NUMERICAL INVESTIGATION OF THE EFFECTS OF LARGE PARTICLES ON TURBULENT CHANNEL FLOW

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Summary A fictitious domain method is used to perform fully resolved direct numerical simulations of particle-laden turbulent flow in a horizontal channel. The effects of large neutrally buoyant particles on the turbulence statistics and structures are investigated for different volume fractions and particle sizes at the channel Reynolds number being 5000.

INTRODUCTION

It has been recognized that suspended particles can modify the characteristic of turbulent flow significantly. A variety of works have been devoted to the study of particle-turbulence interactions. Gore & Crowe[1] and Hetsroni[2] collected the earlier experimental results and concluded that small particles can decrease the turbulence intensity, whereas large particles can enhance the turbulence intensity. Balachandar & Eaton[3] have recently presented a nice review on the particle-turbulence interactions. The fully-resolved direct numerical simulation approach is one kind of newly developed simulation method for particulate flows, in which the interface between the particle and fluid domains needs to be considered and the hydrodynamic force on each particle is determined from the solution of the fluid flow around the particle, and for the flow field the direct numerical simulation method is used if the flow is turbulent. There have been limited works on the fully-resolved simulations of particle-laden turbulent flows[4-5]. In the present study, we employ the direct-forcing fictitious domain (DF/FD) method proposed by Yu & Shao[6] to perform fully resolved numerical simulations of particle-laden turbulent flow in a horizontal channel. The main aim is to investigate the effects of neutrally buoyant particles on the turbulent channel flow.

NUMERICAL METHOD AND PHYSICAL MODEL

The schematic diagram of the particle-laden channel flow is delineated in Fig. 1. The periodic boundary condition is imposed in the streamwise and spanwise directions, and the no-slip condition is imposed on the upper and bottom walls. The parabolic velocity profile with the maximum velocity Um at the centerline of the channel is initially given. In order to compare the results between the particle-free and particle-laden cases at the same Reynolds number based on the flow flux of the suspension, we adopt the constant flow flux condition instead of the constant pressure gradient condition. We employ the direct-forcing fictitious domain (DF/FD) method to conduct fully resolved direct numerical simulations of particle-laden turbulent flows. The dimensionless DF/FD formulation for the incompressible fluid can be written as follows, and the reader is referred to Yu & Shao[6] for the details of the method.

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = \frac{\nabla^2\mathbf{u}}{\mathrm{Re}} - \nabla p + \boldsymbol{\lambda} \quad \text{in } \Omega \tag{1}$$

$$\mathbf{u} = \mathbf{U} + \boldsymbol{\omega}_s \times \mathbf{r} \quad \text{in } P(t) \tag{2}$$

$$\nabla\cdot\mathbf{u} = 0 \quad \text{in } \Omega \tag{3}$$

$$(\rho_r - 1)V_p^*\left(\frac{\mathrm{d}\mathbf{U}}{\mathrm{d}t} - Fr\frac{\mathbf{g}}{g}\right) = -\int_P \boldsymbol{\lambda}\,\mathrm{d}\mathbf{x} \tag{4}$$

$$(\rho_r - 1)\frac{\mathrm{d}(\mathbf{J}^*\cdot\boldsymbol{\omega}_p)}{\mathrm{d}t} = -\int_P \mathbf{r}\times\boldsymbol{\lambda}\,\mathrm{d}\mathbf{x} \tag{5}$$

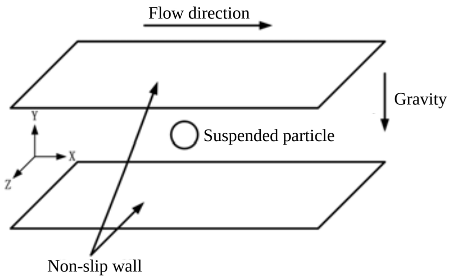

Fig. 1 Schematic diagram for particle-laden channel flow.

RESULTS AND DISCUSSION

The DF/FD method is used to perform fully resolved numerical simulations of particle-laden turbulent flow in a horizontal channel. The effects of large neutrally buoyant particles of diameter 0.05 and 0.1 times the channel height H on the turbulence statistics and structures are investigated for different volume fractions (ϕ=0.79%~7.08%) for the channel Reynolds number being 5000.

