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Channel flow of rigid sphere suspensions: Particle dynamics in the inertial regime

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ABSTRACT

We consider suspensions of neutrally-buoyant finite-size rigid spherical particles in channel flow and investigate the relation between the particle dynamics and the mean bulk behavior of the mixture for Reynolds numbers $500 \leq Re \leq 5000$ and particle volume fraction $0 \leq \Phi \leq 0.3$, via fully resolved numerical simulations. Analysis of the momentum balance reveals the existence of three different regimes: laminar, turbulent and inertial shear-thickening depending on which of the stress terms, viscous, Reynolds or particle stress, is the major responsible for the momentum transfer across the channel. We show that both Reynolds and particle stress dominated flows fall into the Bagnoldian inertial regime and that the Bagnold number can predict the bulk behavior although this is due to two distinct physical mechanisms. A turbulent flow is characterized by larger particle dispersion and a more uniform particle distribution, whereas the particulate-dominated flows is associated with a significant particle migration towards the channel center where the flow is smooth laminar-like and dispersion low. Interestingly, the collision kernel shows similar values in the different regimes, although the relative particle velocity and clustering clearly vary with inertia and particle concentration.

Introduction

Particles suspended in a carrier fluid can be found in many biological, geophysical and industrial flows. Some obvious examples are the blood flow in the human body, pyroclastic flows from volcanos, sedimentations in sea beds, fluidized beds and slurry flows. Moreover, the knowledge of the particle dynamics is relevant, among others, in biomechanical applications for extracorporeal devices and formation of clots. Suspensions are typically employed to transport and mix particles by means of a carrier fluid (Eckstein et al., 1977). The overall effect of particles on the flow dynamics has therefore a significant impact on the energy consumption of biological and industrial processes. Despite the numerous applications, however, it is still difficult to estimate the force needed to drive suspensions and the internal dissipation mechanisms are not fully understood, especially in a turbulent flow. Unlike single phase flows where the pressure drop can be accurately predicted as a function of the Reynolds number and the properties of the wall surface (roughness effects), additional parameters become relevant in the presence of a suspended phase when the properties of the particles (size, shape, density, stiffness, volume fraction, and mass fraction) affect the overall dynamics of the suspension. The behavior of these multiphase flows becomes even more complicated when the particle volume fraction is high, inertial effects are non-negligible and particles have finite size, i.e. size of the order of the relevant flow structures (Campbell, 1990).

In this study we focus on non-colloidal suspensions, mixtures where the dispersed particles are greater than colloidal in size and thermal fluctuations are negligible. As Brownian motion is negligible there is no diffusion to create an equilibrium structure making the problem one of fundamental non-equilibrium physics. The aim of this study is to gain physical understanding of the role of the fluctuations induced by the suspended phase and their coupling to the mean flow, the effect of particle inertia and the modifications of the particle interactions when increasing the (bulk flow) Reynolds number. As shown also here, it is fundamental to examine the local particle concentration, migration and segregation for a full comprehension of the transport processes at work. Inhomogeneities in the particle distribution are documented at low and finite Reynolds numbers, e.g. the so-called Segre–Silberberg effect (Segré and Silberberg, 1961). Here we document how the interactions between the turbulent flow structures and particle-induced disturbances alter the macroscopic flow behavior.

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Only a few studies have been devoted to the inertial flow of suspensions in the presence of finite size particles. Matas et al. (2003) performed experiments with a suspension of neutrally buoyant particles in pipe flow and defined the laminar and turbulent regimes according to the spectra of the pressure fluctuations between the inlet and exit of the pipe. The critical Reynolds number separating the existence of the two regimes exhibits a non-monotonic behavior with the volume fractions for large enough particles. This result is partially reproduced by the numerical simulations in Yu et al. (2013). Since velocity fluctuations exist at all Reynolds numbers, these authors choose the streamwise velocity perturbation kinetic energy as the criterion to distinguish between laminar and turbulent flow. A more detailed study on the transition of finite-size particle suspensions is performed by Loisel et al. (2013) for a fixed volume fraction of about 5%. The observed reduction of the critical Reynolds number is explained by the breakdown of the coherent flow structures to smaller and more energetic eddies, which prevents the flow relaminarization when decreasing the Reynolds number. The characteristics of a fully turbulent channel flow laden with finite-size particles are presented in Picano et al. (2015), such as the decrease in the Von Karman constant with increasing volume fraction and the increase in the overall drag.

The present work extends the analysis of Lashgari et al. (2014) on the inertial flow of suspensions of finite-size neutrally buoyant spherical particles. In this previous study, we document the existence of three different regimes when varying Reynolds number, *Re*, and particle volume fraction, Φ. A laminar-like regime where viscous stress exhibits the strongest contribution to the total stress, a turbulent-like regime where the turbulent Reynolds stress mainly determines the momentum transfer across the channel (see also Picano et al., 2015) and a third regime, denoted as inertial shear-thickening, characterized by a significant enhancement of the wall shear stress that is not due to an increment of the Reynolds stress but due to the strong contribution of the particle stress. In the present work, we move our attention from the bulk flow behavior to the local behavior by studying in detail the particle dynamics, single and pair particle statistics. In particular, we examine the particle local volume fraction, dispersion coefficients and collision kernels for the three regimes introduced in Lashgari et al. (2014). Our dataset is based on fully resolved numerical simulations of the two-phase system.

