SETTLING OF FINITE-SIZE PARTICLES IN ISOTROPICALLY FORCED, HOMOGENEOUS TURBULENCE: INTERFACE-RESOLVED SIMULATIONS

Agathe Chouippe, Todor Doychev & Markus Uhlmann
Institute for Hydromechanics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Abstract We have simulated the gravity-induced settling of finite-size particles in a turbulent background flow which is forced in a statistically-stationary fashion. The simulations are accurately resolving the solid-fluid interface with the aid of an immersed boundary technique [4]. The parameters of the simulation are (apart from background turbulence) identical to those of reference [5], where particle clustering was observed at a Galileo number of 178 and a solid volume fraction of 0.005. In the present case, it is found that a relative turbulence intensity of 0.24 leads to the disappearance of the clusters; as a consequence, the increase in average particle settling velocity found in [5] also vanishes.

INTRODUCTION

Dilute suspensions of finite-size settling particles tend to form wake-induced agglomerations at settling Reynolds numbers of a few hundred [5, 3]. The mechanism is believed to be linked to the reduced drag force that a particle experiences when it is located in the wake region of another particle, which leads to an approaching motion and subsequent close interaction between the particle pair ("drafting-kissing-tumbling", [2]). In the many-particle case considered in [5, 3], clustering occurs in the form of elongated column-like structures with a strong impact upon the average settling velocity (by 12% in [5]). It was shown that the effect is due to a large fraction of particles residing inside the fast-settling fluid regions (i.e. the agglomerations), where they settle relative to their immediate surroundings at a rate which is similar to the one of a single sphere in ambient fluid. In other words, the increased average settling velocity is due to the increase in the settling rate of the cluster region as a whole.
The question which we are addressing in the present contribution is the following: how does background turbulence affect the tendency of particles at intermediate Galileo numbers to cluster? For this purpose we have performed interface-resolved simulations analogous to those in [5] with the addition of a large-scale momentum forcing term. The turbulence forcing procedure is random and time-correlated [1], it can be efficiently implemented in physical space, and – most importantly – it allows for stable integration in the presence of particles.

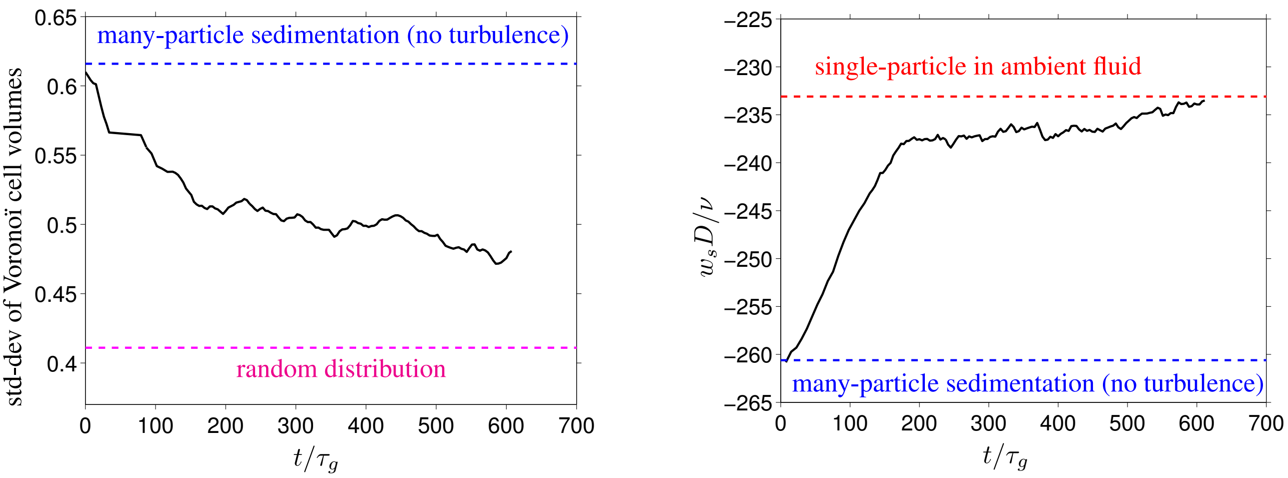

Figure 1. (a) Time evolution of the standard deviation of Voronoï cell volumes. The lower dashed line corresponds to the value of a random distribution of finite-size, non-overlapping spheres at the present volume fraction; the upper dashed line indicates the average value observed in [5] for the case of sedimenting spheres without background turbulence and otherwise identical parameters. (b) Average particle settling velocity w_s (shown in viscous scales) as a function of time. The lower dashed line indicates the average value observed in [5], while the upper one is for a single sphere settling in ambient fluid.

