FLOW REGIMES OF INERTIAL SUSPENSIONS OF FINITE SIZE PARTICLES

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Abstract Inertial regimes in a channel flow of suspension of finite-size neutrally buoyant particles are studied for a wide range of Reynolds numbers: $500 \leq Re \leq 5000$, and particle volume fractions: $0 \leq \Phi \leq 0.3$. The flow is classified in three different regimes according to the phase-averaged stress budget across the channel [2]. The laminar viscous regime at low Re and Φ where the viscous stress is the dominating term in the budget, the turbulent regime at high Re and relatively low Φ where the momentum is mainly transferred by the action of the Reynolds stress and the inertial shear-thickening regime where the particle stress contributes the most to the significant enhancement of the wall shear stress. Particle distribution and dispersion properties provide additional evidence for the existence of the three different regimes.

INTRODUCTION

Inertial suspensions of finite-size particles are almost everywhere from natural flows such as pyroclastic flows and sedimentation transport in rivers, to industrial flows like slurry transports and fluidized beds. In this work, we study inertial suspensions of neutrally buoyant finite-size particles in a channel. A Navier-Stokes solver togheter with an immersed boundary method is employed to evolve fluid and particles which are mutually coupled by direct forcing and near-field interactions (lubrication corrections and soft sphere collision model) [1]. The flow is simulated in a pressure-driven channel with streamwise and spanwise periodic boundary conditions. The box size is $2h \times 3h \times 6h$ in wall normal, spanwise and streamwise directions where h is the channel half width. The particle radius is fixed to $R/h = 1/10$ corresponding to the a value where a strong non-monotonic behaviour of the transitional Reynolds number as a function of particle volume fraction is observed in the experiment on particulate pipe flow in [3]. The simulations are performed at constant mass flux with a high amplitude initial localized disturbance to trigger turbulence and random initial arrangement of the particles.

PHASE DIAGRAM

We study channel flow of finite-size particle suspension over a wide range of Reynolds numbers $Re = 2hU_b/\nu$, $500 \leq Re \leq 5000$, and particle volume fractions, $0 \leq \Phi \leq 0.3$. In figure 1 we display the contour of the box-averaged root mean square (rms) of the streamwise velocity fluctuation in the $Re - \Phi$ plane (the mixture of the fluid and particle velocities is used to calculate the rms velocity). At low Φ, we observe a sharp transition between the laminar and turbulent regimes once above a certain threshold. However, at high Φ the level of fluctuations increases smoothly when increasing the Reynolds number between the laminar and turbulent regimes. The non-monotonic behaviour of the fluctuations is evident in the figure in agreement with the experimental findings. By phase average, one can show that the total stress in the

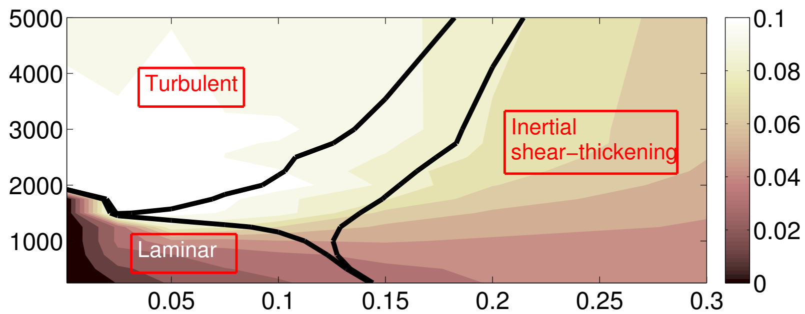

Figure 1. Contour of ensemble-averaged rms of streamwise velocity fluctuations. The black lines represent the boundaries where the contribution of each term in the stress budget is more than 50%

channel flow consists of 3 terms: Reynolds stress, viscous stress and particle stress, which together balance the wall shear stress at the wall (see for the derivation and formulation in the appendix of Picano *et.al.* [4]). The laminar, turbulent and inertial shear-thickening regimes are introduced in [2] considering the individual largest contribution to the total stress. We report in the figure with solid black lines the boundaries where the contribution of the each term is more than 50%

(absolute majority). The regime at high Φ is denoted by initial shear-thickening: here a significant enhancement in the wall shear stress is caused by the particle stress and not by the increment in Reynolds stress. The three regimes coexist everywhere with different relative relevance.

