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Translational and rotational motions of small solid particles in a spatially developing turbulent boundary layer with heat transfer

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ABSTRACT

Direct numerical simulations have been performed to investigate the translational and rotational motions of small solid particles in a spatially developing turbulent boundary layer with heat transfer and two-way coupling, using the Eulerian-Lagrangian point-particle approach. The particles are assumed to be smaller than the Kolmogorov length scale in the dilute gas-solid flow. The simulation results show that the motion of particles is affected by particle inertia, particle preferential concentration and two-way coupling. The mean particle angular velocity is slightly larger than the fluid one in the buffer layer since the small heavy particles preferentially accumulate in regions of high strain rate, whereas the particles rotate slower than the surrounding fluid in the close vicinity of the wall due to their high rotational inertia. In the streamwise direction, the fluid spin intensity exceeds the corresponding particle spin intensity, as a consequence of particle preferential concentration in regions of low streamwise fluid vorticity; while the opposite is true in the wall-normal and spanwise directions. In addition, the differences in the temperature, linear and angular velocities between different inertial particles can be explained in terms of the two-way interactions between dispersed particles and continuous fluid.

1. Introduction

Turbulent flows laden with inertial particles are widely encountered in a great number of natural phenomena as well as industrial and environmental applications. Examples include volcanic eruptions, coal combustion and pollutant dispersion. In the past few decades, extensive laboratory experiments and numerical simulations have been carried out to investigate the interactions between continuous fluid and dispersed particles, focusing on particle dispersion [1–5] and turbulence modulation by particles [6–11]. However, most of these studies have been devoted to isothermal turbulent flows and the research on non-isothermal particle-laden flows has still remained limited.

Sato et al. [12] performed a direct numerical simulation (DNS) of particle-laden decaying isotropic turbulence to investigate the mechanisms of heat and momentum transport by small solid particles. Wetchagarun and Riley [13] numerically studied the dispersion and temperature distribution of inertial particles in stationary and decaying isotropic turbulent flows. Pandya and Mashayek [14] and Zaichik et al. [15] proposed new statistical models for predicting particle transport and heat transfer in turbulent flows. Concerning the particle-laden wall-bounded flows, Arcen et al. [16] analyzed the particle temperature statistics in non-isothermal gas-solid turbulent channel flows and a non-monotonic behavior was observed with increasing particle inertia. Recently, Jaszczur et al. [17] employed the Eulerian-Lagrangian point-particle DNS approach to investigate the heat transport and thermal interactions between particles and fluid. Their results indicated that the mean fluid temperature was significantly larger than the particle temperature in the near-wall and buffer regions of the wall-heated fully developed turbulent channel. Moreover, the difference between mean particle and fluid temperatures increased with particle Stokes number.

In addition to the investigation of particle behavior in non-isothermal turbulent flows, several numerical and experimental studies have also been conducted to examine the effects of particles on the velocity and temperature fields of both the dispersed and fluid phases in isotropic turbulent flows or channel flows [18–21].

In spite of the numerous studies on particle dynamics in isothermal or non-isothermal flows, most have focused either on particle translational motion or on turbulence modulation by particles. However, there is little research reported about the rotational motion of particles in the literature. Ye and Roco [22] experimentally measured the rotational velocity of neutrally buoyant spheres in a planar Couette flow and the mean particle angular velocity was observed to be higher than the strain rate of the

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velocity field in the core region of the Couette flow. Mortensen et al. [23] was the first to study the rotational motion of small particles suspended in a turbulent channel flow via a one-way coupled Eulerian-Lagrangian method. In contrast to the results of Ye and Roco [22], they found that the mean particle spin exceeded the fluid one in the near-wall region. Subsequently, Zhao and Andersson [24] implemented a two-way coupled DNS of turbulent channel flow to investigate the effect of two-way coupling on particle spin. They reported that the modulation of turbulence caused by inertial solid particles has a substantial effect on the rotational motion of spherical particles, especially on the heaviest particles considered.

Different from channel flow in which periodic boundary conditions are usually imposed in the streamwise direction, the boundary layer flow over a flat plate develops spatially along the flow direction. It should be pointed out that, to this date, the investigation of particle rotational and translational motions is still an open question in spatially evolving turbulent thermal boundary layers. In this study, DNS of turbulent thermal boundary layers laden with dispersed particles has been performed using a two-way coupled Eulerian-Lagrangian point-particle approach. The main focus of the present paper is to investigate for the first time, as far as we know, the rotational motion of small heavy particles suspended in a spatially developing turbulent boundary layer over an isothermally heated wall, in addition to the translational motion of inertial particles.

