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Letter

Transition and self-sustained turbulence in dilute suspensions of finite-size particles

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ABSTRACT

We study the transition to turbulence of channel flow of finite-size particle suspensions at low volume fraction, i.e., $\Phi \approx 0.001$. The critical Reynolds number above which turbulence is sustained reduces to $Re \approx 1675$, in the presence of few particles, independently of the initial condition, a value lower than that of the corresponding single-phase flow, i.e., $Re \approx 1775$. In the dilute suspension, the initial arrangement of the particles is important to trigger the transition at a fixed Reynolds number and particle volume fraction. As in single phase flows, streamwise elongated disturbances are initially induced in the flow. If particles can induce oblique disturbances with high enough energy within a certain time, the streaks breakdown, flow experiences the transition to turbulence and the particle trajectories become chaotic. Otherwise, the streaks decay in time and the particles immigrate towards the channel core in a laminar flow.

Understanding the characteristics of suspension flows is of fundamental and practical importance in natural phenomena, e.g. particles in the atmosphere and water, and industry, e.g. transportation and mixing. The focus of this paper is therefore on the transition from the laminar to the turbulent flow of dilute suspensions of finite-size particles, particles larger than the smallest flow scales, a process associated to a significant (usually sudden) alteration of the nature of the flow. Although the dynamics is governed by a single non-dimensional parameter—the Reynolds number, the ratio of inertia to viscous forces, transition of single phase flows has challenged the scientists for a long time and it is not yet completely understood. The behavior of suspensions is more complicated because of the various particle properties such as size, number, shape, deformability, density.

To the best of our knowledge, there exist only few studies of the transition to turbulence of suspensions of finite-size particles (for the case of point particles the reader is referred to Ref. [1] and references therein). The experiments by Matas et al. [2] examine the effects of finite-size neutrally buoyant particles on the transition in pipe flow. These authors report that suspensions of large particles exhibit a non-monotonic behavior of the critical Reynolds number when increasing the particle volume fraction. The different regimes are identified by the pressure drop between the inlet and outlet of the pipe. A decade later and thanks to the improvement of computational algorithms and resources, numerical simulations of finite-size particle suspensions start to emerge. Yu et al. [3] partially simulate the experiments in Ref. [2]. Since the flow is always perturbed by the presence of the particles, the level of streamwise velocity fluctuations is used to define a threshold to distinguish between laminar and turbulent flow. The experimental behavior in Ref. [2] could be reproduced by tuning this threshold parameter, showing the difficulties to define the transition threshold in suspensions. A more detailed analysis of the flow in the transitional regime is reported by Loisel et al. [4] where a fixed particle volume fraction is examined, $\Phi \approx 5\%$. These authors show that the coherent structures of the flow are broken by the presence of finite size particles and smaller eddies (more energetic) prevents the flow from relaminarization when decreasing the Reynolds number; this effect promotes therefore turbulence.

Summarizing, transition delay is attributed to the enhancement of the effective viscosity of the suspensions for smaller particles [2], whereas promotion of transition is, instead, qualitatively attributed to large disturbances induced by particles of large enough size.

Recently Lashgari et al. [5] studied suspensions of spherical neutrally buoyant particles for a wide range of Reynolds numbers, Re, and box-averaged volume fractions, Φ. These authors examine

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the global momentum balance [6] and report the existence of three different regimes when varying Φ and Re. For low Φ and Re, the flow is laminar and the viscous stress dominates. For high Re and sufficiently low Φ, the flow is turbulent and the Reynolds stress contributes the most to the momentum transport as in classic single-phase turbulence. The flow is dominated by the particle stress at moderate Φ.

For the cases at low Φ, transition is sharp when increasing the Reynolds number and can be easily identified, e.g. by the level of fluctuations and wall shear stress; at high Φ, however, all the observables vary smoothly with Re. The latter case is denoted as inertial shear-thickening since it is characterized by a significant increase of the wall friction that is not attributed to an increase of the Reynolds stress but to the enhancement of the particle-induced stress.

The aim of this letter is to examine the reduction of the critical Reynolds number above which turbulence exists in very dilute suspensions of finite size particles. We study in details the mechanism behind the transition promotion and relate this to self-sustained turbulence by analyzing the kinetic energy induced by the particles and transferred from small scales to large scales.

We perform direct numerical simulation of suspensions laden with rigid spherical neutrally buoyant particles. We employ an immersed boundary solver based on the original formulation by Uhlmann [7] and developed by Breugem [8]. The code couples a fixed uniform Eulerian mesh for the fluid phase with a quasi-uniform Lagrangian mesh representing the surface of the particles. The fluid velocity is interpolated on the Lagrangian grids, the immersed boundary forcing is computed based on the difference between the particle velocity and the interpolated fluid velocity at each Lagrangian grid point and finally the forcing spread out from the Lagrangian to the Eulerian mesh. The near field interactions are treated by means of lubrication forces and soft-sphere collision models. The code has been validated against several test cases in Refs. [5,8].

