European Journal of Mechanics / B Fluids 67 (2018) 54–64

Contents lists available at ScienceDirect

European Journal of Mechanics / B Fluids

journal homepage: www.elsevier.com/locate/ejmflu

The effect of polydispersity in a turbulent channel flow laden with finite-size particles

Walter Fornari [a,*], Francesco Picano [b], Luca Brandt [a]

[a] SeRC and Linné FLOW Centre, KTH Mechanics, SE-100 44 Stockholm, Sweden
[b] Department of Industrial Engineering, University of Padova, Via Venezia 1, 35131, Padova, Italy

ARTICLE INFO

Article history:
Received 27 January 2017
Received in revised form 19 June 2017
Accepted 2 August 2017
Available online 23 August 2017

Keywords:
Suspensions
Particle-laden flows
Particle/fluid flow

ABSTRACT

We study turbulent channel flows of monodisperse and polydisperse suspensions of finite-size spheres by means of Direct Numerical Simulations using an immersed boundary method to account for the dispersed phase. Suspensions with 3 different Gaussian distributions of particle radii are considered (i.e. 3 different standard deviations). The distributions are centered on the reference particle radius of the monodisperse suspension. In the most extreme case, the radius of the largest particles is 4 times that of the smaller particles. We consider two different solid volume fractions, 2% and 10%. We find that for all polydisperse cases, both fluid and particles statistics are not substantially altered with respect to those of the monodisperse case. Mean streamwise fluid and particle velocity profiles are almost perfectly overlapping. Slightly larger differences are found for particle velocity fluctuations. These increase close to the wall and decrease towards the centerline as the standard deviation of the distribution is increased. Hence, the behavior of the suspension is mostly governed by excluded volume effects regardless of particle size distribution (at least for the radii here studied). Due to turbulent mixing, particles are uniformly distributed across the channel. However, smaller particles can penetrate more into the viscous and buffer layer and velocity fluctuations are therein altered. Non trivial results are presented for particle-pair statistics.

1. Introduction

Particle laden flows are relevant in several industrial applications and many natural and environmental processes. Among these we recall the sediment transport in rivers, avalanches and pyroclastic flows, plankton in seas, planetesimals in accretion disks, as well as many oil industry and pharmaceutical processes. In most cases the carrier phase is a turbulent flow due to the high flow rates. However, due to the interaction between particles and vortical structures of different sizes the turbulence properties can be substantially altered and the flow may even be relaminarized. Additionally, particles may differ in density, shape, size and stiffness. The prediction of the suspension rheological behavior is hence a complex task.

Interesting and peculiar rheological properties can be observed already in the viscous and low-speed laminar regimes, and for suspensions of monodispersed rigid spheres. Depending for example on the shear rate and on particle concentration, suspensions can exhibit shear thinning or thickening, jamming (at high volume fractions), and the generation of high effective viscosities and normal stress differences [1–3]. More generally, due to the dispersed solid phase, the fluid response to the local deformation rate is altered and the resulting suspension effective viscosity μ_e differs from that of the pure fluid μ [4–7]. In laminar flows, when the particle Reynolds number Re_a becomes non negligible, the symmetry of the particle pair trajectories is broken and the microstructure becomes anisotropic. This leads to macroscopical behaviors such as shear-thickening and the occurrence of normal stress differences [8–10]. Recently, it was also shown that in simple shear flows, the effective viscosity μ_e depends non-monotonically on the system confinement (i.e. the gap size in a Couette flow). In particular, minima of μ_e are observed when the gap size is approximately an integer number of particle diameters, due to the formation of stable particle layers with low momentum exchange across layers [11]. Concerning plane Poiseuille flow in narrow channels and in the Stokes regime, Yeo and Maxey [12] found that the highest particle concentration is found at centerline. However, a particle layer is also found at the walls. Finally, in the Bagnoldian or highly inertial regime the effective viscosity μ_e increases linearly with shear rate due to augmented particle collisions [13].

When particles are dispersed in turbulent flows, the dynamics of the fluid phase can be substantially modified. Already in the transition from the laminar to the turbulent regime, the presence of the solid phase may either increase or reduce the critical

* Corresponding author.
E-mail address: fornari@mech.kth.se (W. Fornari).

http://dx.doi.org/10.1016/j.euromechflu.2017.08.003
0997-7546/

Reynolds number above which the transition occurs. Different groups [14,15] studied for example, the transition in a turbulent pipe flow laden with a dense suspension of particles. They found that transition depends upon the pipe to particle diameter ratio and the volume fraction. For smaller neutrally-buoyant particles they observed that the critical Reynolds number increases monotonically with the solid volume fraction ϕ due to the raise in effective viscosity. On the other hand, for larger particles it was found that transition shows a non-monotonic behavior which cannot be solely explained in terms of an increase of the effective viscosity μ_e. Concerning transition in dilute suspensions of finite-size particles in plane channels, it was shown that the critical Reynolds number above which turbulence is sustained, is reduced [16,17]. At fixed Reynolds number and solid volume fraction, also the initial arrangement of particles was observed to be important to trigger the transition.

For channel flows laden with solid spheres, three different regimes have been identified for a wide range of solid volume fractions ϕ and bulk Reynolds numbers Re_b [18]. These are laminar,turbulent and inertial shear-thickening regimes and in each case, the flow is dominated by different components of the total stress: viscous, turbulent or particle stresses.

