SEDIMENTATION OF LARGE PARTICLES IN TURBULENT ENVIRONMENTS

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Abstract The aim of the present study is to investigate the sedimentation of large non-colloidal spherical particles in both quiescent and turbulent environments. To this aim, Direct Numerical Simulations are performed using an Immersed Boundary Method to account for the dispersed phase. The solid volume fractions considered are in the range $\phi = 0.005 - 0.010$, while the solid to fluid density ratio ρ_p/ρ_f is set equal to 1.02. The particle diameter is chosen to be approximately 12 Komlogorov lengthscales in nominal conditions. The results show that the mean settling velocities V_t decrease in the turbulent cases. The overall drag is increased both by the non-linear finite Reynolds number behavior and by unsteady effects, which are negligible in quiescent cases.

INTRODUCTION

Particle sedimentation is encountered in a wide number of applications and environmental flows. It is a process that usually involves a high number of particles settling in different environments. The suspending fluid can either be quiescent or turbulent, therefore involving eddies of different sizes. Particles themselves may differ in size, shape, density and deformability. Owing to the range of spatial and temporal scales generally involved, the interaction between the fluid and solid phases is highly complex and the global properties of these suspensions can be substantially altered from one case to another. Due to these complexities, our understanding of the problem is still incomplete.

The problem of particle sedimentation in turbulent environments was initially approached analytically. Maxey and Riley [4] proposed an equation for the motion of a single small rigid sphere settling in a non-uniform flow. In the derivation, the particle Reynolds number was assumed to be low so that the viscous Stokes drag for a sphere could be applied. The added mass and the unsteady viscous drag due to a Basset history term were also included.

In a turbulent flow the behaviour and motion of a particle does not depend only on its dimensions and characteristic response time, but also on the ratios among these and the characteristic turbulent length and time scales. The turbulent quantities usually considered are the Kolmogorov length and time scales which are related to the smallest eddies. Alternatively the integral lengthscale and the eddy turnover time can be used. Clearly, a particle smaller than the Kolmogorov lengthscale will behave differently than a particle larger than the smallest flow structures. Even more complexities are introduced when particle suspensions are considered. In these cases, hydrodynamic and steric interactions among particles must also be considered. This regime is usually described as four-way coupled [2].

In the last three decades the problem has been mostly investigated either experimentally or numerically. In most of the numerical studies small and heavy particles are considered, see [5] for an extensive review on the subject. Wang and Maxey [6] studied the settling of heavy particles in homogeneous isotropic turbulence. The particles Reynolds number based on the relative velocity was assumed to be much less than unity so that Stokes drag could be used. The authors showed that heavy particles smaller than the Kolmogorov lengthscale are often swept into regions of downdrafts (the so called preferential sweeping) and in doing so, the particles mean settling velocity is increased respect to the still fluid case. On the other hand, Good et al. [3] studied the settling of particles slightly larger than the Kolmogorov lengthscale both experimentally and numerically. They found a reduction in mean settling velocity respect to the still fluid case.

In the present study we perform direct numerical simulations to investigate the sedimentation of rigid spherical particles larger than the Kolmogorov lengthscale. The Immersed Boundary method originally developed by Breugem [1] is used to account for the presence of the solid phase. In order to generate and sustain an isotropic and homogeneous turbulent flow field a random forcing is added to the right hand side of the Navier Stokes equations. With this forcing we obtain a Reynolds number based on the Taylor microscale of 90 and a Kolmogorov lengthscale which is approximately $1/12$ of particle diameter. The solid to fluid density ratio is set equal to 1.02 while two solid volume fractions ϕ of 0.5% and 1% are considered. From these the Archimedes number $Ar = (\rho_p/\rho_f - 1)g(2a)^3/\nu^2$ (where g is the acceleration by gravity, a is the particle radius and ν is the kinematic viscosity) is found to be approximately 21000. A triperiodic computational box of size $32a \times 32a \times 320a$ in the x, y, z directions is chosen (where z is the direction aligned with gravity). The same simulations are also performed in still fluid to single out the effect of turbulence. The velocity of a single particle settling in a quiescent environment $|V_t|$ is used to normalize the computed mean settling velocities.

