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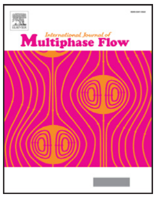

Local dissipation properties and collision dynamics in a sustained homogeneous turbulent suspension composed of finite size particles

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ABSTRACT

Particulate flows are present in many applications and the effect of particle size is still not well understood. The present paper describes three cases of sustained homogeneous turbulence interacting with particles. Simulations correspond to three particle-fluid density ratios and 3% volume fraction in zero gravity field. Fully resolved particle simulations are based on fictitious domain and penalty method.

The local dissipation around particles is studied according to the density ratio. Spatial description of the averaged dissipation is provided. Collision statistics are also investigated. The inter collision time and the angle of collision are compared to the kinetic theory. The effect of the inter particle film drainage is highlighted by simulating the same configurations with and without lubrication model.

1. Introduction

Particle-laden flows can be found in natural environment and many industrial applications. For example, sediments in rivers, solid particles in fluidized beds, droplets in clouds or in combustion chambers (Yang, 2003) could be treated as particles. Depending on the regime, the turbulence can completely govern the particles' behaviour (spatial distribution, collision rate, …). In the case of moderately concentrated to dense flows, the presence of particles can also influence the turbulence, Squires and Eaton (1990), Boivin et al. (1998).

Dimensionless parameters characterizing particle laden-flows are:

- the density ratio $\rho = \frac{\rho_p}{\rho_f}$, with ρ_p and ρ_f the density of the solid and fluid respectively,
- particle volume fraction,
- the Stokes number, defined as the ratio between the particle response time τ_p and a characteristic flow time scale τ_f. For the turbulent case, the Kolmogorov time scale is often chosen for τ_f. In this case the Stokes number is St_k. Nevertheless, this scale loses its relevance to predict finite size particle dynamics, *i.e.*, when the particle size is larger than the Kolmogorov length scale, Lucci et al. (2011).
- for finite-size particles, a new dimensionless parameter has to be considered, *i.e.* the ratio between the particle radius R and the Kolmogorov length scale η.

The motion of finite size particles in turbulent flow has received much less attention than small particles. Indeed, the size of the particles induces new coupling phenomena between fluid and particles, for example with flow scales larger than the Kolmogorov scales. In this case, classical Lagrangian pointwise approaches are not able to model these couplings as scale separation is not satisfied. Due to available CPU resources the computational cost of finite-size particle simulations was not affordable until recent years. More recently, with increasing power of massively parallel computers, the finite-size effect on particle dynamics has motivated many studies.

In Fig. 1, an extensive collection of relevant studies is presented. Experimental data, pointwise simulations and finite-size simulations are plotted together according to St_k, ρ and $\frac{R}{\eta}$. Studies are depicted with filled circles for simulations and open symbols for experiments. In addition, pointwise simulations have been reported as square symbols. It can be observed that pointwise simulations are focused on large density ratios, *i.e.* mostly gas/solid motions, whereas finite-size particle studies are concerned with Stokes numbers and density ratios ranging from 1 to 100. In

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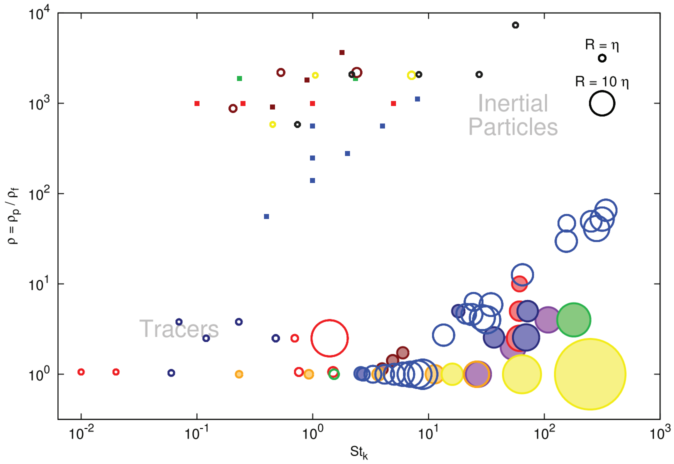

Fig. 1. Representation of turbulent particulate flows according to the density ratio, Stokes number based on Kolmogorov scale and $\frac{R}{\eta}$ for finite size configurations. The square symbols represent the pointwise simulations (red: Ferrante and Elghobashi, 2003, green: Ahmed and Elghobashi, 2000, blue: Sundaram and Collins, 1997, brown: Elghobashi and Truesdell, 1993), the open symbols hold for experimental data (red: Xu and Bodenschatz, 2008, green: Elhimer et al., 2011, blue: Qureshi et al., 2008, brown: Tanaka and Eaton, 2010, orange: Bellani and Variano, 2012, yellow: Wood et al., 2005, dark blue: Poelma et al., 2007, black: Fessler et al., 1994) and the filled circles correspond to the finite size particle simulations (red: Lucci et al., 2010, green: Corre et al., 2008, blue: Zhang and Prosperetti, 2005, brown: Cate et al., 2004, orange: Homann and Bec, 2010, yellow: Cisse et al., 2013, dark blue: Gao et al., 2011 and Shao et al., 2012, purple: present paper). The size of the circle is proportional to the ratio between the particles radii and the Kolmogorov length scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

order to contribute to the understanding of finite-size particle laden flows, fully-resolved turbulent simulations are considered in the present work for moderate density ratios corresponding to liquid/solid suspensions and St_k ranging from 10 to 100. These simulations are also reported in Fig. 1 (purple circles).

