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Contribution of inter-particle collisions on kinetic energy modification in a turbulent channel flow

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The dynamics of dispersed particles or aerosols in turbulence may be strongly influenced by particle-particle interactions. These processes, occurring at the micro-scale may be crucial in determining collision rates, coalescence and breakup of particles. In this work, we use Direct Numerical Simulation and Lagrangian particle tracking to study the binary collisions occurring in a turbulent boundary layer laden with micro-particles two-way coupled with the fluid. In particular, we focus on the effects of collision events on the amount of energy directly transferred from the carrier fluid to the dispersed phase and vice-versa. The approaching angle between two colliding particles is also calculated to characterize the different types of collisions that are responsible for particle accumulation/re-suspension.

1. Introduction

Two-phase flows (gas-particle and gas-droplets) are present in a wide range of applications in both natural and industrial fields, e.g. aerosol processing, pneumatic conveying in pipes or channels, sand transport, dust separation in cyclones, pollutant formation and control, etc. Accurate prediction of the interactions between the fluid flow and the particles is, thus, important to understand the underlying physics, to characterize them from a quantitative viewpoint and to optimize process and product quality.

Two-phase flows are extremely complex since they are governed by simultaneous and interrelated processes: (i) particle-turbulence interaction at different length scales, (ii) particle-particle collisions and (iii) surface sticking characteristics e.g. Van der Waals forces, particle wetness, electrostatic charges, etc.. Experimental study of particle collisions is a difficult task, even with the most sophisticated laser and optical technologies currently available. However it is hard to perform well-controlled experiments in which it is possible to separate the effect of one mechanism from another. Since experiments have provided valuable, but limited information to compare with theoretical models, detailed numerical simulations represent a more reliable tool to investigate the two-phase flow complex dynamics.

In this study Direct Numerical Simulation (DNS) is used to solve completely the Navier Stokes equations down to the Kolmogorov scales to obtain the turbulent flow field in a turbulent channel flow. A Lagrangian particle technique is employed to track the motion of $O(10^6)$ particles released in the air flow under the two-way coupling assumption.

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Previous studies on a channel flow (see Picciotto et al. 2005, Rouson and Eaton, 2001 among others) under dilute conditions have demonstrated that particles tend to collect in correspondence to the walls into high strain and low vorticity regions. When this occurs, the specific assumption for dilute system is no longer valid if the viscous sublayer is considered and the flow becomes locally dense. In addition, the motion of the particles at the wall, in the flow configuration considered here, is dominated by collisions and not by turbulence changes as in the channel core. The main collision effect is to decorrelate particles from the coherent structures responsible for their accumulation and to spread them in the domain. In this way particles may face different fluid velocities with respect to the situation without collisions and so modify their turbulent kinetic energy.

2. Methodology

The Navier Stokes equations are solved using a pseudo-spectral Direct Numerical Simulation. The flow into which particles are introduced is a turbulent Poiseuille channel flow of air (❒ =1.3 kg/m, ■ =15.7 $10^{-6}m^2/s$) assumed incompressible and Newtonian. The reference geometry, visible in Figure 1, consists of two infinite flat parallel walls. Periodic boundary conditions are imposed in the stramwise (x) and spanwise (y) direction and no-slip boundary condition is imposed at the walls. All variables are normalized by the wall shear velocity $u_♦$, the fluid kinematic viscosity ■

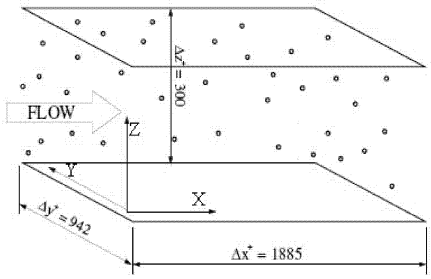

Figure 1: Channel geometry

and the half channel height h. The shear velocity is defined as $u_♦$ 🖬 ☎♦w/❒◑🗁🖘🖹, where ♦w is the mean shear stress at the wall. Calculations are performed on a computational domain of 1885, 942 and 300 wall units in x, y and z direction discretized with 128x128x129 nodes. The shear Reynolds number is $Re_♦ = u_♦ h/■ = 150$. The time step used is $t^+ = 0.045$ in wall time units.

