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Interaction between turbulent structures and particles in roughened channel

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ABSTRACT

The distribution of inertial particles in turbulent flows is highly non-uniform and is driven by the local dynamics of the turbulent structures of the underlying carrier flow field. In the specific context of dilute particle-laden wall-bounded flows, deposition and resuspension mechanisms are dominated by the interaction between inertial particles and coherent turbulent structures characteristic of the wall region. The macroscopic behavior of these two-phase systems is influenced by particle inertia, which plays a role at the microscale of a single dispersed element. These turbulent structures, which control the turbulent regeneration cycles, are strongly affected by the wall roughness. The effect of the roughness on turbulent transport in dilute suspension has been still poorly investigated. The issue is discussed here by addressing direct numerical simulation (DNS), at friction Reynolds number $Re_\tau = 180$, of a dilute dispersion of heavy particles in a turbulent channel flow, spanning two orders of magnitude of particle inertia. The irregular wall roughness is obtained through the superimposition of four sinusoidal functions of different wavelengths and random amplitudes. We use DNS combined with Lagrangian particle tracking to characterize the effect of inertia on particle preferential accumulation, looking at the effect of roughness on particle distribution, by comparing the statistics computed for fluid and particles of different size and observing differences in terms of distribution patterns and preferential sampling.

Introduction

Turbulent dispersed two-phase flows exhibit a variety of interesting aggregation topics for the dispersed phase, closely linked to the carrier-phase turbulent vortical structures. The stochastic nature of both the carrier-phase turbulence and the dispersed-phase makes the problem of turbulent multiphase flow far more complex than its single-phase counterpart. Furthermore, when the dispersed mass is comparable with the fluid one, the back-reaction of the dispersed phase on the carrier phase dynamics cannot be neglected, i.e. two-way coupling (Balachandar and Eaton, 2010). Looking at a dilute dispersed regime, the particle volume fraction is low enough to neglect particle–particle interactions and their back-reaction on the fluid phase, so the dominant effect is that of the turbulent carrier flow on the dynamics of the dispersed phase (i.e. one-way coupling).

Turbulent fluctuations induce suspended particles spreading disuniformly and clustering; the mean flow large scale anisotropy induces a preferential orientation of these clusters. In particular, preferential particle concentration appears in the form of small-scale clustering (see Cencini et al., 2006 and references therein for isotropic turbulence and Gualtieri et al., 2009 for homogeneous anisotropic shear flows, for instance) and turbophoresis for wall-bounded flows (Kaftori et al., 1995a; 1995b; Marchioli and Soldati, 2002; Soldati and Marchioli, 2009).

Small-scale clustering appears in both homogeneous and inhomogeneous flows and consists of loss of spatial homogeneity of particle distribution induced by the interactions between particle inertia and small-scale turbulent fluctuations. The classical explanation for this small-scale behavior is the centrifugal effect due to the flow vortical structures which tend to expel heavy inertial particles from the vortex cores and localize them in the interstice between the vortices. The intense segregation is found for particles with response time of the order of the characteristic time of the local turbulent vortical structure (see Boffetta and De Lillo, 2004; Goto and Vassilicos, 2006). In addition to the vortical centrifugal effect, other mechanisms have been proposed. Goto and Vassilicos (2008) and Coleman and Vassilicos (2009) proposed the so-called sweep-stick mechanism, which consists on the particle preferential accumulation

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in stagnation points of fluid acceleration. Turbophoresis is a distinctive feature of turbulence induced particle segregation which appears in all flows characterized by gradients of turbulent kinetic energy, as described in Caporalini et al. (1975). Extensive further investigations have been described in the works of Reeks (see Reeks, 1983; Reeks et al., 1988) where the turbophoretic particle drift toward the wall was related to the skewness of the wall-normal fluid velocity distribution.

Small scale clustering and turbophoresis are linked to particles' finite inertia which avoids them from following the tracer paths, filters the high-frequency turbulent structures and consequently leads to preferential particle accumulation outside the vortical regions (Balachandar and Eaton, 2010; Picano et al., 2009; Sardina et al., 2012).

In wall-bounded turbulent flows these phenomenologies induce a characteristic particles flux toward the wall, that in the inner region is ruled by sweep-ejection dynamics. Heavy inertial particles selectively respond to turbulent structures and particle number concentration increases down where the turbulence intensity gradients are higher. Inertial particles may achieve large concentrations in the viscous region, up to hundred times the mean value. A number of studies had emerged to investigate on the same problem, but it is beyond the scope of this paper to make a complete literature review. Particle transfer in the wall region is dominated by the coherent structures which control the turbulence regeneration cycle. According to Shoppa and Hussain (2002) wall turbulence is dominated by a cycle in which low-speed streaks generate quasi-streamwise vortices, which in turn generate ejections and sweeps. Finally, these structures contribute to maintain the low-speed streaks. As reported in several previous investigations (see Eaton and Fessler, 1994; Zhang and Ahmadi, 2000), particles are transferred by sweeps in the wall region, where they preferentially segregate into elongated clusters which correlate well with the instantaneous position of the low speed streaks at the wall, whereas ejections transfer particles from the wall region to the outer flow. A possible explanation is to be found in the ratio of particle to fluid structure time-scales. Recently, a new stochastic model based on sweep-ejection quadrant analysis has been developed by Jin et al. (2015) in order to model Lagrangian particle dynamics in RANS (Reynolds-averaged Navier–Stokes) simulation of boundary layer flows. The prediction of the deposition rate for large inertial particles is very good compared with experimental measurements whereas the model underestimates the value for smaller particles.

