TURBULENCE MODULATION IN PARTICLE-LADEN CHANNEL FLOW

Lihao Zhao, Helge I. Andersson
Department of energy and process engineering.
Norwegian university of science and technology
Trondheim, Norway
Lihao.zhao@ntnu.no

Jurriaan J.J. Gillissen
Department of multi scale physics
TU Delft,
Delft, The Netherlands

ABSTRACT

Particle suspensions have been studied extensively for several decades since such flows are common both in the environment and in a variety of industrial fields. The present work aims to investigate the modulations on the turbulence of the carrier fluid due to the presence of tiny inertial spherical particles in a turbulent channel flow, especially the influences of the particle volume fraction and the particle response time. Five cases with different particle loadings and response times were studied and the comparisons between the particle-laden flows and a particle-unladen channel flow were made. The results of the cases with large response times or particle loadings indicate that the presence of the particles leads to an increase of the mean bulk velocity in the channel flow. Additionally, the streamwise turbulent fluctuations is augmented whereas the spanwise turbulent fluctuations and, in particular, the Reynolds shear stress are attenuated compared with the unladen flow. Moreover, the small-scale eddies around walls have been damped and the flow comprises larger eddies than a flow without particles. However, the cases with small amounts of particles or low particle response times did not show obvious modulations on turbulence. To explore in detail the interaction between the particles and fluid, the kinetic energy conversion was examined by means of conditional averaging. The analysis of the mechanical energy transfer between the fluid phase and the particles indicates the particles redistribute the kinetic energy inside flow, i.e. receiving the kinetic energy from fluid in the central channel but transferring the kinetic energy back to the fluid close to the wall regions..

INTRODUCTION

Dilute suspensions of solid particles in a turbulent gas or liquid flow lead problems of more complexity than single-phase turbulence which is inherently unsteady and three-dimensional, but are nevertheless of immense practical concern both in natural flows and in industry. Suspensions of spherical particles in turbulent pipe and channel flows have been extensively studied during the years with the view to better understand the particle transport, concentration and segregation in wall-turbulence and also the influence on the turbulence of the carrier fluid with the presence of particles. When the suspensions are sufficiently dilute, the carrier fluid is almost not affected by the presence of the particles and the focus is on the translational motion of the particles. The current understanding of the complex motions of inertial spherical particles in turbulent wall flows was summarized by Marchioli and Soldati (2002). It is well known that spherical particles tend to concentrate in the near-wall regions of a wall-bounded shear flow and furthermore that the particles are not evenly distributed but rather accumulate in preferred areas. With larger particle loadings the fluid flow is influenced by the solid particles embedded in the flow field. A recent overview article on the previous experimental studies and two-way coupled computer simulations by Balachandar and Eaton (2010) also mentioned the turbulence modulations in the particle-laden flow. In dilute suspensions flow, several factors may lead to attenuation or augmentation of turbulence, for instance, kinetic energy transport between particles and fluid, extra dissipation caused by particles drag or the vortex shedding behind the spherical particles. Depending on the particle size to the turbulence length scale (Gore and Crowe 1991) and also the particle Reynolds number, one or more of those factors can be dominant and result the attenuation or augmentation of turbulence. Tanaka and Eaton (2008) derived the particle moment number Pa and made Re-Pa mappings by a set of experimenal measurements. They observed the turbulence attenuation in a certain Pa-interval whereas the turbulence was augemented for higher and lower Pa-values. Rashidi *et al*. (1990) showed that the number of wall ejections, turbulence intensity, and also the skin-friction can be reduced by the existence of particles. In the pipe-flow experiments by Kartushinsky *et al*. (2005) a pressure reduction was found in the smallest particle case. More recent report by Bari and Yunus (2009) showed the drag reduction for suspensions of either alumina or sand particles in Kerosene over a fairly wide range of turbulent Reynolds numbers. Drag reduction was also found in the numerical simulations by Li *et al*. (2001), but their mesh was too coarse to assure accurate results.

