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Statistics of inertial particle deviation from fluid particle trajectories in horizontal rough wall turbulent channel flow

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ABSTRACT

Previous experimental, theoretical and numerical studies showed that in particle laden wall-bounded flows particles much heavier than the carrier flow preferentially accumulate in low-speed streaks. Depending on the inertia, the distribution of particles in turbulent flows is strongly influenced by the characteristics of the coherent turbulent structures which develop in the carrier flow field. In wall-bounded flows, these coherent structures, which control the turbulent regeneration cycles, are strongly affected by the roughness of the wall, which systematically modifies turbulent structures coherence and shape. Nevertheless, the effects of the roughness of the wall on the particle transport in two-phase turbulent flows has been still poorly investigated. The issue is discussed here by addressing direct numerical simulations (DNS) combined with Lagrangian particle tracking (LPT) with 6 particle sets of different inertia ($St^+ = 0.1, 0.5, 5, 10, 25, 50$). As observed in previous numerical studies devoted to the analysis of particle velocity statistics, in shear flows bounded by a smooth wall, particles lead the fluid near the wall and lag behind the fluid far away from the wall and particle inertia has a great impact on the difference between fluid seen and particle velocities. Here this issue is investigated in flows bounded by a rough wall, considering particles of different inertia, whose size is much smaller than the smallest flow scales (point-particle approach).

1. Introduction

The near-wall transport of solid particles in wall bounded turbulent flows is a research topic of great importance in terms of predicting both particles deposition and near-wall particle concentration. The near-wall accumulation is an important phenomenon when describing systems, such as filters or turbines where particle–fluid–wall interactions play a fundamental role. However the complex nature of shear flows and the mutual interaction between the carrier flow and the transported phase has made this task very challenging to the present date.

Caporaloni et al. (1975) first of all introduced the concept of turbophoresis. Since then, a lot of papers have studied the accumulation of inertial particles in various geometries, using theoretical approaches (Cleaver and Yates, 1975; Marchioli and Soldati, 2002; Portela et al., 2002; Zhang and Ahmadi, 2000), experimental (among others, Kaftori et al., 1995a; 1995b; Kulick et al., 1994; Ninto and Garcia, 1996; Kussin and Sommerfeld, 2002; Righetti and Romano, 2004) and computational techniques (Eaton and Fessler, 1994; Marchioli and Soldati, 2002; Marvuglia and Messineo, 2012; Picciotto et al., 2005a; Portela et al., 2002; Rouson and Eaton, 2001; Soldati and Marchioli, 2009). The origin of preferential particle concentration is still being studied but it is known that particles' trajectories in the wall region are strongly correlated with the carrier flow coherent near-wall structures that force particles deposition and entrainment processes. According to their size, density and flow Reynolds number, particles are observed to get lifted up and entrained into the outer flow by the action of the turbulent structures. Particles resettling to the bottom and preferential segregation are observed to migrate into the low-speed fluid regions of slow moving fluid by the action of the eddy structures (see Soldati and Marchioli, 2009, for a review). In fact, inertia prevents particles from accurately following the fluid trajectories leading to the preferential oversampling of the low streamwise velocity regions in the buffer layer, that is ejection events (Marchioli and Soldati, 2002). The shape, length and persistence with time of these accumulation structures vary with particle size and density, for fixed Reynolds number of the flow, as shown from experimental analysis and theory. The degree of correlation depends on the Stokes number St^+ (Maxey and Riley, 1983), representative of inertial effects, defined as the ratio between a characteristic relaxation time, which describes the time that a particle

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needs to adjust to a change in the flow velocity, and a characteristic time scale of the turbulent flow. The characteristic carrier flow time scale spans from the Kolmogorov time unit $\tau_\eta = \eta^2/\nu$, where η is the Kolmogorov length and ν the kinematic viscosity, associated to small-scale clustering events (Bec et al., 2007; Wang and Maxey, 1993) and larger energy-producing time scale characteristic of the wall region turbulence (Gualtieri et al., 2009). It represents the ratio of the particle response time to some representative time scale of the flow and quantifies the response of the dispersed phase to the perturbations produced by turbulence.