Inertial effects largely depend on the characteristic time scales between the dilute phase and the carrier flow, the latter ones spanning from the Kolmogorov time unit $\tau_\eta = \eta^2/\nu$, where η is the Kolmogorov length and ν the kinematic viscosity, associated with small-scale clustering events (Wang and Maxey, 1993; Bec et al., 2007) and larger energy-producing time scale characteristic of the wall region turbulence (Gualtieri et al., 2009). In order to quantify the importance between the particle time scale and the turbulent flow time scale is usually introduced a dimensionless parameter, the Stokes number *St* (Maxey and Riley, 1983). It is defined as the ratio between the particle relaxation time, characteristic of the dilute phase, and a characteristic time scale of the turbulent flow (Balachandar and Eaton, 2010).

The characteristic time-scale of turbulent structures decreases progressively as the structures lie closer to the wall. Heavier particles, whose inertia is large enough to be influential on their motion, have a larger time-scale and filter out the effects of smaller fluid scales. In the buffer layer, the momentum gained by the dispersed phase through the interaction with the larger turbulent scales (sweeps) may be able to drive particles to the wall. Once in the inner region, experience shows that particles may be trapped in the wall region or re-entrained in the outer flow. Particles driven to the wall by a sweep and not re-entrained to the outer flow by an ejection are bound to remain in the viscous wall layer, and accumulate into specific flow regions, not far from the wall, where they tend to stay long time (Soldati and Marchioli, 2009).

Current state of the art in direct numerical simulation (DNS) with Lagrangian particle tracking (LPT) of pointwise particles is mature enough to ensure comprehension of crucial two-phase flow phenomena such as preferential concentration, deposition and re-entrainment in test case configurations ranging from boundary layers to planar channels and pipes. Nowadays, challenges are represented by particle interaction kernels (to model collisions and/or fluid–particle interplay) and boundary conditions to reproduce particle–wall interactions and particle accumulation rates in more complex geometries than the classical flat walls.

Many engineering and environmental turbulent flows seeded with particles, are often bounded by irregular rough walls that strongly modify turbulent structures distribution and features (Volino et al., 2011; Hong et al., 2011). The coherent structures of the turbulent flows are locally destroyed by the spatial inhomogeneity induced by the wall roughness. In rough walls the streamwise coherence of the streaks is reduced compared to the smooth wall case, while the streak dimension in the spanwise direction is increased. Moreover, the streak location moves away from the wall when compared the smooth-wall case (De Marchis et al., 2010). Therefore, wall roughness strongly influences the particle preferential distribution in turbulent channels.

Particle–wall collisions and their frequency are strongly altered by the presence of complex wall asperities, as reported in Konan et al. (2009), Sommerfeld and Kussin (2004), and Tsuji et al. (1987). Despite the large amount of literature works devoted to the study of the mean and instantaneous turbulent flow structures over irregular walls, extensive detailed numerical studies dealing with particle dispersion over irregular solid boundaries are still lacking.

To the best of our knowledge, only idealized regularly roughened walls have been considered (De Angelis et al., 1997; Chang and Scotti, 2003; Marchioli et al., 2006a,b; 2007a) or a stochastic model for modeling particle–rough wall interactions has been adopted (Sommerfeld and Kussin, 2004; Squires and Simonin, 2006; Konan et al., 2009). In the latter case the deterministic shape of the irregular boundary is not retraced: whenever the particle reaches the wall the rebound process is modeled introducing a smooth flat virtual wall with a characteristic chosen angle in order to reproduce the real rebound effects on the particle's trajectory. This virtual wall modeling implicitly assumes that the roughness height is negligible (Sommerfeld and Huber, 1999; Sommerfeld and Kussin, 2004; Squires and Simonin, 2006; Konan et al., 2009; 2011; Vreman, 2007; Breuer et al., 2012; Mallouppas and van Wachem, 2013) rather than modeling the real geometrical profile of the rough boundary, nevertheless it is able to reproduce the particle transverse dispersion enhancement observed in the experiments (Kussin and Sommerfeld, 2002) as shown in the simulations of Mallouppas and van Wachem (2013).

Starting from this background, in this paper, the authors mainly focus on particle dispersion analysis and preferential wall accumulation mechanisms in particle-laden turbulent channel flows over irregularly roughened walls. In the present analysis we investigate on particles distribution features observed in the turbulent channel flow over a rough wall. The analysis of the interaction between turbulent structures and the suspended phase is used to quantify the effect of a wall roughness over deposition and resuspension mechanisms. We focus on the statistical properties of particles much heavier than the carrier fluid, investigating by means of direct numerical simulations, the particles preferential concentration as a function of the Stokes number. The present study adds to works cited above since it is designed to study the effects of a realistic boundary roughness adopting accurate numerical procedure (DNS). We track different particle sets which cover a broad range of Stokes' numbers and larger particle samples in order to ensure adequate statistical convergence of the results and accurate particle statistics, able to provide a meaningful