Since the mechanisms behind turbulence attenuation and drag reduction are not fully comprehended, the current work aims to obtain better understanding of the mechanism of the interaction between turbulence and solid spherical particles in the channel flow. An effective numerical tool, point-particle Eulerian-Lagrangian DNS simulation, is adopted. Under the assumption of point-particle method, the size of particle should be smaller than the smallest eddy in the turbulence. The two-way coupled method is implemented in current program which is adopted by the same numerical scheme by Zhao *et al*. (2010). Five cases are designed to study the influences of particle characteristics, i.e. particle volume fractions and particle response times, on particle-turbulence interactions. The kinetic energy exchange between particles and local fluid is also looked into and the analysis of kinetic energy transport inside the flow explains the modulations on turbulence.

GOVERNING EQUATIONS

We computed the fully developed turbulent channel flow by means of DNS (direct numerical simulations) in the Eulerian frame. The incompressible, isothermal and Newtonian fluid is governed by the mass and momentum conservation equations:

$$\nabla \cdot \vec{u} = 0; \qquad \rho\left[\frac{\partial \vec{u}}{\partial t} + \left(\vec{u}\cdot\nabla\right)\vec{u}\right] = -\nabla p + \mu\nabla^2\vec{u} + \vec{F}_p \quad (1)$$

Here, $\vec{u}$, ρ and p are the instantaneous fluid velocity vector, density and pressure, respectively. The flow is driven by a constant pressure gradient in the streamwise. The last term $\vec{F}_p$ represents the force per unit volume from the particles, which should be considered in the two-way coupling model. Current simulations were performed with the same Navier-Stokes solver as used by Gillissen *et al.* (2008) and Mortensen *et al.* (2007). A pseudo-spectral method, Fourier series in the homogeneous directions and a second-order finite difference scheme in the wall-normal direction is employed for the spatial derivatives on a staggered grid system. The time advancement is carried out with a second-order explicit Adams-Bashforth scheme.

The particles are represented by a Lagrangian approach. Each individual particle is computed and tracked at every time step. The translational motion of individual spherical particles is governed by the Stokes drag force only in present work, while other forces, such as lift and virtual-mass forces, are neglected. The particle Reynolds number based on the particle radius a and the slip velocity between the particle and local fluid, is assumed to be smaller than unity to satisfy the assumption of Stokes flow. We defined the size of the particles smaller than the Kolmogorov length scale in the flow and then the force on particle number i can be simply treated as a point force:

$$\vec{f}_i(\vec{x}_p) = 6\pi\mu a\left[\vec{u}\left(\vec{x}_p, t\right) - \vec{v}\right] \quad (2)$$

Here, $\vec{u}$ is the fluid velocity evaluated at the particle location $\vec{x}_p$ and time t and $\vec{v}$ is the translational velocity of the particle. The motion of a particle and its velocity can be obtained from:

$$\frac{d\vec{v}}{dt} = \frac{1}{\tau}\left[\vec{u}\left(\vec{x}_p, t\right) - \vec{v}\right]; \qquad \frac{d\vec{x}_p}{dt} = \vec{v}. \quad (3)$$

Additionally, the particle response time τ can be expressed as

$$\tau = \frac{2\rho D a^2}{9\mu} \quad (4)$$

where $D = \rho_p/\rho$ is the density ratio between the particle and fluid densities.

The Lagrangian particle equations (3) are integrated forward in the same time step as the Eulerian equations (1) for the fluid motion in simulation. According to the Newton's third law, each and every particle acts back onto the local fluid with a point force $-\vec{f}_i(\vec{x}_p)$ The feedback from the n_p particles within a given grid cell volume V_{cell} adds up:

$$\vec{F}_p = -\frac{1}{V_{cell}}\sum_{i=1}^{n_p}\vec{f}_i(\vec{x}_p) \quad (5)$$

This is the force per unit volume in the particle-laden Navier-Stokes equation (1). This point-force approach to two-way coupled simulations is essentially the same as that followed by Squires and Eaton (1990) in the simulation of isotropic turbulence and also Li *et al.* (2001), Dritselis and Vlachos (2008) and Zhao *et al.* (2010) in the turbulent channel flow.

