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A model for particles deposition in turbulent inclined channels

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ABSTRACT

A computational model for studying the deposition of particles in duct flows in the presence of thermal force under turbulent flow condition was developed. The V2F turbulence model was used to evaluate the mean flow and temperature fields, as well as the root mean-square fluctuation velocities. The V2F model was selected due to its potential for accurate evaluation of the intensity of turbulent velocity fluctuations normal to the wall. The instantaneous velocity field was simulated with the use of the Kraichnan continuous Gaussian random field model and anisotropic turbulence intensities generated by the V2F model. A Lagrangian particle trajectory model was used for evaluating the transport and deposition of particles. The Stokes drag, lift, Brownian, gravity and thermophoretic forces were included in the particle equation of motion. The predicted deposition velocities for vertical and horizontal ducts in the absence of thermophoresis effects were compared with the available experimental data and earlier empirical models, and good agreements were found. A series of simulations for particle deposition on the lower surface of an inclined duct for different imposed temperature gradient fields was performed. The earlier developed models for particle deposition in vertical and horizontal ducts were extended to inclined ducts in the presence of thermophoresis. The simulation results for particle deposition in turbulent inclined duct flows in the presence and absence of thermophoresis were shown to be in good agreement with the empirical model predictions.

1. Introduction

Analyzing transport and deposition of aerosols suspended in the cold ducts with hot gas flows has attracted considerable attention due to its many industrial applications. Particle transport and deposition are also issues of major concern in heating, ventilation and air conditioning (HVAC) systems, due to its significance in human health. Another interesting example is the commercial kitchen hood ducts where the grease deposition is an issue for their maintenance. Based on the ASHRAE (2011), deposition of grease particles on the walls of exhaust ducts of kitchen hoods is a function of three components: turbulence, thermophoresis, and gravitational settling. Turbulence is a function of airflow velocity (Reynolds number), and interactions of exhaust air with duct walls. Thus, using an accurate turbulence model is important for predicting particle deposition in a turbulent duct flow.

Extensive experimental and computational studies related to particle transport in turbulent flows were reported by Hinze (1975), Hindz (1984), Hidy (1984), Wood (1981a, 1981b), Papavergos & Hedley (1984), and Ahmadi (1993), among

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others. Use of the Reynolds averaged Navier–Stokes (RANS) equations with the aid of a turbulence model for calculating the mean flow, with the one-way coupled Lagrangian particle trajectory analysis has been the most common approach. Tian & Ahmadi (2007) compared the predictions of different models for particle depositions in both horizontal and vertical channels, and concluded that the anisotropy of turbulence and near wall effects significantly affect the accuracy of the simulation results. Recently, Zhang & Chen (2009) used the V2F turbulence model for predicting the airflow and used the wall-normal fluctuation profile to modify the isotropic discrete random walk (DRW) model. Salmanzadeh et al. (2010) investigated particle deposition in a turbulent channel using the Large Eddy Simulation (LES) approach.

Thermophoresis force, caused by the temperature difference between the duct walls and the air stream, is known to be important for micro-particle transport and deposition. Zheng (2002), Keh & Ou (2004) and Tsai et al. (2004) studied the effect of thermophoretic force on the particle movements. He & Ahmadi (1998) simulated the effect of thermophoretic force on particle deposition under laminar and turbulent flow conditions. They also proposed an empirical equation for estimating the thermophoresis effect on particle deposition in turbulent duct flows.

Gravity force also has a significant effect on particle deposition rate, especially, in horizontal and inclined channels. He & Ahmadi (1999) studied the deposition of neutral and charged particles in nearly developed turbulent flow in horizontal and vertical ducts.

In the present work, the V2F turbulence model of FLUENT code (version 6.2) was used and the mean flow and the fluctuation intensities in stream-wise and cross-stream-wise directions in a fully developed turbulent channel flow were evaluated. The Kraichnan Gaussian random field model, along with turbulent fluctuation intensities evaluated by V2F model was used for generating the instantaneous velocity fluctuation fields. The simulated instantaneous velocity field was then employed in the Lagrangian particle tracking analysis. To check the accuracy of the developed model, the deposition velocities in vertical and horizontal ducts were evaluated and the results were compared with the available experimental data and earlier empirical equations. Particle depositions on the lower surface of an inclined duct for different inclination angles and various gas temperature were simulated. The earlier developed model of Fan & Ahmadi (1993) for particle deposition in vertical and horizontal ducts was extended to inclined ducts in the presence of thermophoresis. The simulation results for particle deposition in turbulent inclined duct flows in the presence and absence of thermophoresis were shown to be in good agreement with the new empirical model predictions.

2. Governing equations and model description

2.1. Fluid flow

Velocity and temperature fields are evaluated by solving the coupled continuity, Reynolds Averaged Navier–Stokes and energy equations. The details of the governing equations may be found in Fluent manual (FLUENT, 6.2.3, 2006). The V2F turbulence model was originally developed by Durbin (1991) for the prediction of anisotropy of Reynolds stresses and, in particular, the wall normal fluctuation intensities without using wall functions. In this model four additional equations are solved. There are three transport equations for the turbulent kinetic energy, k, the dissipation of turbulent kinetic energy, ε, the wall-normal stress, $\overline{v}^2$, and an elliptic equation for the relaxation function, f. Additional details of the V2F model may be found in Durbin (1991). The computed turbulence kinetic energy, k, and the wall-normal stress, $\overline{v}^2$, were used for simulation of instantaneous velocity field.

2.1.1. Simulation of instantaneous flow field

The small particle movements are affected by the instantaneous fluctuation velocity field. In this study, the continuous Gaussian random field model suggested by Kraichnan (1970) is used to generate the velocity fluctuations. This method generates a Gaussian random field which resembles a pseudo-isotropic turbulence. Accordingly, the non-dimensional Gaussian random field is given as

$$\vec{u}^{I*}(\vec{x}^*, t^*) = \sqrt{\frac{2}{N}}\left\{\sum_{n=1}^{N} \vec{u}_1(\vec{k}_n)\cos(\vec{k}_n\vec{x}^* + \omega_n t^*) + \sum_{n=1}^{N} \vec{u}_2(\vec{k}_n)\sin(\vec{k}_n\vec{x}^* + \omega_n t^*)\right\} \tag{1}$$

In this equation,

$$\vec{u}_1(\vec{k}_n) = \vec{\zeta}_n \times \vec{k}_n, \quad \vec{u}_2(\vec{k}_n) = \vec{\xi}_n \times \vec{k}_n \tag{2}$$

with

$$\vec{k}_n \vec{u}_1(\vec{k}_n) = \vec{k}_n \vec{u}_2(\vec{k}_n) = 0 \tag{3}$$

which ensures the incompressibility condition. The components of vectors $\vec{\zeta}_n$ and $\vec{\xi}_n$ and the frequencies ω_n are picked from a population of zero-mean Gaussian random numbers with unit standard deviation. Components of $\vec{k}_n$ are also selected from a population of zero-mean Gaussian random numbers with a standard deviation of 1/2.