PARTICLE-TURBULENCE INTERACTION IN NEAR-WALL TURBULENCE

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ABSTRACT

Turbulence modifications due to the presence of particles are investigated using direct numerical simulations of turbulent channel flow. It is shown that a Stokes number plays a key role in the turbulence modification behavior for particles smaller than the Kolomogorov length scale of the fluid. Particles with the Stoke number, St^+, of 0.25 in wall units enhance turbulence near the wall, while particles with $St^+ = 20$ attenuate it throughout the channel. This can be explained in terms of energy exchange between the two phases around streamwise vortices. It is found that the low- and high-Stokes-number particles, respectively, contributed to the positive and negative energy production around streamwise vortices.

INTRODUCTION

Turbulent flows laden with solid particles are of great importance due to their frequent occurrence in engineering applications. Despite numerous experimental and numerical studies that investigate particle-laden turbulence, many fundamental issues remain unclear. For example, turbulence modification due to the presence of particles is a highly complex phenomenon because it is affected by several different mechanisms (Balachandar and Eaton, 2010) and thus has drawn significant attention from many investigators. Kulick et al. (1994) experimentally investigated turbulence modification by solid particles in turbulent channel down flow. Particles smaller than the Kolmogorov length scale of the flow attenuated fluid turbulence and the attenuation level increased with particle Stokes numbers, the particle mass loading, and distance from the wall. In the experiments, Stokes numbers, St^+, in terms of wall units of the channel ranged from 300 to 2000. Subsequently, Yamamoto et al. (2001) and Li et al. (2001) numerically recreated the experimental observations of Kulick et al. using direct numerical simulation (DNS) and large-eddy simulation (LES), respectively. In their simulations, particles were idealized as point sources since the particle size is smaller than the smallest flow scale (i.e. the Kolmogorov length scale). The point-source particles have been generally used in particle-laden turbulence simulations. Dritselis and Vlachos (2008) used DNS to show point-source particles attenuate streamwise vortices in turbulent channel flow. They used $St^+ = 200$ particles. Subsequently, it was shown by Dritselis and Vlachos (2011) that particles with small Stokes numbers of $St^+ = 10$ and 25 attenuate streamwise vortices and fluid momentum more effectively than larger-Stokes-number particles ($St^+ = 100$ and 200).

Since particles behave differently depending on their Stokes number, it is expected that Stokes number greatly influences the way that particles modify turbulence. Despite numerous efforts to investigate the effects of Stokes number on turbulence modification, there have been no attempt to simulate turbulent flows laden with low-Stokes-number particles of $St^+ < 1$ in near-wall turbulence. In this study, we investigate the effects of low Stokes number ($St^+ = 0.25$) on turbulence modification in near-wall turbulence. We perform DNS of turbulent channel flow at a shear Reynolds number, Re_τ, of 150, based on the frcition velocity, u_τ and viscosity, ν. We also consider high-Stokes-number particles with $St^+ = 20$ for comparison purpose. We present the different modification behaviours according to varying Stokes numbers.

TURBULENT CHANNEL FLOW SIMULATION

The governing equations for incompressible flow are given by

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{DU_i}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x_j} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} - F_i \quad (2)$$

Table 1. Particle properties. St^+ is particle Stokes number based on wall units and ρ_p/ρ is the particle-to-fluid density ratio, and N is the total number of particles.

St^+	ρ_p/ρ	N
0.25	18	29314829
20	1440	366435

where, U_i is the fluid velocity and p, ρ, and ν are the fluid pressure, fluid density, and the kinematic viscosity, respectively. Here, F_i represents the particle feedback force per unit mass of fluid. For point-source particles, F_i can be approximated as follows:

$$F_i = \frac{1}{m_f} \sum_{k=1}^{N_p} (D_i)_k\,, \tag{3}$$

in which m_f is the fluid mass of a fluid cell including a given grid point, and N_p and D_i are the number of particles and the hydrodynamic drag force, respectively, in that cell.

We perform direct numerical simulation (DNS) using 128^3 grid points of turbulent channel flow at a shear Reynolds number of $Re_\tau = 150$, based on the frcition velocity, u_τ and viscosity, ν. A pseudo-spectral method was used to solve the Navier-Stokes equation. The domain size in the streamwise (x), wall-normal (y) and spanwise (z) directions is $4\pi\delta \times 2\delta \times 1.2\pi\delta$, where δ is the channel half width. The flow was driven by a fixed mean pressure gradient in the x direction during all simulations.