Fluid statistics

The comparison of the r.m.s. of the fluid velocity fluctuations between the particle-free and particle-laden cases in the near-wall region (y<0.3H) is shown in Fig. 2. We see that the addition of the particles decreases the r.m.s. of the

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streamwise velocity fluctuation u_{rms} at its maximum, but enhances it in the region very close to the wall. The transverse and spanwise velocity fluctuation intensities are increased in the near-wall region. In addition, for the core region of the channel, the particles increase the r.m.s. of the streamwise velocity fluctuation, but their effects on the transverse and spanwise velocity fluctuations are relatively small. The comparison of the fluid statistics between cases for different particle volume fractions and particle sizes shows that, the effects of the particles on the velocity fluctuations are more pronounced at higher particle volume fractions for the same particle size and smaller particle sizes for the same volume fraction in the parameter range studied.

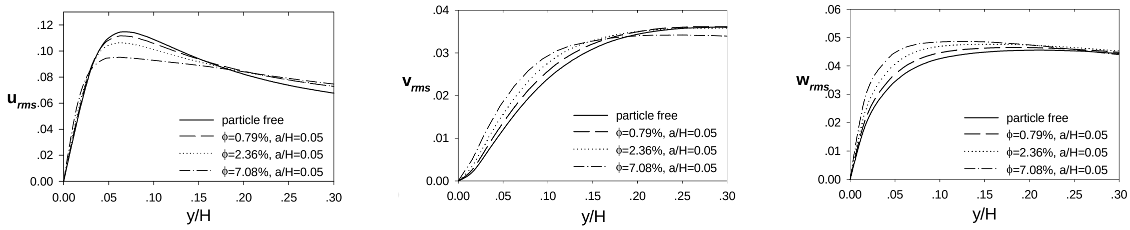

Fig. 2 The r.m.s. of velocity fluctuations in the near-wall region for *a/H*=0.05 cases.

Flow structures

Fig. 3 shows the vortex structures for the particle-free case(the oblique view for lower half-channel). We see that the flow is dominated by large-scale quasi-streamwise vortices in the near-wall region (|y|>0.7H). Fig. 4 shows the vortex structures for ϕ=7.08% and a/H=0.05. From the comparison between Fig. 3 and 4, the addition of the particles weakens the strength of large-scale streamwise vortices, which results in the reduction of the strength of the fast/slow velocity streaks near the wall. This explains why the maximum r.m.s. of the streamwise velocity fluctuations is reduced by the particle effect. On the other hand, the particles induce many smaller-scale vortices in the near-wall region, which is expected to be responsible for the enhancement in the transverse and spanwise velocity fluctuations in the wall region, as well as the streamwise r.m.s. velocity in the region very close to the wall. The suppression of the large-scale streamwise vortices by the particles is probably due to the fact that the particles entrained by the large-scale vortices serve as the dissipation source, and the other particles that are not in the large-scale vortices induce the smaller-scale structures, which may hinder the development of the large-scale streamwise vortices. A possible reason for the more significant effects in case of a/H=0.05 compared to a/H=0.1 at the same volume fraction is that the fluid inertial effects of a single particle for both cases differ less significantly compared to the effects caused by the particle number difference; The number of the particles for a/H=0.05 is 8 times higher than for a/H=0.1 at the same volume fraction.

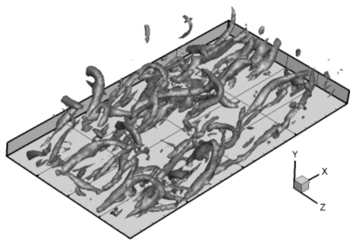

Fig. 3 Flow structures for the particle-free case.

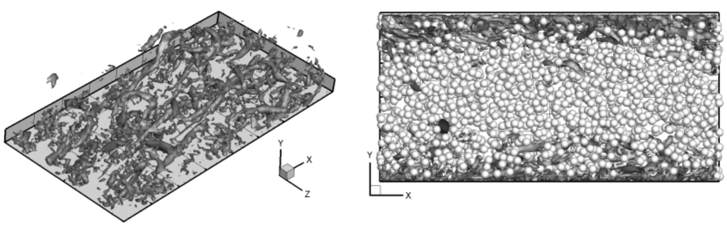

Fig. 4 Flow structures for ϕ=7.08%, a/H=0.05.

CONCLUSIONS

The effects of large neutrally buoyant particles on turbulent channel flow are investigated with fully resolved direct numerical simulations. The results indicate that: The presence of particles decreases the maximum r.m.s. of streamwise velocity fluctuation near the wall by weakening the intensity of the large-scale streamwise vortices, while increasing the r.m.s. of the streamwise fluctuating velocity in the region very close to the wall and in the center region. On the other hand, the particles increase the r.m.s. of transverse and spanwise fluctuating velocities in the near-wall region via inducing the small-scale vortices. The effects of the particles on the velocity fluctuations are more pronounced at higher particle volume fractions and smaller particle sizes.

Acknowledgments

The work was supported by the National Natural Science Foundation of China (Nos. 11072217 and 11132008).

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