MECHANICS OF DENSE SUSPENSIONS IN TURBULENT CHANNEL FLOWS

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Abstract Dense suspensions are usually investigated in the laminar limit where inertial effects are insignificant. When the flow rate is high enough, i.e. at high Reynolds number, the flow may become turbulent and the interaction between solid and liquid phase modifies the turbulence we know in single-phase fluids. In the present work, we study turbulent channel flows laden with finite-size particles at high volume fraction by means of Direct Numerical Simulations. A direct-forcing Immersed Boundary Method has been adopted to couple liquid and solid phases. We will show that the turbulence is attenuated in dense cases, even though the overall drag is increased because of the particle contribution to the total stress.

INTRODUCTION

Dense suspensions of solid particles are frequently encountered both in the environment, such as pyroclastic currents in volcano eruptions, avalanches or sediments in rivers, and in industrial processes, such as slurry transport and fluidized beds. While several works study the rheological problem of dense suspensions in laminar viscous flows [2], few investigations consider the high inertial regime where the flow becomes turbulent. For example, it is well known that particles dispersed in a viscous fluid increase the effective viscosity of the suspension. When the inertia, i.e. the Reynolds number, is high enough peculiar rheological features are found in laminar dense suspensions such as shear-thickening or normal stress differences, e.g. [5, 4]. In this work, we study dense suspensions of neutrally buoyant finite-size particles in a turbulent channel flow. We focus on the interaction between particle dynamics and the turbulent velocity fluctuations associated with the typical structures of wall turbulence. We will show that at high volume fractions, the turbulence level is reduced together with the turbulent shear stress, but the overall drag is increased with respect to the unladen case because of an increase of the particle stress.

METHODOLOGY

The Navier-Stokes equations are solved using a second order finite-difference scheme associated to a direct-forcing immersed boundary method to couple fluid and solid phases. Short-range interactions occurring below the mesh size are considered using lubrication corrections and a soft-sphere collision model [1]. The numerical code has been validated in several studies where test cases can be found, e.g. [4, 3]. The flow is driven by a mean pressure gradient in the streamwise direction which imposes a constant flow rate fixing the Reynolds number at $Re = 2hU_b/\nu = 5600$ with h the channel half-width, U_b bulk velocity and ν the fluid kinematic viscosity. Periodic boundary conditions have been applied in the streamwise and spanwise directions, while no-slip wall are prescribed at the boundary of the channel width. The box size is $6h \times 2h \times 3h$ in the streamwise, wallnormal and spanwise directions. The particle radius is fixed to $R/h = 1/18$ corresponding to about 10 viscous wall units. Three different volume fractions, i.e. $\Phi = 0.05$; 0.1; 0.2 have been considered varying the number of particles up to 10000.

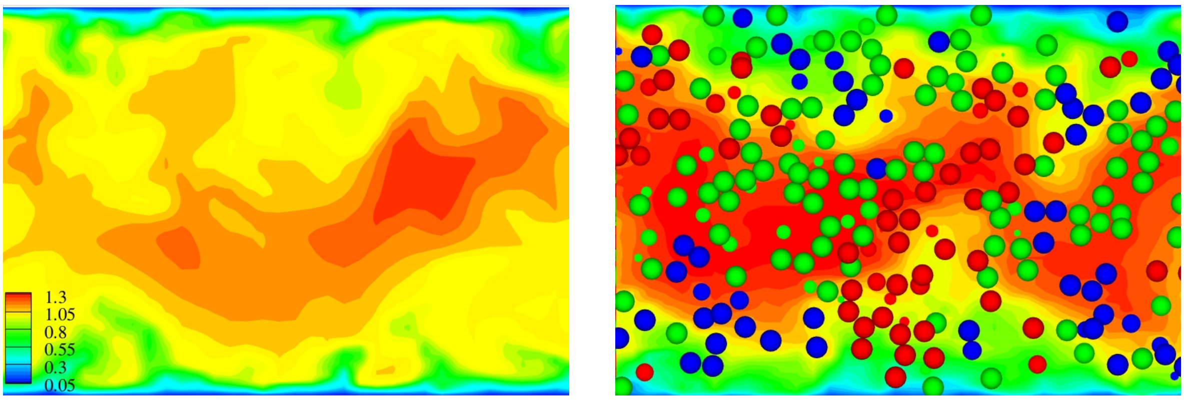

Figure 1. Contour of streamwise fluid velocity in the cross stream plane for the unladen case (left panel) and for $\Phi = 0.2$ (right panel). Particles are colored by their upward wallnormal velocity: blue $< -0.025U_b$, red $> 0.025U_b$, otherwise green.

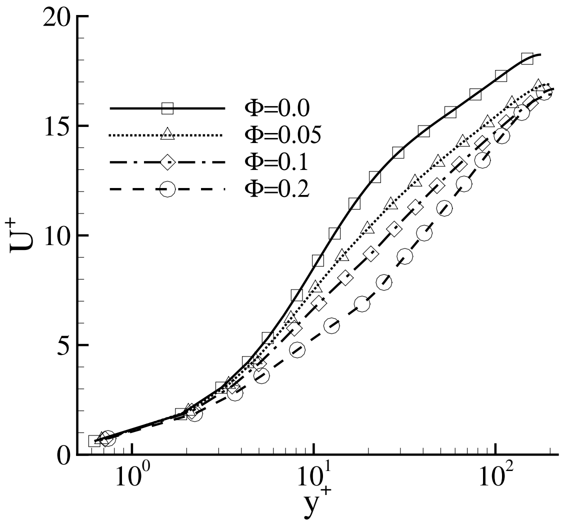

Figure 2. Mean fluid velocity U^+ vs the wallnormal distance y^+ in inner units.

RESULTS AND DISCUSSION

Figure 1 reports the instantaneous snapshots of the streamwise fluid velocity in a cross stream plane for the unladen case and for the densest case here investigated $\Phi = 0.2$. Particles strongly alter the usual turbulent flow behavior. In the unladen case, the near-wall flow is organized in low and high speed streaks which are modulated by larger structures living in the bulk flow. On the contrary, it appears that the presence of particles suppressed the small streaks and the flow appears characterized only by wide coherent structures (of the size of the half-channel width) with a superimposed small-scale noise induced by isolated particle perturbation. Particles are not evenly distributed but they appear to flow in clusters of nearly touching particles. As can be appreciated by the color denoting their vertical velocity, these aggregates are constituted by several particles that move coherently together within the large and wide streaks that characterize the turbulent dense suspension.

The particle back reaction on the fluid affects the usual turbulent wall dynamics. Figure 2 shows the mean fluid velocity normalized by the friction velocity, U^+, as a function of the wall normal distance normalized by the viscous length, y^+. The progressive lowering of the mean velocity profiles denotes a growth of the overall drag increasing the volume fraction Φ. We still observe the presence of a log-layer $U^+ = (1/K)log(y^+) + B$ even for the densest case. In particular, the slope of the log-layer is found to grow with the volume fraction Φ, i.e. lower von Karman constant K. This is usually observed in turbulent drag reducing flows and is associated to a reduction of the Reynolds shear stress and to a widening of the streaks. However, as shown by the mean profiles, the higher the volume fraction, the higher the overall drag becomes for the present cases. This behavior is found to be related to an increase of the particle induced stress and not to an increase of the turbulent stress [3]. This result open the question if it is possible to achieve an overall drag reduction by changing some parameters of the suspensions such as, the Reynolds number and/or the particle density and size. In the final contribution we will investigate how turbulence is affected when varying the particle size and density.

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