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DNS of vertical plane channel flow with finite-size particles: Voronoi analysis, acceleration statistics and particle-conditioned averaging

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A B S T R A C T

We have performed a direct numerical simulation of dilute turbulent particulate flow in a vertical plane channel, fully resolving the phase interfaces. The flow conditions are the same as those in the main case of Uhlmann (2008), with the exception of the computational domain length which has been doubled in the present study. The statistics of flow and particle motion are not significantly altered by the elongation of the domain. The large-scale columnar-like structures which had previously been identified do persist and they are still only marginally decorrelated in the prolonged domain. Voronoi analysis of the spatial particle distribution shows that the state of the dispersed phase can be characterized as slightly more ordered than random tending towards a homogeneous spatial distribution. It is also found that the p.d.f.'s of Lagrangian particle accelerations for wall-normal and spanwise directions follow a lognormal distribution as observed in previous experiments of homogeneous flows. The streamwise component deviates from this law presenting significant skewness. Finally, a statistical analysis of the flow in the near field around the particles reveals that particle wakes present two regions, a near wake where the velocity deficit decays as x^{-1} and a far wake with a decay of approximately x^{-2}.

1. Introduction

Fluid flow with suspended solid particles is encountered in a multitude of natural and industrial systems. Examples include the motion of sediment particles in rivers, fluidized beds and blood flow. Despite the great technological importance of these systems our understanding of the dynamics of fluid–particle interaction is still incomplete at the present date. Recently, however, significant progress has been made based on data provided by new experimental methods as well as numerical simulations. While most past investigations of numerical type have been performed in the context of the point-particle approach, it has now become possible to simulate the motion of a considerable number of finite-size particles including an accurate description of the surrounding flow field on the particle scale (Pan and Banerjee, 1997; Kajishima and Takiguchi, 2002; Ten Cate et al., 2004; Uhlmann, 2008; Lucci et al., 2010, 2011). Although the complexity of these particle-resolved simulations (in terms of Reynolds number, number of particles and computational domain size) is still limited, new insight into the physics of fluid–particle systems is beginning to emerge from such studies.

Uhlmann (2008) has simulated turbulent flow in a vertically-oriented plane channel seeded with heavy spherical particles with a diameter corresponding to approximately 11 wall units at a solid volume fraction of 0.4%. The pressure-driven upward flow (at constant flow rate) was found to be strongly modified due to the particle presence, with increased wall-shear stress and strongly enhanced turbulence intensity. The average relative flow, corresponding to a Reynolds number (based on particle diameter) of approximately 135, lead to the establishment of wakes behind individual particles. Additionally, the formation of very large-scale, streak-like flow structures (essentially spanning the entire box-size), absent in corresponding single-phase flow, was observed. At the same time the dispersed phase did not exhibit any of the common signs of preferential concentration.

In the present study we are revisiting the same flow configuration of vertical particulate channel flow, expanding upon the previous analysis of Uhlmann (2008) by addressing several unanswered questions. First, we wish to determine the influence of the streamwise length of the computational domain upon the largest flow scales. For this purpose we have performed new simulations analogous to the ones conducted by Uhlmann (2008), but with twice the value of the original streamwise period, while keeping all remaining parameters unchanged.

Second, we intend to provide a more complete description of the turbulent fluid–particle interaction in vertical channel flow.

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To this end we have analyzed three aspects of the flow dynamics which had previously not been considered by Uhlmann (2008): Voronoi analysis of the spatial structure of the dispersed phase, analysis of particle acceleration statistics, and particle-conditioned averaging of the fluid flow field.

Voronoi analysis is a relatively recent addition to the arsenal of tools for the description of particles suspended in fluids (Monchaux et al., 2010). In the present flow configuration it turns out that this methodology provides a more sensitive measure of the particle phase geometry than previously employed criteria.

The statistical properties of particle acceleration have received increasing attention in recent years (Toschi and Bodenschatz, 2009). Since particle acceleration is (up to particle mass) equivalent to the resulting forces acting upon the particles, its analysis can be instrumental in understanding turbulence–particle interaction mechanisms. One application where the influence of turbulence upon particle acceleration statistics is believed to be of key importance is the growth of rain drops by collisions in atmospheric clouds (Warhaft, 2009). Modern experimental results on the acceleration of *finite-size* particles (Qureshi et al., 2007; Xu and Bodenschatz, 2008; Brown et al., 2009) have only started to emerge around the date of publication of the precursor paper (Uhlmann, 2008). Therefore, such an analysis was not carried out therein. Here we present a statistical analysis of particle acceleration/hydrodynamic forces, relating the findings to available experimental results.