We aim to connect our results to the seminal work by Bagnold (1954). Using experimental data of a suspension of neutrally buoyant solid particles in an annular domain between two concentric cylinders, Bagnold understood that the shearing of closely spaced particles would generate a normal or dispersive stress in addition to the shear stress (Hunt et al., 2002). He used the ratio between the grain inertia and the viscous stress to define different flow regimes. The viscous and inertial regimes introduced by Bagnold are characterized by a linear and quadratic relation between the wall shear/normal stress and the shear rate, respectively. Inspired by Bagnold's experiment, Fall et al. (2010) performed a similar study in plane Couette flow; these authors show a smooth transition from the Newtonian (viscous) to the Bagnoldian (inertial) regime by increasing the shear-rate. The laminar flow at high volume fractions behaves similarly to dry granular flows (Campbell, 1990): the flow experiences discontinuous shear-thickening and fast particle migration toward the regions of low shear. Both effects (shear-thickening and particle migration towards region with low shear) have been observed in several previous investigations of dense suspensions at low Reynolds number, see Hampton et al. (1997), Brown and Jaeger (2009) and Yeo and Maxey (2011) among others. Shear-thickening at higher volume fractions is examined among others in Haddadi and Morris (2014) who clearly identify the role of friction among particles in relative motion. The origin of shear-thickening at lower volume fractions and in the presence of non-negligible inertia is attributed to an additional excluded volume, i.e., the shadow region behind each particle where it is very unlikely to find a second particle, see Picano et al. (2013). The effective volume fraction of the suspension increases because of the shadow region (a region with statistically vanishing relative particle flux) around the particles. Particle migration across the channel is not an inertial effect and is observed also in Stokes flow at high volume fractions (Yeo and Maxey, 2011). The particles tend to migrate from regions of high to low shear due to the imbalance of the normal stress resulting from the particle interactions (Guazzelli and Morris, 2011).

Less is known of the inertial Bagnoldian regime. It is worth mentioning that, for the same bulk behavior, the Bagnoldian regime can be either Reynolds stress or particle stress dominated, as deduced from the data in Lashgari et al. (2014). This finding motivated the present study where we focus on the particle dynamics to understand the two different underlying physical mechanisms.

Understanding the dynamics of particle dispersion and collisions, especially when the particle inertia is non-negligible and the suspension is not dilute, is therefore important due to their direct connection to the flow bulk properties, as also demonstrated in this study. The mutual and hydrodynamic interactions between the particles produce irregular motions, promote lateral migration from the instantaneous average particle trajectories and induce dispersion (for more details see Eckstein et al., 1977; Breedveld et al., 1998; Sierou and Brady, 2004). As an example, we report in Fig. 1 the instantaneous particle distribution for two different regimes: (i) a turbulent flow where transport is mainly determined by the Reynolds stresses and (ii) a shear-thickening flow dominated by the particle stress. Note that the wall normal direction is amplified by a factor 5 for the sake of clarity and the particle colors represent the magnitude of their translational velocities. We note a uniform concentration for the turbulent-like flow (left panel) and an accumulation towards the channel center for the flow dominated by the particle stress (right panel) that will be quantified and analyzed in this paper.

Particle collisions are also relevant to the total momentum transfer and can be estimated from the relative position and velocity of the particle pairs (Sundaram and Collins, 1997): these can be directly connected to the particle diffusivity in the cross-stream direction and to accumulation in specific regions (Cunha and Hinch, 1996; Reade and Collins, 2000; de Motta et al., 2012). The opposite is true for Brownianan suspensions where the particle concentration variation arises from gradient-induced diffusivity (Breedveld et al., 1998), and finite-size effects are less important. In this work we show a strong shear-induced self-diffusivity at high particle volume fractions which is not dependent on the Reynolds number and plays an impor-

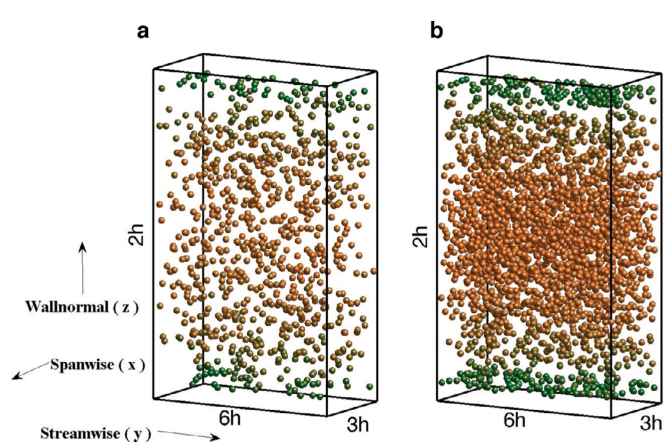

Fig. 1. The instantaneous particle arrangement for (a) a turbulent-like flow, $Re = 5000$ & $\Phi = 0.1$, and (b) a particle-stress dominated flow, $Re = 2500$ and $\Phi = 0.3$. The streamwise and spanwise coordinates and particle diameters are shown at their actual size, however the wall normal coordinate is stretched for a better visualization. The particle diameter is equal to $h/5$. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)