Since the kinetic energy transport in a particle-turbulence system is one of the main mechanisms in the turbulence modulations, detailed analysis on it is focused in present work. In two-way coupled system, the linkage (5) between fluid and particles is the Stokes drag force. To compute the Stokes force on the particle, the local fluid information is interpolated from the surrounding 27 grid-points onto the particle position, which enables us the velocity of local fluid. The time step in computing the particle equations is the same as that used in integration of Navier-Stokes equations, which is sufficiently small compared with particle response time. Based on Newton's third law, the point force on particles $\vec{f}_i(\vec{x}_p)$ and the force on local fluid -$\vec{f}_i(\vec{x}_p)$ are always of opposite signs. In mathematics, the work W_p done to accelerate a particle during one time step dt is given by the dot product of force and displacement $\vec{L}_p$:

$$\vec{L}_p = \vec{v}dt$$
$$W_p = \vec{f}_i(\vec{x}_p)\cdot\vec{L}_p = \vec{f}_i(\vec{x}_p)\cdot\vec{v}dt = 6\pi\mu a\left[\vec{u}(\vec{x}_p,t)-\vec{v}\right]\cdot\vec{v}dt \quad (6)$$

When the W_p is positive, it physically means the local fluid does positive work on the particle, in other words, the particle extracts the kinetic energy from the fluid. This concept can be used to illustrate the kinetic energy transport between fluid and particles.

Similarly, the work W_f done to accelerate the local fluid element during one time step by the particles can be deduced as:

$$\vec{L}_f = \vec{u}dt$$
$$W_f = -\vec{f}_i(\vec{x}_p)\cdot\vec{L}_f = -\vec{f}_i(\vec{x}_p)\cdot\vec{u}dt = -6\pi\mu a\left[\vec{u}(\vec{x}_p,t)-\vec{v}\right]\cdot\vec{u}dt \quad (7)$$

We can sum up W_p and W_f and then obtain the extra viscous dissipation term ε_p caused by flow passing the spherical particles:

$$W_f + W_p = \varepsilon_p$$
$$W_f + W_p = -6\pi\mu a dt(\vec{u}-\vec{v})\cdot(\vec{u}-\vec{v}) \le 0 \quad (8)$$
$$\alpha = 6\pi\mu a dt$$

RESULTS AND DISCUSSIONS

Table 1. Simulated cases.

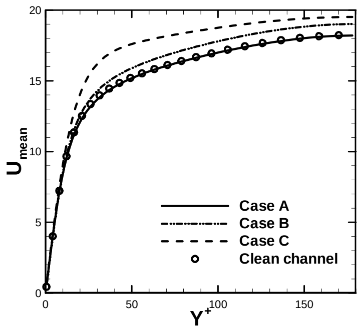
τ^+_p is the scaled particle response time; D is the density ratio; n_p is the number of particles in the flow.

Case	τ^+_p	D	n_p
A	30	1042	$1*10^5$
B	30	1042	$1*10^6$
C	30	1042	$4*10^6$
D	5	174	$5*10^6$
E	50	1736	$5*10^6$

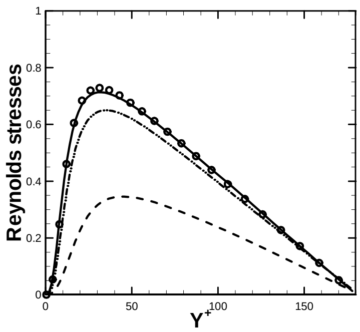
As shown in Table 1, with the focus of modulations on turbulence by particles we computed five cases with various particles numbers and different particle response times. All cases were performed at a friction Reynolds number Re = 360. The size of the computational domain was 6h and 3h in the streamwise x-direction and the spanwise z-direction, respectively. Periodic boundary conditions were imposed in these homogeneous directions and no-slip and impermeability were enforced at the solid walls at y = 0 and y = h. The computational mesh consisted of 128^3 grid points. Cases A, B and C are with the same particle response time but have different particle numbers, whose results could provide the insight in the effect of particle loadings on turbulent modulations. Furthermore, we designed case C, D and E with different particle response times but similar particle volume fractions to investigate how the particle response time influences the turbulent flow. To obtain more details concerning flow-particle interactions, the typical case C is focused on to explain the physics of turbulence modifications by studying the kinetic energy transport between fluid and particles.