The main results obtained in the literature are now summarized:

- *Turbulence modulation:* The dispersed phase can modify the turbulent characteristics. This modulation can be split into three contributions. The first one is due to the force exerted by the particles on the fluid. For pointwise models, it can be written as the ensemble averaging $\langle \mathbf{u} \cdot \mathbf{f} \rangle$ obtained from the scalar product of the fluid velocity at the position of the particle $\mathbf{u}$ and the force $\mathbf{f}$ (see for example Ferrante and Elghobashi, 2003). It was concluded that modulation depends on the Stokes number based on the Kolmogorov time scale. For different Stokes numbers, it was observed that point particles could enhance turbulence or dissipate energy. The second contribution is a transfer of energy from large to small scales, Ferrante and Elghobashi (2003), Boivin et al. (1998). Finally, a third contribution comes from the modification of local dissipation around the particles. This is typically a finite-size effect which cannot be accounted for by classical pointwise simulations.

  The effect of finite size particles on turbulence modulation was studied numerically in Zhang and Prosperetti (2005). It is shown that the rate of decay of the turbulence is more important for the finite size case than for single-phase and particulate pointwise simulations. Actually, it is still necessary to understand and explain this effect. From the instantaneous dissipation fields obtained in the simulations of Cate et al. (2004), it can be observed that a local dissipation appears around particles. Later, the study of Lucci et al. (2010) verifies that the averaged dissipation increases around particles. In order to quantify this effect, the authors computed the averaged dissipation upstream and downstream of particles. The local increase of the dissipation is more important in the front and its spatial extension is about one diameter long. A similar conclusion is drawn in Cisse et al. (2013) in which a tentative explanation is given: the wake generated behind the particles decreases the turbulent dissipation level. These results are confirmed by the experiments of Tanaka and Eaton (2010) concerning the study of dissipation around particles settling in a turbulent flow. The dissipation is multiplied by 3 in the front of the particles. The local dissipation will be analysed in the present paper.

  The local dissipation is not the only finite size effect in turbulence modulation. In fact, as shown by Poelma et al. (2007), finite size particles can modify the turbulence structures without modifying the energy content. Finally, Lucci et al. (2010) shows that the coupling term $\langle \mathbf{u} \cdot \mathbf{f} \rangle$ is positive (energy enhancement) for finite size particles. For pointwise particles, this term generally dissipates energy.
- *Collision regime:* The study of the collision regime is important for many applications such as the prediction of coalescence rate of droplets. The collision rate represents the number of collisions per unit time. It can be obtained from the relative velocity of the particles $|w_r|$ and the radial distribution at contact g_0, as follows,

  $$f_c = \frac{1}{\tau_c} = \frac{1}{2} g_0 n_p^2 \pi \, (2R)^2 \langle |w_r| \rangle \tag{1}$$

  where $\langle . \rangle$ is the ensemble average, τ_c is the collision time and n_p is the particle number density. The particle collision frequency in turbulent flow is relatively well described for two cases. In the first case, for particles with small response time (tracers), the collisions are driven by the local shear in the flow. The collision rate can be correlated to the dissipation rate of the flow, Saffman and Turner (1956). In the second case, where the particles are inertial, the Tchen–Hinze correlation (Hinze, 1975; Tchen, 1947) links the particle kinetic energy to the turbulent statistics. Thus, the collision rate can be computed, Abrahamson (1975). For intermediate cases, many models have been proposed (Kruis and Kusters, 1997; Lavieville, 1997; Williams and Crane, 1983).

  For finite size particles, only the study of Cate et al. (2004) has addressed collision statistics. This study showed that secondary collisions appear. The secondary collisions are consecutive collisions between pairs that stay correlated during a relatively long time. These collisions are not predicted by previous models. In the present paper, the secondary collision frequency will be analysed.

This article presents a study of a sustained homogeneous turbulent flow seeded with finite-size particles. First of all, the numerical method is summarized in Section 2. The choice of the turbulent particle laden flow parameters is discussed in Section 3. From this turbulent case, two major phenomena are studied. The first one is the averaged flow around particles which is described in Section 4. The second phenomenon is the collisional regime detailed in Section 5 where we focus on lubrication effects on collisional regime. Conclusions and perspectives are finally drawn in the last section.

2. Simulation of finite size particles

The modelling and simulation of fully resolved finite size particles in turbulent incompressible and isothermal fluid is investigated by means of a single fluid model (Kataoka, 1986) generalized for particulate flows (Vincent et al., 2014). The key idea is to use a fictitious domain approach in which an Eulerian description of the two-phase flow is introduced by a characteristic function C, also called volume of fluid (VOF). This function is 0 in the fluid phase