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Solid sediment transport in turbulent channel flow over irregular rough boundaries

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ABSTRACT

The presence of a loading of dispersed particles in a turbulent flow affects the dynamics of the carrier flow field which, in turn, drives grains movement. The focus of the paper is on the analysis of the coupling effects between near-bed turbulence structures and the dynamics of dispersed suspended solid particles in wall-bounded turbulent multiphase flows. We consider turbulent horizontal channel flows bounded by rough boundaries. The friction Reynolds number of the unladen flow is $Re_\tau = 180$ and the dispersed phase spans one order of magnitude of particle diameter. To analyze sedimentation and suspended phase transport, we adopt concepts and modeling ideas derived from the Euler-Lagrange approach, using Direct Numerical Simulations (DNS) for the carrier phase coupled with Lagrangian Particle Tracking (LPT) for the dispersed phase. The analysis takes into account fluid-particle interaction (two-way coupling) in the frame of the Particle-Source-In-Cell (PSIC) method. The effect of the wall's roughness is taken into account modeling the elastic rebound of particles onto it, instead of using a virtual rebound model.

1. Introduction

In the framework of fluid dynamics, the motion of heavy particles suspended in boundary-layer-type flows is a feature relevant to many applications of technological, industrial, biological and environmental interest. In such flows turbulence plays a fundamental role in mass, momentum and energy exchange between fluid phase and suspended inclusions.

A reliable prediction of heavy particles transport in a viscous fluid depends on the particles/fluid interaction. In fact, the mechanisms which drive the motion of suspended particles are highly complex and involve a large range of spatial and temporal scales. Particles do not fully follow the Eulerian statistics of the turbulent flow field, rather they preferentially sample coherent structures and do it in different ways, as a function of their inertia. As known, turbulence is characterized by many different spatial and temporal active scales and the motion of each particle depends on the ratios of particle and turbulent characteristic length and time scales. Moreover, particle motion feels the effect of gravity, so the ratio between gravitational and viscous forces acting on a submerged particle is another parameter to take into account. In this context, the motion of rigid particles suspended in horizontal wall-bounded flows is a topic of fundamental interest to understand the detailed mechanisms which drive the strong correlation between coherent wall structures, local suspended particle segregation and accumulation at the wall.

According to several literature findings, the ratio between the particle relaxation time, τ_p, and a characteristic time scale of the turbulent flow, known as Stokes number St^+, is used to quantify the importance between the time scale of the particle and that of the turbulent flow (Balachandar and Eaton, 2010). In wall-bounded turbulent flows the natural choice for the characteristic time scale is the viscous time scale ν/u_τ^2; accordingly, the viscous Stokes number is defined as $St^+ = \tau_p u_\tau^2/\nu$.

There is strong experimental (Kaftori et al., 1995a; 1995b; Nino and Garcia, 1996; Kiger and Pan, 2002; Righetti and Romano, 2004) and numerical (Pan and Banerjee, 1996; Rouson and Eaton, 2001; Gualtieri et al., 2009; Soldati and Marchioli, 2009; Milici and De Marchis, 2016) evidence that near-wall coherent structures play a fundamental role on sediment dynamics in particle-laden turbulent flows. On the other hand, looking at the fluid phase, the well known stochastic nature of the carrier-phase turbulence is affected and further complicated by the random distribution of the dispersed phase.

In the last decades, there has been great interest in turbulence modulation by suspended sediments, which led to a lot of numerical studies (Li et al., 2001; Dritselis and Vlachos, 2008; Zhao et al., 2010). Among other insights yielded to date,

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experimental and numerical analysis confirms a measurable velocity lag between streamwise fluid and sediment velocities, whose magnitude varies with the elevation and sediment concentration (Tanière et al., 1997; Nino and Garcia, 1996; Kiger and Pan, 2002). Additionally, it has been shown that turbulence modulation depends on particles' inertia, that is turbulence may be enhanced or reduced (Rogers and Eaton, 1991; Kulick et al., 1994; Hwang and Eaton, 2006) depending on the dimension of the suspended particles compared to turbulence length scales (Rashidi et al., 1990; Kulick et al., 1994; Elghobashi and Truesdell, 1993; Crowe et al., 1996).

Despite the observations cited above and other studies in the literature, a detailed understanding of the mechanisms responsible for turbulence modulation by heavy suspended particles is still lacking (Eaton, 2009; Balachandar and Eaton, 2010), as findings from these studies are not unanimous. For example, turbulence attenuation and augmentation have been observed for small and large particles, respectively, and the modification has been found to depend on the solid volume fraction loaded (Rashidi et al., 1990; Kulick et al., 1994; Pan and Banerjee, 1996) whereas some other studies indicated turbulence augmentation for small particles (Rani et al., 2004). Particles ability to modulate fluid turbulence depends, in fact, on a lot of non-dimensional parameters that include the particle volume fraction, Ψ_v, particle Reynolds number, Re_p, particle relative diameter, d_p/δ, where δ represents a fluid characteristic length scale, particle Stokes number, St^+, particle-to-fluid density ratio, ρ_p/ρ and the friction Reynolds number, Re_τ. Further investigation on the subject is needed to develop tools for modeling additional turbulence closure terms to be included in the governing equation of such flows when DNS/LES cannot be performed. In fact, the performance of a turbulence closure model is determined by its ability to correctly model turbulence modulation by suspended sediments, with the aim to include it in traditional mixed-flow (or combined phase) models, that treat sediment-laden flows essentially as flow of a single fluid.