Firstly, it is not surprising to observe in Fig.1 that there is no significant influence on the flow in Case A compared with unladen flow case since the particle volume fraction is small. Secondly, there is an obvious increase of streamwise mean velocity in both case B and C. With higher particle volume fraction the mean streamwise velocity raises up more. Additionally, the modifications on the turbulence intensities and Reynolds stresses in case C have been reported by Zhao *et al*. (2010).

Similarly, the cases with various particle response times are compared in Fig. 2. We found out that there is no noticeable influence on the mean streamwise velocity when τ^+ is small, i. e. Case D, even though the volume fraction is similar with other cases; but the attenuations are observed on the Reynolds stresses. Those attenuations should be caused by the extra dissipation induced by the particles with τ^+=5 response time which not fully respond to the turbulent fluctuations in spanwise and also wall-normal directions. Conversely, the Case C τ^+=30 and Case E τ^+=50 show stronger effect on modulations on the flow compared with Case D τ^+=5.



(a)



(b)

Figure 1. Comparison between clean channel flow and particle-laden flows (Case A, B and C). (a) Mean streamwise velocity, (b) Reynolds stresses $-\langle u^+v^+\rangle$

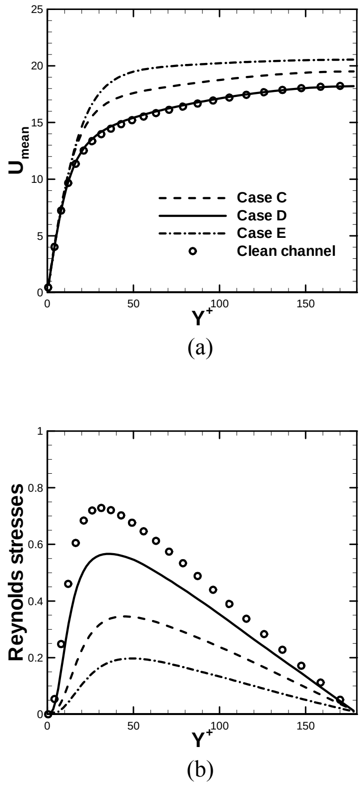


Figure 2. Comparison between clean channel flow and particle-laden flows (Case C, D and E). (a) Mean streamwise velocity, (b) Reynolds stresses $-\langle u^+v^+\rangle$

To have further understanding of the physics of turbulence modulations, one typical case (Case C) is selected to be analyzed in more detail. Firstly, the instantaneous contours are shown to give the direct impression of the particulate flow. Fig.3 gives the streamwise velocity contour of fluid (a), streamwise velocity of particles (b) and streamwise Stokes force contour (c) in Y-Z plane. Fig. 3 (a) shows that the smaller scale-eddies close to the walls have been damped and particles are distributed in preferred regions. Both fluid velocity and particle velocity are positive in the whole region. So based on equations (6) and (7) we can conclude that the fluid makes positive work on particle when the Stokes forces are positive as in the red zones. Since most of positive Stokes force contours are in the central channel, while negative contours are mostly distributed around wall regions, the moving particles receive the kinetic energy from large-scale eddies around center of channel and release the kinetic energy back to the small-scale eddies around wall region.

Under these sweep and injection effects, the process of kinetic energy transport is cyclized. In another view, the existence of particles enhances the exchange of kinetic energy inside of the flow. Correspondingly, the structures of turbulence close to the walls are modified, which results in an increase of anisotropy of near-wall turbulence. The statistical results lead to the same conclusion in Fig.4 with what we discussed above. As shown in the Equation (6)-(8), the work on fluid W_f and the work on the particles W_p are always of opposite sign and the cross point is around y+=30 and W_p and W_f have the equal negative value. Moreover, the total sum is the viscous dissipation ε_p. ε_p is negative all the way from the wall to the center of the channel and implies a loss of kinetic energy. The sampling and averaging method is by using the conditional averaging rather the traditional averaging method. This method has been employed by Mortensen *et al.* (2007), which extracts the fluid information at the locations of particles to make fair and accurate comparison with particles terms. We found out that with different sampling methods the statistical results give different results in the fluid descriptions. Our analysis on the Stokes force and kinetic energy transport is also using conditional averaging method.