The wall roughness strongly modifies their characteristics, reducing the streaks streamwise coherence and increasing their dimension in the spanwise direction compared to the smooth-wall case. Moreover, streaks location moves away from the wall when compared with the smooth-wall case (De Marchis et al., 2010). As expected the wall roughness can significantly alter particle statistics (Milici et al., 2014; Sommerfeld, 2003) and the effects of wall roughness on particle distribution patterns are more or less intense as a function of particle diameter and density at fixed Reynolds number of the flow, as expected. Small St^+ represent particles that behave almost as fluid tracers, whereas large relaxation times correspond to particles that are unaffected by turbulent fluctuations. Therefore, the roughness of the wall modifies coherent structures in the carrier flow, respect to the smooth flat boundary, and changes in turbulent structures characteristics affect particle distribution over the flow field giving rise to macroscopic effect in term of particle mass transport which, as expected, depend on particle inertia. However, the particle Stokes number being equal, accounting for the roughness of the wall may produce accumulation effects different from the smooth flat-wall case. In fact, particles that collide with a rough wall have a tendency to be re-suspended into the flow more often (Sommerfeld and Kussin, 2004). When considering a smooth flat wall, turbophoresis is maximum if the particle relaxation time is of the order of the characteristic time of the near-wall coherent structures (buffer layer), corresponding to about 15–20 viscous time scales ν/u_τ with $u_\tau = (\tau_w/\ \rho)^{0.5}$ the friction velocity and τ_w the stress at the wall (Soldati and Marchioli, 2009). As shown in Milici et al. (2014), in the rough channel solid phase seems not to be affected by turbophoresis, as highlighted in the smooth channel. Therefore the wall roughness not only modifies the shape and the length of particle accumulation structures but also affects particle distribution over the wall-normal direction.

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) or boundary conditions (to reproduce particle–wall interactions and particle accumulation rates in more complex geometries than simple flat walls). Despite the large amount of literature works devoted to the study of the mean and instantaneous turbulent flow structure over irregular walls, extensive detailed numerical studies dealing with particle dispersion over irregular solid boundaries are still lacking. In fact, investigations of a dispersed phase in turbulent flow bounded by a rough wall is difficult to perform, therefore, numerical and experimental data are very rare in literature. To the best of our knowledge, only idealized regularly roughened walls have been considered (Chang and Scotti, 2003; De Angelis et al., 1997; Marchioli et al., 2006; 2007a; Vreman, 2015) or a stochastic model for modeling particle-rough wall interactions have been adopted (Konan et al., 2009; Sommerfeld and Huber, 1999; Sommerfeld and Kussin, 2004; Squires and Simonin, 2006). 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 (Konan et al., 2009; Sommerfeld and Huber, 1999; Squires and Simonin, 2006) rather than modeling the real geometrical profile of the rough boundary. The orientation of the wall is sampled from an experimentally determined distribution of wall roughness.

Large part of available numerical studies on particle-turbulence interaction track the location and other properties of each individual particles (the so-called Lagrangian approach). Most common is the so-called "point-particle" approach (Marchioli and Soldati, 2002; Narayanan et al., 2003; Picciotto et al., 2005a; Rouson and Eaton, 2001), limited to particles sizes which are much smaller than the smallest flow scales (Kolmogorov scale of the fluid) and consider particles with density larger than that of the carrier phase and dilute conditions thus neglecting particle momentum transfer toward the fluid (i.e. no modification of the carrier phase flow due to momentum exchange with the dispersed phase) and mutual particle interactions (one-way coupling).

Following the above mentioned approaches, in this paper, the authors aim at providing a statistical characterization of density-weighted particle velocity to analyze the influence of roughness on the mean transport as a function of particles' inertia. Due to inertia, in fact, the particle velocity differs from that of the surrounding carrier flow and fluid velocity fluctuations show significant decorrelation along the particle trajectory. The difference between the fluid velocity at the particle location (fluid velocity seen hereinafter) and the particle velocity is a measure of the interaction between the discrete particle phase and the continuous fluid phase and affects the mean transport features as it is the flow variable which determines the drag experienced by the solid phase. As expected the wall roughness strongly enhances the transverse dispersion of the particles and their fluctuating velocities throughout the channel and causes a significant reduction of the mean horizontal velocity of the particles.

2. Computational methodology and setup

2.1. Flow governing equations

A coupled Eulerian–Lagrangian numerical method has been used to perform the simulations of a particle-laden turbulent channel flow. Particle size and concentration are supposed to be small enough to consider no back-reaction of the transported phase on the carrier fluid flow, the so called one-way coupling among the particles and the turbulent field (see Elghobashi and Truesdell, 1992; Armenio and Fiorotto, 2001). Even though the accumulation process can produce local peaks of particle number density near the wall, it was shown that turbulence structures seem to modify only from a quantitative viewpoint (Kaftori et al., 1995a; 1995b). Therefore, the Eulerian fluid field is evaluated by DNS of the standard continuity and Navier–Stokes equations, which for incompressible, isothermal and Newtonian fluid, in the conventional summation approach, read:

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} - \frac{1}{Re_\tau}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{\partial p}{\partial x_i} + \Pi\delta_{ij} = 0;$$
$$\frac{\partial u_i}{\partial x_i} = 0 \qquad i, j = 1, \ldots, 3 \tag{1}$$

where all variables have been made non-dimensional with the friction velocity u_τ and the channel half-width δ in terms of wall units, taking ν/u_τ and ν/u_τ^2 as the reference length and time. In the Eqs. (1) x_i is the ith non-dimensional coordinate, u_i is the ith