SETUP AND RESULTS

We consider a case with a solid-to-fluid density ratio of $\rho_p/\rho_f = 1.5$, a solid volume fraction $\phi_s = 0.005$, and a Galileo number of $Ga = 178$ (note that the Galileo number is defined as $Ga = u_g D/\nu$ with $u_g = \sqrt{(\rho_p/\rho_f - 1)|\mathbf{g}|D}$). These parameter values are identical to those of the strongly clustering case in reference [5]. The numerical parameters are also

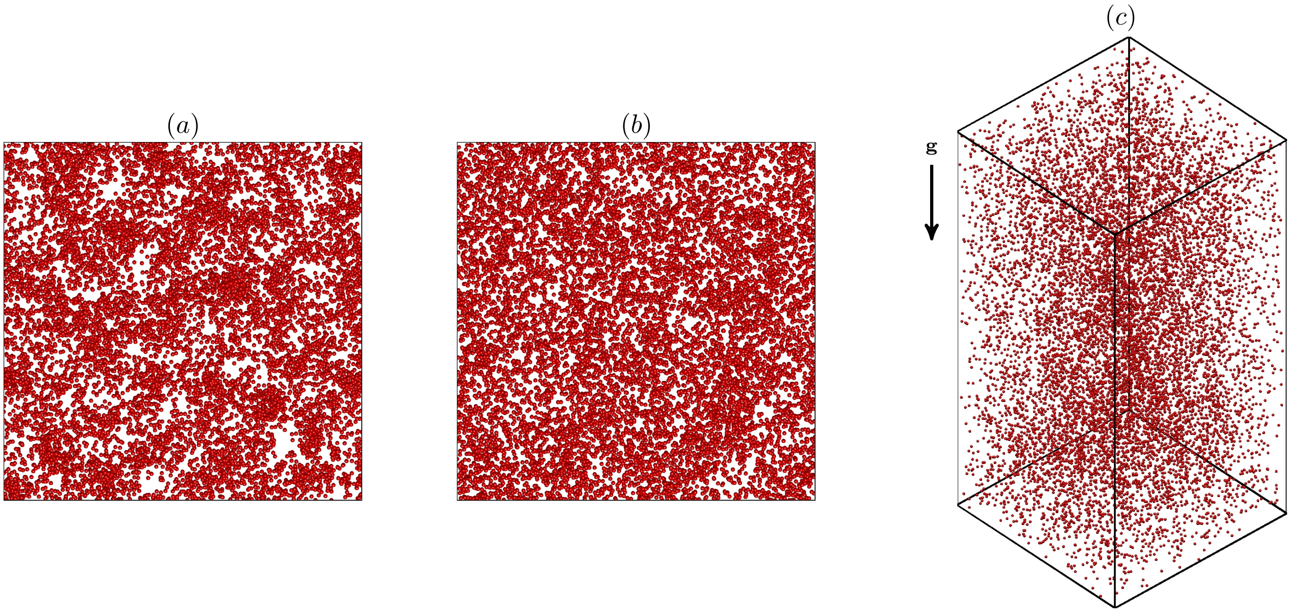

Figure 2. Particle positions at two instants during the current simulation. (a) Top view, showing the initial state ($t = 0$) which contains columnar clusters, as observed in [5]. (b) The same as (a), but towards the end of the simulation interval ($t/\tau_g = 513$). (c) The same instant as in (b), but showing a perspective view of the particle positions.

kept the same as in the latter reference; in particular, the domain size measures $85D \times 85D \times 170D$ and a resolution of 24 points per particle diameter is used. In the present simulation, the large-scale forcing is adjusted such that (in the absence of particles) we obtain a homogeneous-isotropic turbulent flow with the a Taylor micro-scale Reynolds number of $Re_\lambda = 140$ and a size ratio between the integral scale and the box size of $\mathcal{L}_{box}/L = 22$. In the particulate case, the length scale ratio between the particle diameter and the integral scale is $D/L_{int} = 0.26$, and the ratio with the Kolmogorov length is $D/\eta = 13$; the relative turbulence intensity in this case measures $u_{rms}/u_g = 0.24$.

The simulation is initialized with a flow field towards the end of the simulation without turbulent background flow [5] which features strong agglomerations. Once turbulence forcing is switched on, the spatial structure of the particle field is gradually modified, as can be seen in figure $1(a)$: the standard deviation of the cell volumes in Voronoï tesselations decreases with time, approaching the value of a random distribution of finite-size particles, i.e. the agglomerations disappear. Direct visualization of the particle field (such as the one in figure 2) suggests that the particle phase in the presence of turbulence is not randomly distributed, yet with a more intricate pattern than in the pure sedimentation case.

The impact upon the average particle settling velocity, $w_s = \langle w_p \rangle_p - \langle w_f \rangle_f$, can be seen in figure $1(b)$. It is obvious that background turbulence drives the average value close to the value of a single sphere settling in ambient fluid [6]. It should be noted that the present simulation covers a time interval of more than 20 integral time scales.

OUTLOOK

An additional simulation has been performed for the opposite problem: starting with an initially random particle distribution and background turbulence, then advancing in time. This cross-check yields analogous results, namely the absence of column-like clusters. Further analysis of the present data includes a more detailed investigation of the micro-structure of the flow field around the particles, as well as evaluation of the complete set of Eulerian and Lagrangian statistics.

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