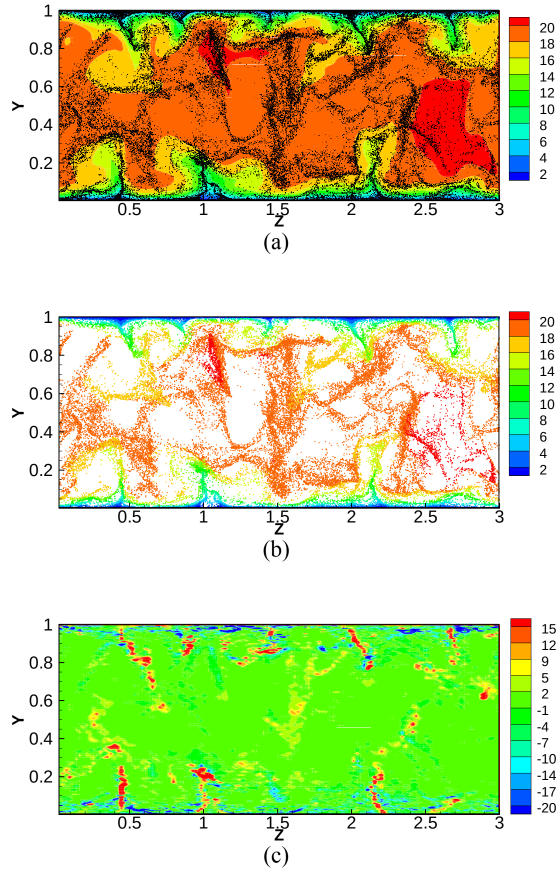


Figure 3. Instantaneous contours in cross-section Y-Z plane (Case C).(a) Streamwise fluid velocity contour, (b) Streamwise particle velocity contour, (c) Streamwise volume Stokes drag force contour.

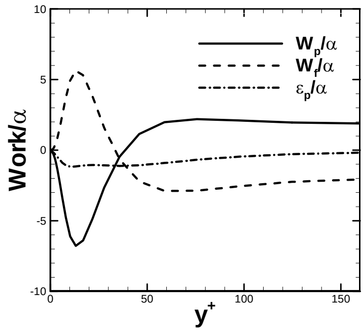


Figure 4. Statistical results of W_p, W_f and ε_p (averaged in x,z and time).

CONCLUDING REMARKS

Current work aims to study the turbulence modulations in a turbulent channel flow with tiny spherical particles with Eulerian-Lagrangian point particle approach with two-way coupling. Several cases with various particle loadings and particle response times were simulated and the modulations on the flow were described and discussed. To explore the mechanism of the interactions between the fluid and particles, we have looked into the kinetic energy exchange inside the mixture. We found out that there is no noticeable influence on the mean streamwise velocity when the particles loadings and reponse times are small in Case A and D, however, the results reveal that there is a significant increase of the mean velocity in the channel flow with the presence of the particles with higher inertia and volume fractions as shown in Case B, C and E. Moreover, the Reynolds shear stress is attenuated compared with the un-laden flow. Additionally, the overall turbulence is suppressed, i.e. the small-scale eddies are been damped, and the flow comprises larger eddies than a flow without particles. In the analysis of the Stokes drag force contour and also sampling results of kinetic energy in Case C we also found out that the moving particles receive the kinetic energy from large-scale eddies around center of channel and release the kinetic energy back to the small-scale eddies around wall region. Due to the sweep and injection effects, the process of kinetic energy transport is cyclic. In another view, the existence of particles enhances the exchange of kinetic energy inside of the flow. Correspondingly, the structures of turbulence close to the walls are modified, which results in an increase of anisotropy of near-wall turbulence.

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