Finally, the understanding of the interaction between solid particles and fluid turbulence does not seem complete without a statistical analysis of the flow in the near-field around the particles. In order to investigate the characteristics of particle-induced wakes and with the aim to provide data which might be useful for the purpose of two-phase flow modelling, we have undertaken a study of particle-conditioned averaging of the flow field. Reference data for fixed particles swept by (essentially) homogeneous-isotropic flow (Bagchi and Balachandar, 2004; Amoura et al., 2010) as well as wall-bounded shear flow (Wu and Faeth, 1994; Legendre et al., 2006; Zeng et al., 2010) is available and has been used for the purpose of comparison.

2. Computational setup

2.1. Numerical method

The numerical method employed in the current simulations is identical to the one detailed in Uhlmann (2005) which was already used for the previous simulations of vertical particulate channel flow by Uhlmann (2008). The incompressible Navier–Stokes equations are solved by a fractional step approach with implicit treatment of the viscous terms (Crank–Nicolson) and a three-step Runge–Kutta scheme for the non-linear terms. The spatial discretization employs second-order central finite-differences on a staggered mesh. The no-slip condition at the surface of moving solid particles is imposed by means of a specially designed immersed boundary technique (Uhlmann, 2005). The motion of the particles is computed from the Newton equations for linear and angular motion of rigid bodies, driven by buoyancy, hydrodynamic forces/torque and contact forces (in case of collisions). Since the suspension under consideration is dilute, collisions are treated by a simple repulsive force mechanism (Glowinski et al., 1999) formulated such as to keep colliding particles from overlapping non-physically. The same treatment is applied to particle–wall encounters. It should be noted that the employed computational grid is uniform and isotropic. The chosen grid width $\Delta x = \Delta y = \Delta z$ yields a particle resolution of $D/\Delta x = 12.8$, a resolution of the channel half-width of $h/\Delta x = 256$ and $\Delta x^{+} = 0.67$ in terms of wall units. Further information on our extensive validation tests and grid convergence can be found in Uhlmann (2005, 2008) and further references therein.

2.2. Flow configuration

Fig. 1 shows the flow configuration under consideration as well as the coordinate system. The plane channel is oriented vertically, x being the streamwise coordinate direction, y is the wall-normal (with the channel width equal to 2 h) and z the spanwise direction. Fluid flow is directed upwards (in the positive x direction), driven by a streamwise pressure-gradient. The bulk velocity u_b is maintained at a constant value, such that the Reynolds number based upon the bulk velocity, $Re_b = u_b h/\nu$, is imposed (cf. Table 1 for the values of the principal physical parameters). A large number ($N_p = 8192$) of monodispersed, rigid, spherical particles is suspended in the flow. The nominal terminal velocity of the particles (computed from an equilibrium of buoyancy force and standard drag force, Clift et al., 1978) is set equal to the bulk velocity of the fluid phase. Consequently, the average particle settling velocity obtained in the actual simulation is roughly zero. The chosen density ratio $\rho_p/\rho_f = 2.2077$ (where ρ_p, ρ_f are the particle and fluid densities) is comparable to the case of glass particles in water. The particle diameter D, approximately equal to 11 wall units, is comparable to the cross-sectional scales of buffer layer flow structures. Finally, Table 1 shows that the suspension is indeed dilute, with less than one half percent of solid volume fraction.

As can be seen from Table 2, the present simulation is performed in a computational domain which has twice the streamwise period as compared to Uhlmann (2008), while maintaining an identical small-scale resolution. The table also shows that an observation interval of approximately 90 bulk time units (defined

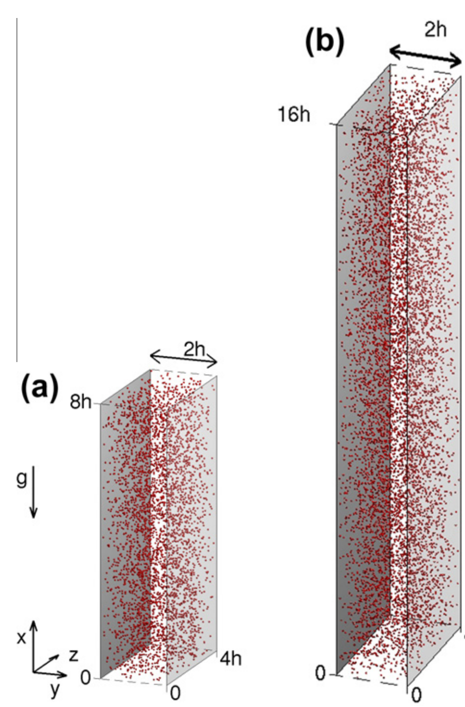

Fig. 1. Illustration of the computational domain, which is bi-periodic in the streamwise (x) and spanwise (z) directions. (a) shows the domain used in Uhlmann (2008), (b) the current domain which is a streamwise extension of the former (by a factor of two). The red spheres indicate actual instantaneous particle positions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)