PhD Thesis: Modulation of wall-bounded turbulent flows by large particles: effect of concentration, inertia, and shape

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The effect of particles on turbulence is a key phenomenon in many practical industrial applications encountered in petroleum engineering, chemical reactors and food or solid processing (transport of slurries in pipes, reactive fluidized beds, and pneumatic transport of particles), environmental engineering (such as sand storm and Particulate Matter (PM) Pollution), and biological fluid mechanics (e.g. drug delivery in blood flow and inhaled particles through the respiratory system). The experiments of Matas et al. (2003) have highlighted the non-monotonous effect of neutrally buoyant particles on the laminar-turbulent flow transition, depending on the particle-to-pipe size ratio and on the suspension volumetric concentration. A small amount of finite size particles allowed sustaining the turbulent state and decreasing the transition threshold significantly. The complex mechanisms related to particle flow interactions are often difficult to elucidate experimentally. During the last 4 decades, direct numerical simulations have proven to be a powerful tool for understanding the features of single-phase turbulent flows. Currently, it starts to play an important role in the investigation of suspension flows as well. Almost a decade after the experiments of Matas et al. (2003), particle-resolved numerical simulations are able to evidence that at moderate concentration, particles have a significant impact on the unsteady nature of the flow, enhancing the transverse turbulent stress components and modifying the flow vortical structures (Loisel et al. 2013; Yu et al. 2013; Lashgari et al. 2015).

In this work, we use particle-resolved numerical simulations to understand the effect of finite sized particles on wall-bounded (pressure-driven or plane Couette) turbulent flows, slightly above the laminar-turbulent transition limit. We focus on the unsteady flow features, trying to correlate them with the local particle distribution. For this purpose, we use simulation domains that contain a minimal set of coherent flow structures, sufficient to sustain the flow turbulence. The fluid flow and particle motions are coupled using the Force Coupling Method (FCM) approach. This method is based on a low-order, finite force multipole representation of the particles in the fluid flow (Maxey 2017). The scheme is further extended to moderately inertial and ellipsoidal particles. A repulsive potential model is used to prevent overlapping between particles under dilute to moderately concentrated regimes. Low grid resolution per particle diameter ($d/\Delta x\sim 6$) makes this method advantageous when compared to other fictitious domain methods ($d/\Delta x>12$). The study particularly investigates the effect of concentration and particle size on the mixture flow features. The particles are neutrally buoyant in most of the cases. The effect of particle-to-fluid density ratio is considered in some flow configurations, while gravity effect is always neglected.

In turbulent Couette flow, wall-normal profiles of the flow velocity and Reynolds stress components reveal that there is no significant difference between single phase and two-phase flows at equivalent effective Reynolds number, except that the wall shear stress is higher for the two-phase flow. Spherical particles have a negligible effect on both the intensity and intermittency of the Reynolds stress. However temporal and modal analysis of flow fluctuations, suggest that besides increasing small scale perturbation due to their rigidity, particles have an effect on the regeneration cycle of turbulence (streak formation, streak breakdown and streamwise vortex regeneration). Indeed, the shape of the streaks and the intermittent character of the flow (amplitude and period of
oscillation of the modal fluctuation energy) are all altered by the particle presence, and especially by the inertial particles (Wang et al. 2017). Nevertheless in channel flow, neutrally-buoyant spherical particles enhance the intensity of the Reynolds stress although the frequency of burst events is decreased (see fig. 1). Particles enhance the lift-up effect and act continuously within the buffer layer (0<y<40). Moreover, they increase the vorticity stretching, leading to smaller and more numerous wavy streaks for suspension flows compared to the single-phase configuration.

Furthermore, we investigate the behavior of suspensions with oblate and prolate particles (aspect ratio <1 and >1 respectively) in turbulent plane Couette flow configuration. The flow statistics correspond to a compromise between spherical suspension flow statistics at equivalent concentration, with a size ranging from the minor to the major axis of particles. However, the particle distribution in the flow cross-section is dependent on the particle shape. The prolate particle distribution is similar to the case of spherical particles in the Couette gap, whereas the local volume fraction of oblate particles is considerably increased in the flow ejection region close to the wall, where their axis of symmetry is mostly oriented in the spanwise direction (see fig. 2).

![Fig 1](image1.png)

**Fig 1:** Temporal and wall-normal evolution of the Reynolds shear stress in Couette (left) and channel (right) flows. (a) and (b) are for single-phase flow. (c) and (d) are for two-phase flow. The ratio between the particle diameter and the gap between walls is 1/20 and the solid volumetric concentration is 5%.

![Fig 2](image2.png)

**Fig. 2:** Instantaneous particle distribution and orientation projected on the transverse plane of a Couette flow. Colors represent the fluid velocity and particle tumbling rate. Left and right panels show respectively prolate (Ar=2, Ly/d(minor)=20), and oblate (Ar=0.5, Ly/d(minor)=20) particles, at a solid volumetric concentration of 2.5%.
REFERENCES