PARTICLE DISPERSION

The bulk behavior of the flow in the different regimes can be directly connected to the dynamics of the particles. Here we examine the dispersion of the particles for different flow cases corresponding to the different regimes. In figure 2 we show the spanwise mean square particle displacement, defined as $< \Delta x^2(\Delta t) > /R^2 =< [x_p(t+\Delta t) - x_p(t)]^2 >_{p,t} /R^2$, where $x_p(t)$ is the spanwise trajectory of the particles and $<>_{p,t}$ indicates the average over time and the number of the particles. For all the cases studied, we observe a quadratic behavior at early times, followed by a linear behavior of dispersion. Initially the particle velocity remains strongly correlated implying a displacement proportional to Δt, i.e. $< \Delta x^2 > \propto \Delta t^2$. At longer time, the trend changes and we find a classical diffusive behavior which is induced by particle-particle and hydrodynamic interactions that de-correlate the trajectory of the particles. The slope of the linear part determines the dispersion coefficient in the spanwise direction. The case of $Re = 500$ and $\Phi = 0.05$ represents the laminar regime where the particle dispersion is the lowest (high particle correlations). The case of $Re = 5000$ and $\Phi = 0.1$ represents the turbulent regime where the chaotic flow strongly affects the particle trajectories and dispersion is significantly high. Note that similar values of the mean square displacement are obtained for the other laminar and turbulent flows studied. The inertial shear-thickening cases are shown by the green symbols; the dispersion at low Reynolds number, $Re = 500$, is slightly higher than that of the laminar regime and increases smoothly by increasing the Reynolds number, yet considerably lower than that of the turbulent regime even at the highest Reynolds number examined, $Re = 5000$ (The green arrows indicate the range of variation of the mean square displacement for all the inertial shear-thickening cases). This behavior suggests that cases belonging to different regimes can share the same amplitude of wall shear stresses (effective viscosity), but present very different behaviors as concerns the particle dispersion because the underlining physics are different.

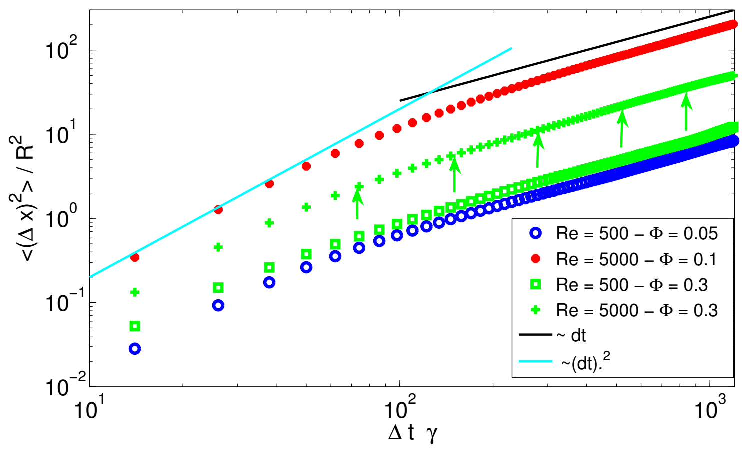

Figure 2. Mean square displacement of the particle position in the spanwise direction, $< \Delta x^2(\Delta t) > /R^2$, versus time normalized by $\gamma = U_b/h$.

The analysis of the particle dynamics such as single (particle dispersion) and pair particle statistic (not shown here), provides further evidence for the existence of the three different regimes in the inertial flow of particle suspensions identified in [2] using the two-phase stress budget.

References

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