Moreover, phenomena responsible for the creation and evolution of turbulence structures (in shape and size) are of interest not only from a fluid mechanics point of view but they are of great practical application for suspended sediment entrainment: the modification of the structure of the turbulent flow by which particles are carried out, in turn, affects the transport of sediments (see among others Nikora et al., 2013). A number of studies have emerged, till recently, to investigate on particles' response to the coherent eulerian motion, both over smooth (Rouson and Eaton, 2001; Soldati and Marchioli, 2009) and rough (Chang and Scotti, 2003; Vreman, 2015; Sommerfeld and Kussin, 2004; Squires and Simonin, 2006) boundaries, but it is beyond the scope of this paper to make a complete literature review. Upon examination of most of the published works, it emerges that particle inertia influences preferential concentration of sediments and transfer rates, responsible for deposition or resuspension of relatively large, heavy particulates, within horizontal, wall-bounded shear flow.

Although much work has been done on this topic, there are still many aspects of the particle turbulence interaction within the wall-bounded region that are only known qualitatively, or under a limited set of parameters. Extensive research efforts during the last few decades have only partially elucidated the complexities of suspended sediment transport but an adequate formulation and quantification of the interaction between suspended particles and the carrier liquid still lacks. Moreover the focus has been so far mainly directed at flows over smooth surfaces, over regularly roughened walls (Marchioli et al., 2006; Vreman, 2015) or over surfaces whose roughness has been modelled by the adoption of a stochastic model for particles-wall collisions (Sommerfeld and Kussin, 2004; Squires and Simonin, 2006; Konan et al., 2011; Alletto and Breuer, 2013). It is reasonable to expect that coherent structures that characterize turbulent wall-bounded flows over rough boundaries will have a fundamental role on sediment entrainment. The interest in two-phase flows bounded by rough surfaces lies on the action of roughness, that strongly modifies turbulent structures distribution and features (Bhaganagar et al., 2004; De Marchis et al., 2010).

The complex physics of sediment transport raise the need for highly resolved data under controlled flow conditions. Nowadays, computational resources are available to perform Direct Numerical Simulations (DNS) of such phenomena, which enables the analysis of any quantity of interest with great spatial and temporal precision, albeit at a large computational cost and for somehow idealized situations. Computational investigations using Eulerian–Eulerian and Lagrangian–Eulerian techniques have provided valuable insight, as clearly shown in the recent Large Eddy Simulation carried out by Dallali and Armenio (2015), where two-way coupling suspended sediment transport is investigated using the Eulerian–Eulerian methodology.

In this context, the proposed research is mainly aimed at investigating on the transport of fully suspended sediments in water and turbulence modulation by it, in a channel flow bounded by irregular rough walls, focusing on the comparison between the one-way and two-way coupling approaches. The simulations are carried out in a horizontal turbulent channel flow at low Reynolds number, $Re_\tau = u_\tau \delta/\nu = 180$, where u_τ is the friction velocity, δ the half channel height and ν the kinematic viscosity; we assume $\nu = 10^{-6}$ m^2/s. Looking at typical hydraulic condition, dilute suspensions are investigated by means of statistical quantities as well as instantaneous plots. We mainly focus on the interactions between the fluid and the solid phase, at a rather small total solid volume fraction (≈ 0.002), considering particles of different inertia, in order to ensure accurate particle statistics able to provide a meaningful quantitative description of the phenomena under investigation. The back-reaction of the solid phase on the turbulent flow is modelled by means of a modified version of the Particles Source-In-Cell method (PSIC) method (Squires and Eaton, 1990; Pan and Banerjee, 1996; Li et al., 2001; Ferrante and Elghobashi, 2003). As pointed out by Ahmed and Elghobashi (2001), in wall bounded flows with dilute suspensions, a Lagrangian point-particle approach is suitable to simulate flows laden with suspended particles , so we decide to perform DNS coupled with point-particle approach, best suited to capture vertical fluxes to and off the wall in dispersed flow conditions (Toorman, 2008). According to the Elghobashi's diagram (Elghobashi, 1994), the solid volume fraction makes it possible to neglect particle-particle collisions.

The present study adds to previous works since, unlike in the references mentioned above, it is designed to study the effects of a realistic roughness at the solid boundary, without the adoption of a virtual wall model (i.e. Squires and Simonin, 2006; Vreman, 2007; Breuer et al., 2012), matching statistical results obtained in the one- and two-way coupling regime.

The organization of the paper is as follows: in Section 2 we introduce the numerical methods; results of channel flow simulations are present in Section 3; finally, concluding remarks are collected in Section 4.

2. Physical model and numerical method

This section provides provides a review on the governing equations of fluid flow and coupled fluid-solid system Section 2.1 and motion of a solid sphere in a flow field Secton 2.2.

2.1. Continuous phase

The fluid phase is assumed to satisfy the principle of conservation of momentum and mass for an incompressible newtonian