In the fully turbulent regime, most of the previous studies have focused on dilute or very dilute suspensions of particles smaller than the hydrodynamic scales and heavier than the fluid. In the one-way coupling regime [19] (i.e. when the solid phase has a negligible effect on the fluid phase), it has been shown that particles migrate from regions of high to low turbulence intensities [20]. This phenomenon is known as turbophoresis and it is stronger when the turbulent near-wall characteristic time and the particle inertial time scale are similar [21]. In these inhomogeneous flows, Sardina et al. [22,23] also observed small-scale clustering that together with turbophoresis leads to the formation of streaky particle patterns [22]. When the solid mass fraction is high and back-influences the fluid phase (i.e. in the two-way coupling regime), turbulence modulation has been observed [24,25]. The turbulent near-wall fluctuations are reduced, their anisotropy increases and eventually the total drag is decreased.

In the four-way coupling regime (i.e. dense suspensions for which particle–particle interactions must be considered), it was shown that finite-size particles slightly larger than the dissipative length scale increase the turbulent intensities and the Reynolds stresses [26]. Particles are also found to preferentially accumulate in the near-wall low-speed streaks. This was also observed in open channel flows laden with heavy finite-size particles [27].

On the contrary, for turbulent channel flows of denser suspensions of larger particles (with radius of about 10 plus units), it was found that the large-scale streamwise vortices are attenuated and that the fluid streamwise velocity fluctuation is reduced [28,29]. The overall drag increases as the volume fraction is increased from $\phi = 0\%$ up to 20%. As ϕ is increased, turbulence is progressively reduced (i.e. lower velocity fluctuation intensities and Reynolds shear stresses). However, particle induced stresses show the opposite behavior with ϕ, and at the higher volume fraction they are the main responsible for the overall increase in drag [29]. Recently, Costa et al. [30] showed that if particles are larger than the smallest turbulent scales, the suspension deviates from the continuum limit. The effective viscosity alone is not sufficient to properly describe the suspension dynamics which is instead altered by the generation of a near-wall particle layer with significant slip velocity.

As noted by Prosperetti [31], however, results obtained for solid to fluid density ratios $R = \rho_p/\rho_f = 1$ and for spherical particles, cannot be easily extrapolated to other cases (e.g. when $R > 1$). This motivated researchers to investigate turbulent channel flows with different types of particles. For example, in an idealized scenario where gravity is neglected, we studied the effects of varying independently the density ratio R at constant ϕ, or both R and ϕ at constant mass fraction, on both the rheology and the turbulence [32]. We found that the influence of the density ratio R on the statistics of both phases is less important than that of an increasing volume fraction ϕ. However, for moderately high values of the density ratio ($R \sim 10$) we observed an inertial shear-induced migration of particles towards the core of the channel. Ardekani et al. [33] studied instead a turbulent channel flow laden with finite-size neutrally buoyant oblates. They showed that due to the peculiar particle shape and orientation close to the channel walls, there is clear drag reduction with respect to the unladen case.

In the present study we consider again finite-size neutrally buoyant spheres and explore the effects of polydispersity. Typically, it is very difficult in experiments to have suspension of precisely monodispersed spheres (i.e. with exactly the same diameter). On the other hand, direct numerical simulations (DNS) of particle laden flows are often limited to monodisperse suspensions. Hence, we decide to study turbulent channel flows laden with spheres of different diameters. Trying to mimic experiments, we consider suspensions with Gaussian distributions of diameters. We study 3 different distributions with $\sigma_a/(2a) = 0.02, 0.06$ and 0.1, being σ_a the standard deviation. For each case we have a total of 7 different species and the solid volume fraction ϕ is kept constant at 10% (for each case the total number of particles is different). We then consider a more dilute case with $\phi = 2\%$ and $\sigma_a/(2a) = 0.1$. The reference spheres have radius of size $a = h/18$ where h is the half-channel height. The statistics for all $\sigma_a/(2a)$ are compared to those obtained for monodisperse suspensions with same ϕ. For all ϕ, we find that even for the larger $\sigma_a/(2a) = 0.1$ the results do not differ substantially from those of the monodisperse case. Slightly larger variations are found for particle mean and fluctuating velocity profiles. Therefore, rheological properties and turbulence modulation depend strongly on the overall solid volume fraction ϕ and less on the particle size distribution. We then look at probability density functions of particle velocities and mean-squared dispersions. For each species the curves are similar and almost overlapped. However, we identify a trend depending on the particle diameter. Finally, we study particle-pair statistics. We find that collision kernels between particles of different sizes (but equal concentration), resemble more closely those obtained for equal particles of the smaller size.

2. Methodology

2.1. Numerical method

In the present study we perform direct numerical simulations and use an immersed boundary method to account for the presence of the dispersed solid phase [34,35]. The Eulerian fluid phase is evolved according to the incompressible Navier–Stokes equations,

$$\nabla \cdot \mathbf{u}_f = 0 \tag{1}$$

$$\frac{\partial \mathbf{u}_f}{\partial t} + \mathbf{u}_f \cdot \nabla \mathbf{u}_f = -\frac{1}{\rho_f}\nabla p + \nu \nabla^2 \mathbf{u}_f + \mathbf{f} \tag{2}$$

where $\mathbf{u}_f$, ρ_f, p and $\nu = \mu/\rho_f$ are the fluid velocity, density, pressure and kinematic viscosity respectively (μ is the dynamic viscosity). The immersed boundary force $\mathbf{f}$, models the boundary conditions at the moving particle surface. The particles centroid linear and angular velocities, $\mathbf{u}_p$ and $\boldsymbol{\omega}_p$ are instead governed by the Newton–Euler Lagrangian equations,

$$\rho_p V_p \frac{d\mathbf{u}_p}{dt} = \oint_{\partial \mathcal{V}_p} \boldsymbol{\tau} \cdot \mathbf{n}\, dS \tag{3}$$

$$I_p \frac{d\boldsymbol{\omega}_p}{dt} = \oint_{\partial \mathcal{V}_p} \mathbf{r} \times \boldsymbol{\tau} \cdot \mathbf{n}\, dS \tag{4}$$