INFLUENCE OF PREFERENTIAL CONCENTRATION ON THE SETTLING OF HEAVY PARTICLES IN HOMOGENEOUS TURBULENCE

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Abstract We analyze one-way and two-way coupling Direct Numerical Simulation (DNS) data of heavy particles settling in homogeneous turbulence. An extended range of particle Stokes numbers (St), Rouse numbers (R) and mass loading is considered. Influence of preferential concentration on the settling velocity enhancement is addressed from statistics of particle and flow field quantities conditioned on the local concentration by making use of Voronoï diagrams. Gravity is found to have almost no influence on the global characteristics of preferential concentration, while the conditional statistics evidence a refined preferential sampling of the flow field resulting from the gravitational effects. A 2D analysis of the Voronoï cells is also presented to investigate their shape and orientation with respect to gravity direction.

INTRODUCTION

The interest in turbulent flows laden with inertial particles has continuously increased in the last decade due to their many natural and industrial applications (engine and chemical reactors optimization, cloud physics…) but also because of the fundamental questions they raise. Striking features in these flows are the observation of preferential concentration of particles and of the increase of their settling velocity that have been both reported by many authors [1][2]. Experiments by Aliseda and co-workers [3] have suggested that both behaviors may be intertwined. In order to address more quantitatively the interaction between particle preferential concentration and settling enhancement, we extract and analyse statistics conditioned on the local concentration of velocity and acceleration of both fluid and particles. The particle inertia, gravity and mass loading effects are separately examined by making use of one-way coupling DNS (momentum transfer from particles to the carrier fluid is not accounted for) and two-way coupling DNS (transfer momentum from particles to the fluid is included).

PREFERENTIAL CONCENTRATION AND SETTLING VELOCITY

Simulation and analysis procedure

The one-way and two-way coupling DNS have been performed for particles settling in homogeneous and isotropic turbulence at the microscale Reynolds number $R_\lambda = 40$. In both cases, the forces acting on the particle are the Stokes drag and gravity. The considered Stokes numbers (defined as $St = \tau_p/\tau_\eta$, where τ_p is the particle response time and τ_η is the Kolmogorov time scale) range from 0.36 to 6, and the Rouse numbers (defined as $R = v_t/u'$ where v_t is the particle terminal velocity and u' the turbulence intensity) from 0 to 1. The values of volume fraction vary from 1.5×10^{-5} to 7×10^{-5} and the associated number of particles from 10^5 to more than 10^7. In the case of one-way coupling DNS the number of particles is fixed to 3.2×10^5. A detailed description of the simulations used here is provided in [5].

The particle concentration is assessed by calculating the 3D Voronoï diagrams from which we extract the value of the local concentration around each particle [4]. This method allows an easy calculation of the fluid and particle statistic quantities (velocity, acceleration, Okubo-Weiss parameter…) at the particle location, conditioned on the local concentration.

One-way coupling DNS

The 3D Voronoï analysis shows that preferential concentration is mostly governed by particle inertia and slightly modified by gravity. Similar to all previous studies, as displayed in figure 1-left, preferential concentration is present for any St and increases when St approaches unity. The correlation between settling velocity and particle concentration is well illustrated in figure 1-right for $R = 0.25$. It clearly shows that the settling rate increases with particle concentration. This is also found for all the values of R considered. Note that as R increases (figure 1-left), the distribution of particles tends to be more homogeneous, but this effect is still small at $R = 1$, the largest value considered here. The physical mechanisms responsible for preferential concentration are thus robust under gravity influence. Nevertheless, the 2D Voronoï analysis performed in planes along and across gravity shows that if the Voronoï cells' shape is mainly governed by the Stokes number, their orientation is influenced by gravity: particles tend to be closer to each other along the gravity direction.

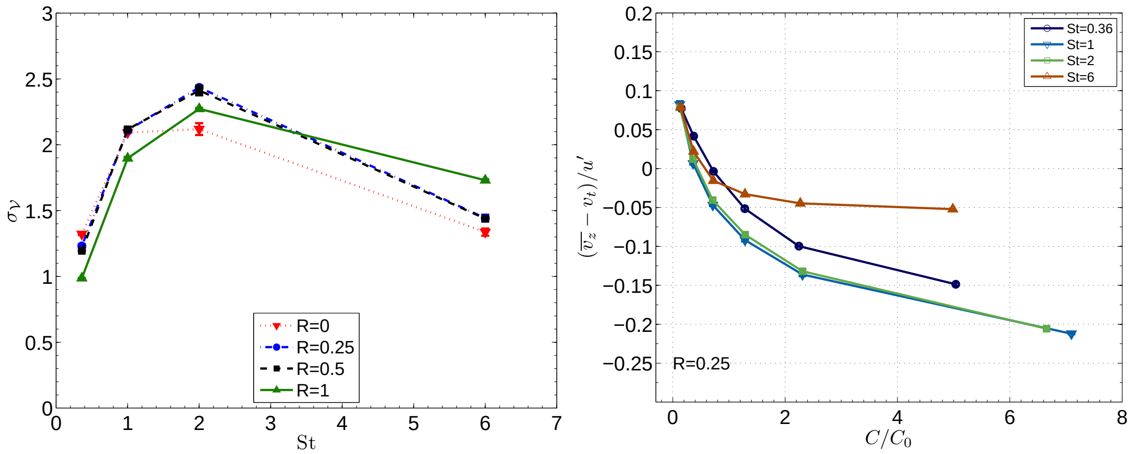

Figure 1. Left: standard deviation of the Voronoï volumes $\sigma_\mathcal{V}$ as a function of St for various values of R ($\sigma_\mathcal{V} = 0.44$ corresponds to a uniform distribution of particles). Right: conditional average of the settling rate normalized by the turbulence intensity u' given for $R = 0.25$; C/C_o is the normalized local concentration.

The statistics of fluid quantities show that centrifugal effects prevail gravity up to $R \simeq 0.5$ and are small for $R \simeq 1$. Still, non-homogeneities of particle concentration remain important even for high gravity fields and a strong correlation between preferential concentration and fluid acceleration is found. We show that particles tend to accumulate in regions where fluid vertical velocity and vertical acceleration are important. This preferential sampling of the flow results in the observed settling velocity enhancement and is optimum for $St \simeq 1 - 2$ and $R \simeq 0.25 - 0.5$.

Two-way coupling DNS

We extend our study to the more practical and relevant situation where the back reaction of the particles on the fluid is present, the so called two-way coupling approach. This allows a more accurate comparison between our results and the experimental measurements of Aliseda and co-workers [3]. In particular, we are able to address local concentration effects that could be linked to collective behavior (mass loading effects) as suggested by these authors.

CONCLUSIONS

This study allowed us to quantify the relation between preferential concentration and settling velocity enhancement in turbulent flows laden with inertial particles at moderate Reynolds number. The one-way and two-way coupling approach used here make possible to question separately the local concentration effects and the collective effects suggested by Aliseda et *al.* and thus to get more insight in the physical mechanisms underlying the interaction between preferential concentration and settling enhancement.

References

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