Investigation on particle-fluid energy transfer in turbulent channel flow

Lihao Zhao*a), Helge I. Andersson* & Jurriaan J. J. Gillissen**
*Department of Energy and Process Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway
**Department of Multi-Scale Physics, TU Delft, 2628 BW Delft, The Netherlands

Summary To investigate the mechanism of turbulence and tiny spherical particles interactions in wall turbulence, in present paper the two-way coupled direct numerical simulation (DNS) with Eulerian-Lagrangian point-particle approach were performed. The physical mechanisms involved in the particle-fluid interactions were analyzed in one particle class. It was observed that the fluid transferred energy to the particles in the core region of the channel whereas the fluid received kinetic energy from the particles in the wall region. Locally an imbalance in the work performed by the particles on the fluid and the work exerted by the fluid on the particles was observed. This imbalance gave rise to a particle-induced energy dissipation which represents a loss of mechanical energy from the fluid-particle suspension. An independent examination of work associated with the different directional components of the Stokes force revealed that the dominating energy transfer was associated with the streamwise component. The streamwise turbulence intensity was enhanced in the buffer region due to work performed by the particles on the local fluid. Both the mean and fluctuating parts of the Stokes force promoted streamwise fluctuations in the near-wall region. The kinetic energy of the flow field in a cross-sectional plane was damped due to work done by the particles, and the energy was dissipated rather than recovered as particle kinetic energy. This explained the significant damping of the cross-plane velocity components. The observed modulations of the turbulence field could be thereby completely understood.

INTRODUCTION

Particle-laden flows are commonly seen in our local environment and are also of crucial importance in many engineering applications. Turbulent flows of particle suspensions have been extensively studied during the past decades with a variety of different motivations. Either attenuation or augmentation of the turbulent kinetic energy in the presence of solid particles has been observed in both experiments and numerical simulations [1][2][3][4] .

In the present computational study of particle-laden channel flow, we therefore focus on the interactions between the turbulence and the inertial solid particles. Two-way coupled point-particle Eulerian-Lagrangian DNS simulation is performed with the same Navier-Stokes solver and two-way coupling scheme as used by Zhao *et al.* [4]. In current simulation four millions particles with response time 30 (in viscous time unit) were tracked in the fully developed turbulent channel flow at a frictional Reynolds number 360 based on the channel height. The computation domain is 6h* h*3h (x, y and z) in streamwise, wall-normal and spanwise directions, respectively, discritized with 128^3 grid-nodes.

MATHEMATICAL MODEL AND METHODOLOGY

Fluid and particle representations

The motion of the incompressible and isothermal fluid is governed by the mass and momentum conservation equations. The particles in the flow are represented by means of the Lagrangian point-particle approach. The Stokes drag force on a given particle with radius a is expressed as:

$$\vec{F} = 6\pi\mu a\left[\vec{u}\left(\vec{x}_p, t\right) - \vec{v}\right] \tag{1}$$

where $\vec{u}$ is the local fluid velocity evaluated at the particle location $\vec{x}_p$ at time t and $\vec{v}$ is the particle velocity.

Kinetic energy transfer, conversion and dissipation

The mechanical work done by a force on an object is the dot product of the force vector and the displacement vector. In two-way coupled simulation, the only linkage between the fluid and the particles is the drag force as given in eq. (1). The work W^P done by the local fluid to move a particle a distance $\vec{L}^p = \vec{v}dt$ during one time step dt can be expressed as:

$$W^p = \vec{F}\cdot\vec{L}^p = \vec{F}\cdot\vec{v}dt = 6\pi\mu a\left[\vec{u}(\vec{x}_p, t) - \vec{v}\right]\cdot\vec{v}dt\,. \tag{2}$$

The power associated with the motion in the β-direction on the particle can be written as:

$$\dot{W}_\beta^P = 6\pi\mu a\left[u_\beta - v_\beta\right]v_\beta = \alpha\left[u_\beta - v_\beta\right]v_\beta\ ,\quad \alpha = 6\pi\mu a \tag{3}$$

Similarly the associated power on fluid $\dot{W}^f = W^f / dt$ becomes:

$$\dot{W}_\beta^f = -6\pi\mu a\left[u_\beta - v_\beta\right]u_\beta = -\alpha\left[u_\beta - v_\beta\right]u_\beta\,. \tag{4}$$

The sum of $\dot{W}^f$ and $\dot{W}^P$ represents the net loss or gain of mechanical energy per unit time. By summing up the over all three coordinate directions, we obtain the particle dissipation as:

$$\dot{W}^f + \dot{W}^P = -\alpha(\vec{u}-\vec{v})\cdot(\vec{u}-\vec{v}) \equiv -\varepsilon^P \le 0\,. \tag{5}$$

a) Corresponding author. Email: lihao.zhao@ntnu.no.

RESULTS

By decomposing the turbulent velocity field into mean and fluctuating parts as shown in Fig.1 (a)-(b), we found that the fluid transferred energy to the particles in the core region of the channel whereas the fluid received kinetic energy from the particles in the wall region. The extra energy dissipation, which is due to the particle-fluid interactions, was not sufficient to prevent the streamwise intensity to increase. It leads to the conclusion based on Fig.1 (c)-(d) that, as far as motions in the cross-section plane are concerned, energy is drained from the fluid motion and dissipated rather than transferred to the particle motions. The inertial particles are unable to follow the eddy motion in the cross-sectional plane and the unresponsive particles give rise to extra dissipation which in turn plays a crucial role in the attenuation of the wall-normal and spanwise turbulence intensities.