RESULTS

Once the turbulent flow field is fully developed, the particles are placed randomly in the computational domain with zero initial velocity and rotation. After a transient of approximately 10 eddy turnover times corresponding to about 40 particle relaxation times, statistics of the particle and fluid velocities are collected.

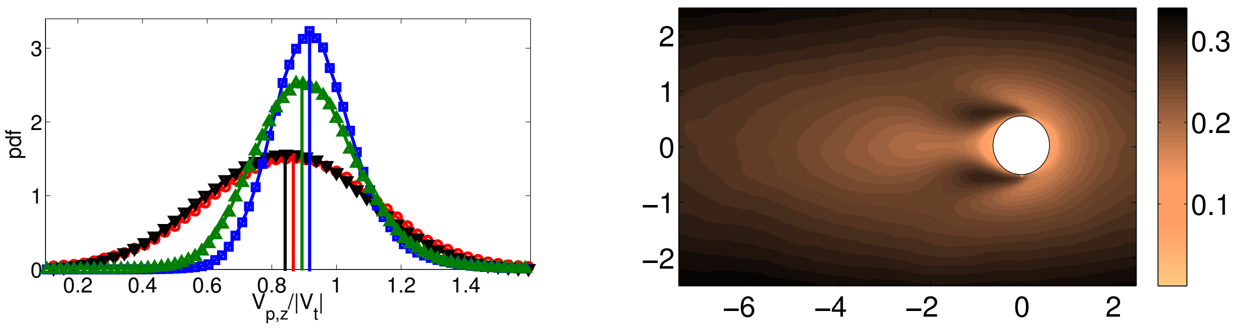

Figure 1. Panel (a): probability density functions of the particle velocity component aligned with gravity for the quiescent cases (blu line with squares for $\phi = 0.5\%$ and green line with upward-pointing triangles for $\phi = 1\%$), and for the turbulent cases (red line with circles for $\phi = 0.5\%$ and black line with downward-pointing triangles for $\phi = 1\%$). The velocities are normalized by the single-particle settling velocity $|V_t|$. Panel (b): isocontours of $U'_{rel,z}$ for $Ar = 21000$ averaged over time and the number of particles.

Comparing to a single particle sedimenting in free space, we find reductions of the mean settling velocities of about 6% and 8.5% in the quiescent cases for $\phi = 0.5\%$ and 1%, and 14.5% and 16% in the corresponding turbulent cases. Therefore in the turbulent cases particles tend to settle more slowly than the still fluid cases, especially at the smallest volume fraction considered. In figure (1a) we show the probability density functions of the particle velocities along the direction of gravity $V_{p,z}$. In the quiescent cases (blu line with squares for $\phi = 0.5\%$ and green line with upward-pointing triangles for $\phi = 1\%$) the probability density functions show a positive skewness indicating that it is more probable to find particles settling with higher and intense velocity than the mean. This is attributed to the interactions among wakes and incoming particles. As expected the velocity is reduced at higher volume fractions. In the turbulent cases (red line with circles for $\phi = 0.5\%$ and black line with downward-pointing triangles for $\phi = 1\%$) the probability density functions resemble more closely a Gaussian distribution. In a turbulent flow, the particle wakes are rapidly disrupted by a strong coupling between the flow around particles and turbulent fluctuations. These aspects are responsible for the overall reduction of their settling velocity.
Since the time-scale of the fluid velocity fluctuations is smaller than the particle response time (not reported here), a substantial amount of relative motion between the two phases is generated. The nonlinear component of the mean particle drag is estimated calculating the mean relative velocities $\vec{U}_{rel}$ and the corresponding drag coefficients from empirical expressions. Due to the drag non-linearity, appreciable upward forces can be produced on the particles thereby reducing the mean settling velocity. We find that in the turbulent cases the mean drag is further increased due to unsteady effects absent in the quiescent cases. In figure (1b) we show the fluctuations of $U_{rel,z}$ (normalized by $|V_t|$) averaged over time and the number of particles for the turbulent case with $\phi = 0.5\%$. Fluctuations due to vortex shedding can be clearly noticed, which are absent in the simulations in still fluid (figure not shown).
In the final contribution we will discuss the effect of density ratio and turbulence intensity on the sedimentation in turbulent flows.

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