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Direct numerical simulation of particle interaction with ejections in turbulent channel flows

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ABSTRACT

Direct numerical simulations (DNS) of incompressible turbulent channel flows coupled with Lagrangian particle tracking are performed to study the characteristics of ejections that surround solid particles. The behavior of particles in dilute turbulent channel flows, without particle collisions and without feedback of particles on the carrier fluid, is studied using high Reynolds number DNS ($Re = 12{,}500$). The results show that particles moving away from the wall are surrounded by ejections, confirming previous studies on this issue. A threshold value separating ejections with only upward moving particles is established. When normalized by the square root of the Stokes number and the square of the friction velocity, the threshold profiles follow the same qualitative trends, for all the parameters tested in this study, in the range of the experiments. When compared to suspension thresholds proposed by other studies in the Shields diagram, our simulations predict a much larger value because of the measure used to characterize the fluid and the criterion chosen to decide whether particles are influenced by the surrounding fluid. However, for intermediate particle Reynolds numbers, the threshold proposed here is in fair agreement with the theoretical criterion proposed by Bagnold (1966) [Bagnold, R., 1966. Geological Survey Professional Paper, vol. 422-1]. Nevertheless, further studies will be conducted to understand the normalization of the threshold.

1. Introduction

Interactions between solid particles and turbulent structures in a channel flow are an important topic in a great number of environmental systems, from sediment transport within rivers to atmospheric dispersion of pollutants or solid deposition in marine flows. Particle transport mechanisms in the vicinity of a wall are characterized by complex interactions between turbulent structures and the dispersed phase (Kaftori et al., 1995a,b). Although much work has been done on this topic Kulick et al. (1994), Rouson and Eaton (2001), there are still many aspects that are only known qualitatively, or under a limited set of parameters.

It has been speculated for more than 30 years that wall generated turbulent bursts are primarily responsible for the suspension and transport of solid particles within the flow (Jackson, 1976; Sumer and Oguz, 1978; Sumer and Deigaard, 1981). However, the detailed mechanisms have not been elucidated yet. Since the development of new experimental techniques and high resolution numerical simulations, a better understanding of turbulent burst structures within wall bounded flows has been achieved (Adrian et al., 2000). By experimental observations, Liu et al. (1991) found that regions containing high Reynolds stress are associated with the near-wall shear layers, terminated in regions of rolled-up spanwise vorticity, which are interpreted to be the heads of hairpin vortices. There is now a consensus among researchers that particles in the near wall region preferentially concentrate in low speed streaks (Kaftori et al., 1995b; Kiger and Pan, 2002; Marchioli and Soldati, 2002; Soldati and Marchioli, 2009). These low-speed fluid regions move through the inclined loop of the hairpin by vortex induction from the legs and the head (Adrian et al., 2000).

Despite this general agreement on several features of particle behavior near the wall, numerous mechanisms for particle–wall turbulence interactions have been proposed. For example, from their experiments Kaftori et al. (1995a) suggested that funnel-shaped vortices sweep along the bottom and push particles out of the way, throwing the particles out of their core and therefore creating avenues of particles to the sides of the vortex path. By means of numerical simulations in a turbulent channel at a shear Reynolds number $Re_\tau = 150$, Marchioli and Soldati (2002) found that particles are trapped in the near wall region by the rear-end of a quasi-streamwise vortex, which prevents particle suspension

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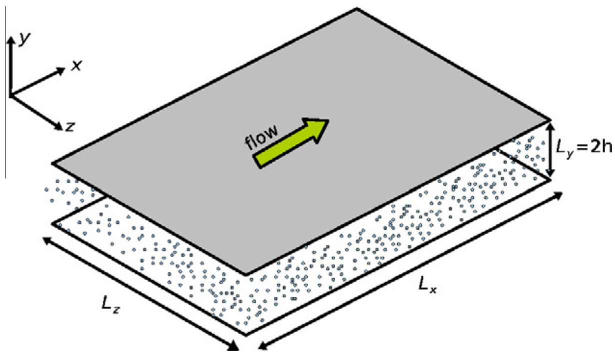

Fig. 1. Channel flow. *x*, *y*, *z* represent the streamwise, the vertical and the transverse directions respectively.

by larger, farther from the wall, structures. Finally, Niño and García (1996) used particle and dye visualization in open channel flow experiments. The authors claim that particles are picked up from the bed by flow ejection events, trapped in the core of the shear layer and raised toward the outer regions of the wall as the flow structure is stretched out into such regions. Assertion of one of the proposed mechanisms can be fully achieved only by more quantitative experimental and numerical studies of these processes. In particular, further insight may be obtained by simultaneous Lagrangian tracking of the solid phase and the flow structure surrounding the particles.

