownian diffusivity
F_D	drag force
F_L	lift force
F_B	Brownian force
F_E	electrostatic force
g	gravitational acceleration
J	wall mass flux
k	Boltzmann constant
k_s	effective roughness height
q	particle's electrical charge
Re_p	Reynolds number based on velocity of particles relative to air
R	radius of channel
Re_τ	Reynolds number based on the shear velocity
Sc	Schmitt number
T	fluid absolute temperature
T_L	Langragian time scale
t_p	relaxation time
u_τ	shear velocity
u_p	particle velocity in x-direction
u_F	air flow velocity in x-direction
v_F	air flow velocity in y-direction
v_p	particle velocity in y-direction
V_E	electrostatic drift velocity
V_{dep}	particle deposition velocity
v'_p	particle fluctuation velocity in normal direction
v'_F	air flow fluctuation velocity in normal direction

Greek symbols

ρ_p	particle concentration
μ	fluid viscosity
β	tilt angle
μ	fluid viscosity
ρ_{p0}	mean particle concentration
$\rho_{p\max}$	maximum particle concentration
ζ	fraction of the maximum charge
ε_0	electric permittivity of vacuum
λ	mean free path of the air molecules
ρ_f	fluid density
v_t	air flow turbulent viscosity
v_t^p	particle turbulent viscosity
$-$	mean
$+$	non-dimensional

of the Eulerian model. Cleaver and Yates [12] developed a theory for particle deposition based on the bursts and ejections of turbulent fluid into the laminar sublayer based on Eulerian approach. They did not account for the finite dispersion in the core flow, but even so they reproduced acceptable experimental data. Reeks [13] deduced the migration effect (turbophoresis) and showed that turbulent migration could have a strong impact on particle deposition. Guha [14] developed a unified model which considers all the transfer mechanisms of particle deposition. His results were validated when compared with the experimental data. Nazaroff and Lai [15] developed an Eulerian particle deposition model, in which some of transport mechanisms in the particle deposition were not considered. Their model prediction agreed reasonably well with the experimental data. Zhao and Wuo [16] considered the turbophoretic forces in the Nazorrof model and improved their results. However, they did not consider the lift and electostatic forces, but borrowed the turbulence features from the literature. Zhao and Chen [17] used the Nazaroff model with the k-ε turbulence model for predicting the air flow turbulence features. However, they did not consider the turbophoretic force and their results underestimated the measured data in some cases. Even if the turbophoretic force was taken into account, the k–ε model was not able to give accurate near wall fluctuations.

The previous studies were mainly concentrated on the particle phase and borrowed the required information of air flow from literature, this makes Eulerain approach less flexible. This paper tends to adopt a numerical approach based on boundary layer analysis to obtain detailed information of turbulence features. The turbulence features of flow were found using v2-f turbulence model. This is the beauty of v2-f model which provides real quantities for the normal fluctuations near the wall. The numerical results were validated when compared with the measured data from literature, and then applied to study the particle deposition rate on a tilted surface under different conditions. The effects of Brownian, turbophoretic, lift, electrostatic and gravitational forces on the particle deposition rate were examined. The deposition of particles at different tilt angles and shear velocities was then studied.

2. Modeling of air flow and turbulent features

Accurate prediction of air flow and turbulence is very important to the success of modeling the particle deposition on the surfaces [9]. The v2-f model for predicting the air flow in this study was developed by Lien and Kalitzin [18] and Davidson et al. [19]. It has been shown that this model has a good accuracy in predicting the mean flow and the turbulence features compared to other turbulence models [20]. The model formulation has the general form of:

$$\rho\frac{\partial\overline{\phi}}{\partial t}+\rho\overline{u}_j\frac{\partial\overline{\phi}}{\partial x_j}-\frac{\partial}{\partial x_j}\left[\Gamma_{\phi,\mathrm{eff}}\frac{\partial\overline{\phi}}{\partial x_j}\right]=S_\phi \tag{1}$$

where $\overline{\phi}$ represents the independent flow variables, $\Gamma_{\phi,\mathrm{eff}}$ the effective diffusion coefficient, S_φ the source term, ρ the flow density and the bars denote the Reynolds averaging. In Table 1 the mathematical form of each transport equation of the v2-f model are summarized. p is the air pressure, μ_t the turbulent viscosity, S the rate of strain, f a part of the v'^2 source term and T the turbulent time scale.

The appropriate boundary conditions of turbulence variable near the wall are as follows:

$$k=v'^2=f=0,\quad \varepsilon=2\upsilon\frac{k}{y_p^2} \tag{2}$$

y_p is the distance from the cell center to the wall.

3. Particle phase modeling

The particle phase as well as the fluid phase is described in the Eulerian frame of reference. The Ramshaw approach [21] described the motion of a particle cloud in a fluid flow. It is assumed that a dilute particle phase with no coupling between the particles and the fluid is under investigation. A criterion for having a dilute suspension is that the particle phase bulk density is negligible when compared with the gas phase density, i.e., $\rho_{\mathrm{Bulk,p}} << \rho_{\mathrm{Bulk,gas}}$. In this study the particles are assumed to be heavy, $\rho_{\mathrm{particle}} >> \rho_{\mathrm{fluid}}$. The motion of particle phase is governed by the continuity and momentum equations. Fig. 1 shows a tilted surface where the particle phase is moving above the surface.