LAGRANGIAN PARTICLE TRACKING

For solid spheres ($\rho_p/\rho \gg 1$, ρ_p is the particle density), the particle equation of motion is

$$\frac{dX_i}{dt} = V_i, \tag{4}$$

$$D_i = m_p \frac{dV_i}{dt} = m_p \frac{\gamma}{\tau_p}(U_i^p - V_i), \tag{5}$$

in which X_i is the particle position, V_i is the particle velocity, m_p is the particle mass, $\tau_p = {d_p}^2\rho_p/(18\rho\nu)$ is the particle response time scale, and U_i^p is the fluid velocity at the particle position. The coefficient γ indicates the nonlinear drag correction factor accounting for high-particle-Reynolds-number effects,

$$\gamma = 1 + 0.15 Re_p^{0.687}, \tag{6}$$

where $Re_p = |\vec{U}^p - \vec{V}| d_p/\nu$ is the particle Reynolds number. In order to obtain $\vec{U}^p(\vec{X})$, the four-point Hermite interpolation scheme in the x and z directions and fifth-order Lagrange polynomial interpolation in the y direction were used.

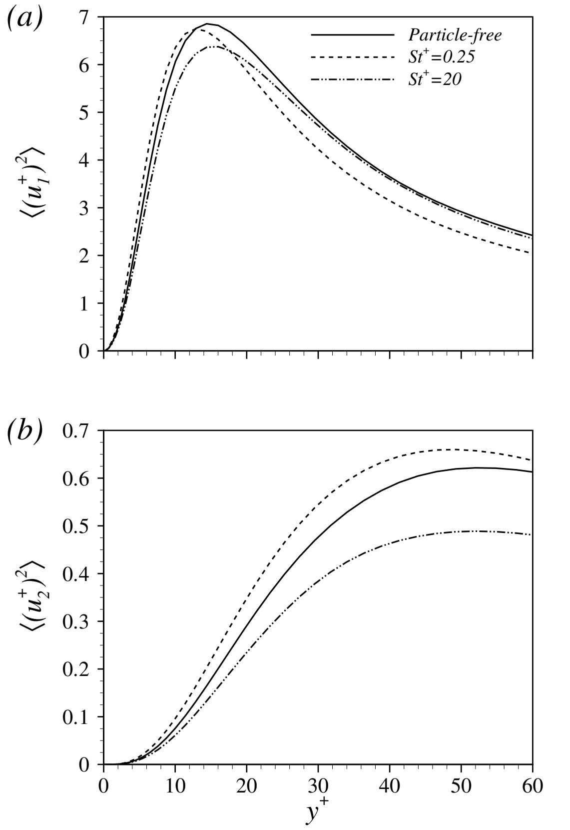

Figure 1. Turbulence intensities: streamwise (a) and wall-normal (b) components.

Initially, rigid spheres are scattered randomly in the computational domain, and the initial particle velocity is assumed to be identical to the fluid velocity at the initial particle position Particle-particle collisions are assumed to be negligible.

Particle properties are listed in table 1. We consider two different particle classes according to Stokes numbers; low-Stokes-number particles of $St^+ = 0.25$ and high-Stokes-number particles of $St^+ = 20$. In all the cases, the particle mass loading is $\phi_m = 0.1$, and the particle diameter is $d_p^+ = 0.5$. Note that the particle size is smaller than the Kolomogorov length scale of the fluid.

The time step is $\Delta t^+ = 0.1$. Statistics for the fluid were time-averaged from $t^+ = 250$ up to $t^+ = 900$.

RESULTS AND DISCUSSIONS

Figure 1(a) and (b) show changes in turbulence intensities in the streamwise (x) and wall-normal (y) directions, respectively, due to the presence of particles in the near-wall region. The result for the particle-free case is also presented for comparison purpose. Note that in the current paper, all variables are normalized by wall units (i.e., the friction velocity, u_τ and viscosity, ν) of the particle-free flow and denoted by the superscript $+$. Particles with $St^+ = 0.25$ slightly increase the streamwise turbulence intensity in the region where $y^+ < 12$ and decrease it in the remaining part of the channel. On the other hand, no enhancement of the streamwise intensity is observed when $St^+ = 20$. The different modification behavior between the low- and high-Stokes-number particles becomes more evi-