2. Methodology

2.1. Governing equations of fluid phase

In the present study, the fluid is assumed to be incompressible and Newtonian. Typically, the air with density $\rho_f = 1.205\ \mathrm{kg\ m^{-3}}$, kinematic viscosity $\nu = 1.5 \times 10^{-5}\ \mathrm{m^2\ s^{-1}}$ and Prandtl number $Pr = 0.71$ is considered. The three-dimensional continuity, momentum and energy equations for the fluid phase can be written in dimensionless form as

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re_{\theta_{in}}} \nabla^2 \mathbf{u} + \mathbf{f}, \tag{2}$$

$$\frac{\partial \Theta}{\partial t} + \mathbf{u} \cdot \nabla \Theta = \frac{1}{Re_{\theta_{in}} Pr} \nabla^2 \Theta + q, \tag{3}$$

where $\mathbf{u} = (u, v, w)$ is the instantaneous fluid velocity vector, u, v and w are the velocity components in the streamwise (x), wall-normal (y) and spanwise (z) directions, respectively; p is the fluctuating kinematic pressure; Θ is the dimensionless temperature, $\Theta = (T - T_w)/(T_\infty - T_w)$, where T_w and T_∞ represent the wall temperature and free-stream temperature, respectively; $Re_{\theta_{in}} = U_\infty \theta_{in}/\nu$ is the inlet momentum thickness Reynolds number based on the free-stream fluid velocity U_∞, the inlet momentum thickness θ_{in} and the kinematic viscosity ν; the Prandtl number is defined as $Pr = \rho_f \nu c_f / k_f$, where c_f and k_f are the specific heat and thermal conductivity of the fluid, respectively; $\mathbf{f}$ is the feedback force exerted by the particles on the fluid and q is the heat transfer rate from particles to fluid.

The fractional step method is employed to solve the governing equations of the fluid phase on staggered grids [25]. The convective and wall-parallel diffusion terms are treated explicitly, while the diffusion terms in the wall-normal direction are treated implicitly. Time integration of fluid is performed using a low-storage third-order Runge-Kutta scheme for terms treated explicitly and a second-order Crank-Nicolson scheme for terms treated implicitly. A fourth-order compact central difference scheme is used to discretize the spatial derivatives in the convective terms and fourth-order Lagrange interpolating polynomials are used to discretize the derivatives in the diffusion terms [26,27]. The BiConjugate Gradient Stabilized (BICGSTAB) solver with multigrid preconditioner is employed to solve the pressure Poisson equation. In our recent study [28], the algorithm has been validated in a single-phase turbulent boundary layer with heat transfer.

A schematic diagram of the computational domain is given in Fig. 1. The origin of the Cartesian coordinate system is located on the wall at the leading edge of the flat plate. The computational domain is $440 \leqslant x/\theta_{in} \leqslant 904$ in the streamwise direction, $0 \leqslant y/\theta_{in} \leqslant 109$ in the wall-normal direction and $0 \leqslant z/\theta_{in} \leqslant 27$ in the spanwise direction. The grid size is $4096 \times 512 \times 128$ along x, y and z directions, respectively. Grid spacings are uniform in the streamwise and spanwise directions, with $\Delta x^+ = 5.36$ and $\Delta z^+ = 9.98$; while the grids in the wall-normal direction are stretched using a hyperbolic-tangent function, defined as

$$\frac{y_j}{L_y} = 1 - \frac{\tanh[\alpha(1 - (j-1)/N_y)]}{\tanh(\alpha)}, \quad j = 1, 2, \ldots, N_y + 1, \tag{4}$$

where L_y is the height of the computational domain, N_y is the number of grid points along the wall-normal direction and α is a stretching parameter which determines the degree of grid compression in the near-wall region, $\alpha = 2.555$. The closest grid point to the wall is located at $\Delta y^+_{min} = 0.62$, smaller than the minimum Kolmogorov length scale of the single-phase flow $\eta^+_{min} = 1.39$. It should be pointed out that the Kolmogorov length scale $\eta = (\nu^3/\varepsilon)^{1/4}$ is changed in the particle-laden flows with respect to the single-phase flow, as shown in Fig. 2. Unless otherwise stated, all variables written in wall units (identified by superscript +) are non-dimensionalized using the dimensionless wall-friction velocity

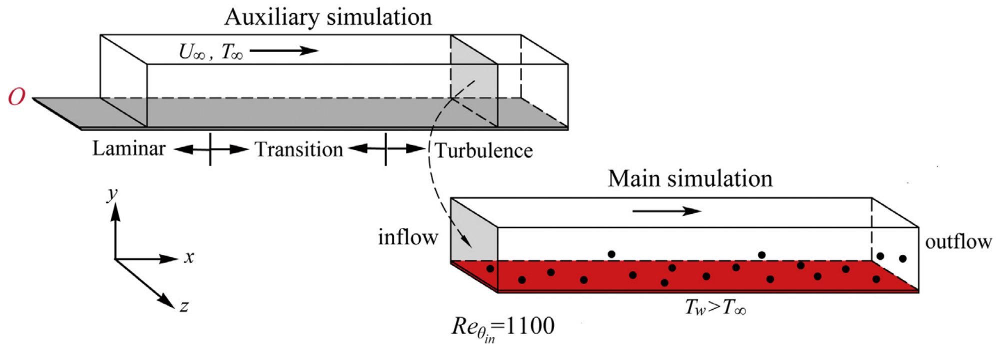

Fig. 1. Schematic diagram of the computational domain.