We simulate the flow in a pressure-driven channel flow with streamwise and spanwise periodic boundary condition and no slip condition at the walls. The box size is $2h \times 3h \times 6h$ in the wall-normal, spanwise, and streamwise directions where h is the half channel height. The domain is larger than the minimal unit channels used for transition in Newtonian fluids [9] and polymer suspensions [10]. The number of Eulerian grid points is $160 \times 240 \times 480$ with 746 Lagrangian points used to resolve the surface of each particle. The ratio between the channel height and particle diameters is fixed to 10 (with 16 grid points per particle diameter). The particle diameter is that pertaining the case in the experiment [2] where the strongest non-monotonic behavior of the critical transition threshold is observed. We denote streamwise coordinate and velocity by v and y, wall normal by w and z, and spanwise by x and u. The simulations are performed imposing a constant mass flux, with the bulk velocity denoted by U_b. The Reynolds number is defined as $Re = 2U_b h/\nu$ where ν is the fluid kinematic viscosity. In order to calculate the characteristics of the two-phase flow, a phase field indicator (mask), ξ, is created for the total field such that $\xi = 1$ indicates the solid phase and $\xi = 0$ the fluid phase. The parameters of the fluid phase, e.g. root mean squared (rms) velocities, are then obtained by taking average over all the Eulerian points with $\xi = 0$ and similar for the particle phase with $\xi = 1$.

In this work, we study the transition and self-sustained turbulence in a channel flow laden with few finite-size neutrally-buoyant particles (dilute regime) and compare the results with the one of the single-phase (Newtonian) flow. We use only 10 particles corresponding to a particle volume fraction $\Phi \approx 0.001$.

It is known that the transition threshold in Poiseuille flow depends on the initial disturbance; one strategy to obtain the threshold for sustained turbulence is to decrease the Reynolds number of the turbulent flow until the flow re-laminarizes (see among others [11,12]). For the single phase flow, we use as initial disturbance high amplitude localized stream-wise vortices, see Ref. [13] for the analytical expression of the disturbance velocity field. The time histories of the streamwise rms perturbation velocity of the unladen flow are depicted in Fig. 1(a). Note that the rms velocities are normalized by U_b and time in units of h/U_b. The critical Reynolds number is found to be $1750 < Re_c < 2000$ for this particular flow domain and a maximum wall normal velocity of the initial disturbance equal to 10 times of the bulk velocity; fluctuations are sustained at $Re = 2000$ but they decay and eventually vanish at $Re = 1750$. In the next step, we initiate the simulations with a turbulent velocity field at $Re_b = 2000$, decrease the Reynolds number to 1800 and run the simulation for a long time: the fluctuations remain and therefore the threshold value of the sustained turbulence of the unladen flow is identified approximately, $Re_c \approx 1775$.

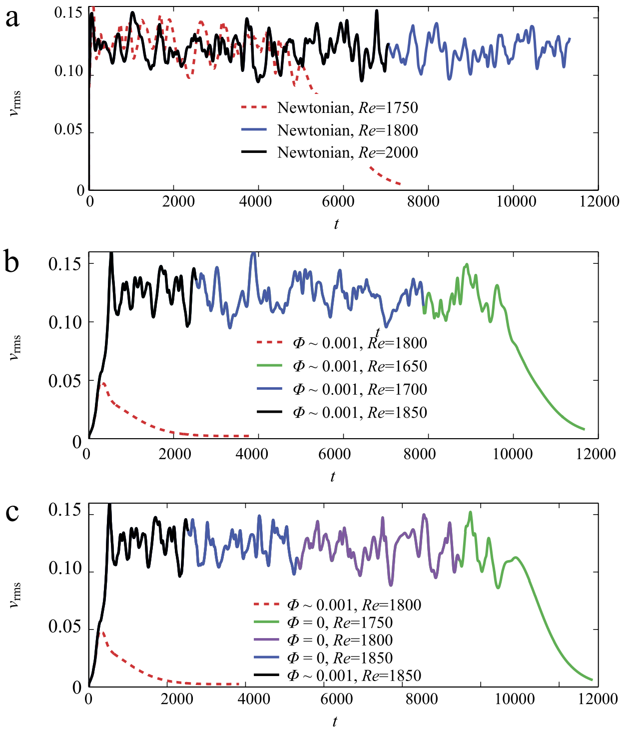

Fig. 1. (Color online) Time history of the streamwise velocity fluctuations for (a) Newtonian flow and (b, c) two different paths in particle laden flow (See text).

The initial condition for the particle-laden flow is given by a random arrangement of the particles, all moving with the local fluid velocity and initial angular velocity equal to half the value of the local vorticity. The initial disturbance source is due to the flow adjustments to the particle presence and therefore depends on the particle position. We initially keep the same initial condition and run simulations at different Reynolds numbers. We observe that the fluctuations, induced by the particles, eventually decay at $Re < 1800$ while they grow to the turbulent regime at $Re > 1850$ (see the fluid streamwise rms velocity in Fig. 1(b)). Note that the initial particle arrangement strongly affects the disturbance growth and transition. Therefore, the threshold value of $1800 < Re_c < 1850$ is only valid for this particular initial configuration; a different behavior is most likely to be observed with another random initial distribution. We will come back to this point when we analyze the trajectory of the particles. As for the unladen flow, we therefore reduce the Reynolds number of the particulate turbulent flow and monitor the Reynolds number at which flow re-laminarizes. The results in the figure reveal that turbulence is sustained at $Re = 1700$ while it decays at $Re = 1650$. Based on these set of simulations, the critical value for sustained turbulence in the