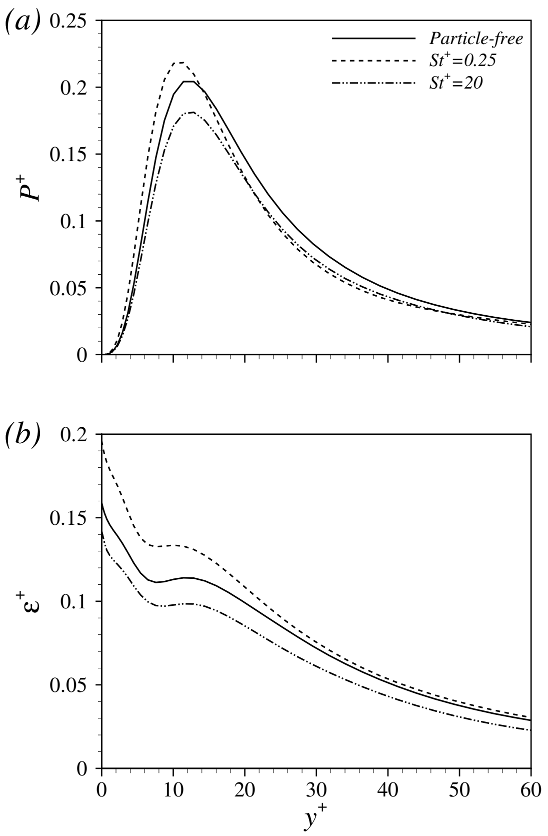

Figure 2. Turbulence production (*a*) and dissipation (*b*).

dent for the wall-normal turbulence intensity.

Figure 2 shows modifications of turbulence production and dissipation due to the presence of particles, compared with the particle-free case. In the near-wall region, production and dissipation are increased and decreased due to the presence of the low- and high-Stokes-number particles, respectively.

The observations reveal that generally, the low-Stokes-number particles augment turbulence activity near the wall, while the high-Stokes-number particles attenuate it. This can be explained in terms of energy exchange between the two phases. Figure 3 shows energy exchange $\vec{u} \cdot \vec{f}$ between the two phases around streamwise vortices, where $\vec{u}$ and $\vec{f}$ indicate the fluctuating parts of fluid velocity and particle feedback force, respectively. In order to visualize vortex cores, the λ_2 method was used (Jeong and Hussain 1995). It is observed that particles with $St^+ = 0.25$ contribute to the positive energy production around the vortex. Therefore, the turbulence is enhanced. On the other hand, the reverse is true for particles with $St^+ = 20$. The high-Stokes-number particles produce mainly the negative $\vec{u} \cdot \vec{f}$ around the vortex. This indicates that the particles obstruct the fluid path and thus attenuate the turbulence.

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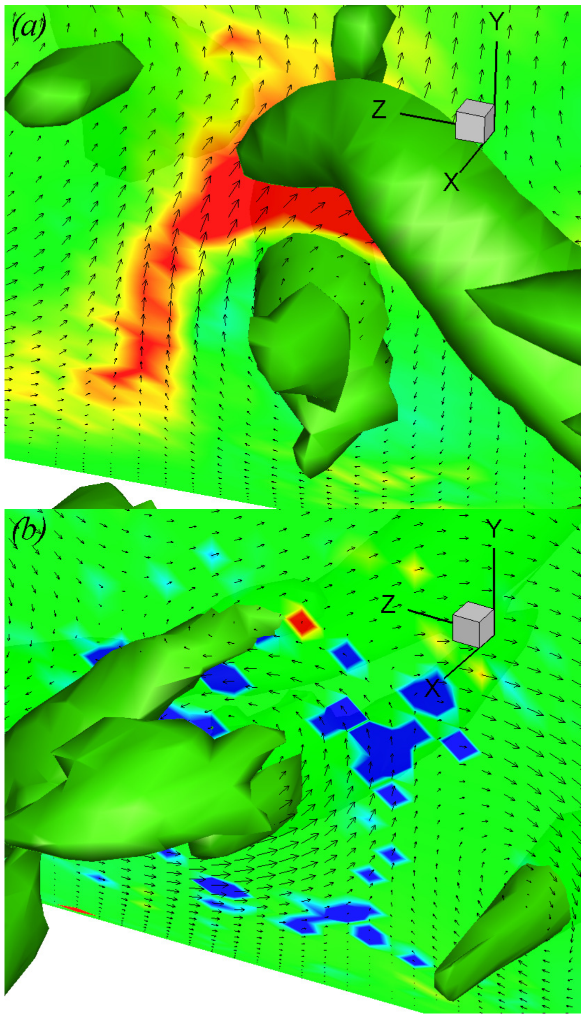

Figure 3. Particle-fluid interaction around streamwise vortices for particles with $St^+ = 0.25$ (*a*) and $St^+ = 20$ (*b*). 3-D isosurfaces visualize streamwise vortices obtained from λ_2 method. Color contours represent $\vec{u}^+ \cdot \vec{f}^+$, where $\vec{u}^+$ and $\vec{f}^+$ are the fluctuating parts of fluid velocity $\vec{U}^+$ and particle feedback force $\vec{F}^+$, respectively (red and blue indicate, respectively, positive and negative values). Arrows indicate $\vec{U}^+$.