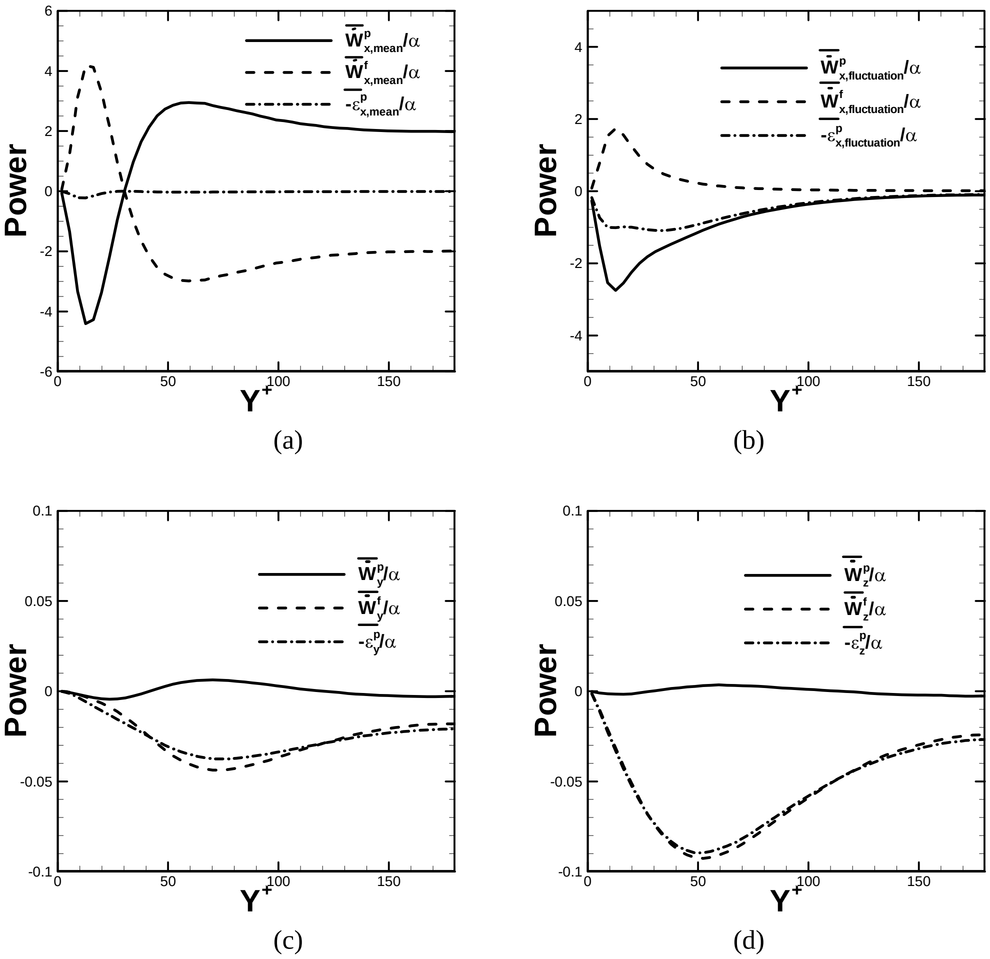

Figure 1 Profiles of the mean values of the power transferred from the fluid to the particles $\overline{\dot{W}^{P}}$ and from the particles to the fluid $\overline{\dot{W}^{f}}$ and the particle dissipation $\overline{\varepsilon_{P}}$. (a) contributions from the mean velocities in the streamwise direction; (b) contributions from the velocity fluctuations in the streamwise direction; (c) contributions from the velocity fluctuations in the wall-normal direction; (d) contributions from the velocity fluctuations in the spanwise direction.

CONCLUSIONS

By means of the present statistics of the power exchange between the two phases, we can conclude that the particles play two distinctly different roles in the flow. One is to redistribute the kinetic energy in the flow and the other one is to provide an extra drain of energy from the suspension by means of particle dissipation. The physical mechanisms responsible for the turbulence modulations [4] caused by the presence of tiny point-particles have been fully explained by means of the present analysis. The more detailed results and discussions would be presented in further conference presentation.

References

[1] Rashidi, M., Hetsroni, G. & Banerjee, S.: Particle-turbulence interaction in a boundary layer. *Int. J. Multiphase Flow* **16**: 935–949, 1990.

[2] Kulick, J. D., Fessler, J. R. & Eaton, J. K: Particle response and turbulence modification in fully developed channel flow. *J. Fluid Mech.* **277**: 109-134, 1994.

[3] Squires, K. D., & Eaton, J. K: Particle response and turbulence modification in isotropic turbulence. *Phys. Fluids A* **2**: 1191–1203, 1990.

[4] Zhao, L.H., Andersson, H. I. & Gillissen, J. J. J.: Turbulence modulation and drag reduction by spherical particles. *Phys. Fluids* **22**: 081702, 2010.