Experimentally, this has been achieved by simultaneous particle image velocimetry (PIV) for the carrier fluid, and particle tracking velocimetry (PTV) for the solid phase, by Lelouvetel et al. (2009). In that study, Lelouvetel et al. (2009) showed that particle movement away from the wall is correlated with strong ejection events. The challenge for numerical simulations is then to compute cases with high precision and sufficiently high Reynolds numbers close to experimental conditions.

In light of the above discussion, the current study focuses on determining which ejection events are responsible for particle transport away from the wall. High Reynolds number direct numerical simulations (DNS) coupled with Lagrangian tracking of solid particles are used. The DNS are conducted at high shear Reynolds number Re_τ = 590, in the range of the experimental values of Lelouvetel et al. (2009). Carrier fluid and particle characteristics are obtained simultaneously and conditioned statistical analyses are performed. The simulations allow for the identification of the ejections responsible for particle transport away from the wall. A normalized threshold for characterizing the ejections is established. Its value is compared to other studies and experiments. In future work this threshold will be used for choosing the right ejections for the simultaneous Lagrangian tracking of the solid and fluid phase.

This paper presents the numerical simulations that are performed. Results confirming the preferential concentration of solid particles in low-speed streaks are briefly shown. The conditioned statistical analysis of the flow surrounding the solid phase is then described and the segregation threshold is introduced. Finally, the segregation threshold is tested on the experimental data of Lelouvetel et al. (2009) and compared to suspension thresholds proposed in the literature.

2. Numerical simulation

2.1. Flow

The flow considered is an incompressible turbulent channel flow. The governing equations for the fluid in dimensionless form are given by:

$$\vec{\nabla}.\vec{u} = \vec{0} \tag{1}$$

$$\frac{\partial \vec{u}}{\partial t} + \left(\vec{\nabla} \times \vec{u}\right) \times \vec{u} + \vec{\nabla}\left(\frac{p}{\rho} + \frac{u^2}{2}\right) - \frac{1}{Re}\Delta\vec{u} = -\frac{1}{\rho}\vec{\nabla}p_0 \tag{2}$$

where $\vec{u}$ is the velocity vector, p the fluctuating pressure, ρ the fluid density and $\vec{\nabla}p_0$ the mean pressure gradient that drives the flow. In the following, the velocity components along the x (streamwise), y (vertical) and z (transverse) directions will be denoted u, v and w, respectively. Re is the Reynolds number based on the mean velocity U at the center of the channel, the channel half height h and the viscosity ν. In the above equations (Eq. (1) and (2)), all variables are dimensionless and h and U are the characteristic length and velocity scales.

The computational domain consisting of two infinite parallel walls is illustrated in Fig. 1. Periodic boundary conditions are imposed on the fluid velocity field in x and z directions and no-slip boundary conditions are imposed at the walls. The calculations are performed for two Reynolds numbers, Re = 2660 and Re = 12,500. Details on the simulation characteristics are given in Table 1, where N_i and L_i are the number of grid points and the domain length in direction i. Typical space and time steps are also given. At last, $Re_\tau = u^* h/\nu$ is the Reynolds number based on the friction velocity u^*. The superscript "+" denotes quantities expressed in wall units, normalized by the friction velocity u^* and the viscosity ν.

The incompressible Navier–Stokes equations in a turbulent channel flow are solved using a Galerkin spectral approximation (Fourier Chebyshev) and a variationnal projection method on a divergence free space as described by Pascal (1996) and Buffat et al. (2009). This code has been successfully applied to the study of turbulent channel flow by DNS using a very large number of grid points (~100 million) by Laadhari (2002) and Laadhari (2007).

2.2. Particles

Particles are injected into the flow at low concentrations in order to consider dilute systems. Particle–particle interactions are neglected as well as the influence of particles on the carrier fluid. Mirror conditions are applied for particle-wall bouncing. Furthermore, particles are considered to be pointwise, spherical, rigid and to obey the following Lagrangian dimensionless equation of motion:

$$St\frac{d\vec{v}_p}{dt} = (\vec{u} - \vec{v}_p)f(Re_p) - \left(1 - \frac{\rho}{\rho_p}\right)\gamma\vec{y} \tag{3}$$

$$\frac{d\vec{x}_p}{dt} = \vec{v}_p \tag{4}$$

Here, $\vec{v}_p$ and $\vec{x}_p$ are the dimensionless particle velocity and position. The action of gravity is first neglected and then in a second set of

Table 1
Characteristics of the numerical simulations for the fluid flow.

Re_τ	Re	$N_x \times N_y \times N_z$	$L_x \times L_y \times L_z$	$\Delta x^+ \times \Delta y^+ \times \Delta z^+$	dt^+
150	2660	192 × 193 × 192	$3\pi h \times 2h \times \frac{4}{3}\pi h$	9 × (0.02 ~ 3) × 4	0.03
587	12,500	384 × 257 × 384	$\frac{3}{2}\pi h \times 2h \times \frac{3}{4}\pi h$	7.2 × (0.04 ~ 7.2) × 3.6	0.033