A Lagrangian particle tracking coupled with the DNS code is used to calculate particles trajectories in the flow field. Since the particle density is much greater than the fluid, the equation of particle motion can be reduced only to the significant forces acting on the

particle. Due to the complicative effects of particle-particle collisions and two-way coupling taken into account in this work, only the Stokes drag has been considered to influence the particle motion. The equation of particle motion becomes:

$$\frac{dv}{dt} = -\frac{3}{4}\frac{C_D}{d_p}\frac{}{}(v - u)|v - u| \tag{1}$$

where v and u are the particle and fluid velocity vectors, d_p is particle diameter. The drag coeffcient C_D is given by:

$$C_D = \frac{24}{Re_p}(1 + 0.15 Re_p^{0.687}) \tag{2}$$

where the particle Reynolds number is equal to $Re_p = d_p |u-v| / \nu$, being ν fluid kinematic viscosity. Correction for C_D is necessary since Re_p does not necessarily remain small, in particular for depositing particles. A 4th order Runge-Kutta scheme is used to integrate the equation of motion and 6th order Lagrangian polynomials are employed to interpolate fluid velocities at particle position.
One set of 10^6 particles characterized by a relaxation time equal to $\tau_p^+ = d_p^2 \rho_p / 18 \mu \tau_f = 25$ has been considered in the simulation. Particle relaxation time is made dimensionless using wall variables and it is equal to the Stokes number.
At the beginning of the simulation, particles are distributed homogeneously over the computational domain and their initial velocity is set equal to that of the fluid at particle position. Moreover, particles are assumed to be pointwise, rigid and spherical. Periodic boundary conditions are imposed on particles in both streamwise and spanwise directions, elastic reaction is applied when the particle centre is a distance less than $d_p/2$ from the wall. Elastic reaction was chosen since it is the most conservative assumption when studying the particle prefential concentration in a turbulent boundary layer.

2.1 Two-way coupling

To account for the action of the dispersed particles onto the fluid a source term $\tilde{f}^k_{2w}$ has been added to the Navier Stokes equation. ($f^k_{2w} = 0$ for simulations run under the one-way coupling assumption). For a generic volume of fluid Φ_p containing a particle, the action-reaction law imposes that:

$$\int_{\Phi_p} f_{2w}(x)\, dV = -f_{fl} \tag{3}$$

where f_{fl} is the force exerted on the particles by the fluid. The term $\tilde{f}_{2w}$ can be obtained by adding the contributions of each particle:

$$f_{2w}^{k} = \sum_{p=1}^{n_p} f_{2w}^{k}{}_{p} \qquad (4)$$

where n_p is the number of particles. With the point-source approximation, $f_{2w}(x) = -f_{fl}\,\Omega(x - x_p)$, where $\Omega(x)$ is the Dirac's delta function.

2.2 Particle-particle interactions

An hard sphere collision model has been implemented into the code. The assumptions for particle-particle collisions are: (i) the particle deformation is neglected so that the distance between the particle center of mass is equal to the sum of the radii throughout the collision process; (ii) Collisions are instantaneous, inelastic and frictionless; (iii) particle kinetic energy and momentum are perfectly conserved i.e. the restitution coefficient is equal to 1.

The particles are allowed for multiple collisions within a single time step and their time advancement can be broadly divided into five steps: (i) update particle velocity by solving the equation of motion described in the previous section; (ii) use this velocity to identify the particles that will collide within the current time step by calculating the time to collision for each particle pair; (iii) advance particles to the minimum time to collision; (iv) enact the elastic collision between the two identified particles; (v) search for any other possible collision within the same time step or go to the next time step.

A neighbour approach with the linked list method proposed by Sundaram and Collins, (1996) has been used to reduce the computational cost required to seek for possible collisions in the domain. To this aim, the channel has been divided into a special exploring lattice, so that the search is limited to the 26 neighbouring cells of the one containing the particle.

The time to collision is calculated as the time required by a particles pair to reach a relative distance equal to the sum of the radii using the following equation:

$$\left| r_{ij} + v_{ij} t_{ij} \right| = d_p^2 \qquad (5)$$

The post-collisional particle velocity is calculated in a cartesian reference frame centered in the center of mass of one of the particles and it is then translated back into the global reference frame. Based on the previous assumptions the post-collisional velocity of the two particles is derived from a simple momentum and energy conservation law.

The approaching angle between two colliding particles, calculated from the dot product between the particle relative velocity and their relative distance as proposed by Chen et al., (1998) is used to have a better comprehension on particle collision dynamics.

3. Results

3.1 Fluid statistics

Object of this paper is to study the energy modification for both particles and fluid due to two-way coupling and collision effects. In this section we will briefly discuss the

results obtained from two-way coupling simulations with and without collisions with those obtained from one-way coupling simulation.

The mean velocity profiles calculated under the one-way coupling assumption deviate only slightly, if not negligibly, from those obtained with the two-way coupling without collision. We do not show the Figures of the mean fluid velocity since they exhibit the expected behavior and do not add to the discussion.

Due to the high computational cost required to carry on the calculations, the simulations with inter-particle collisions are still running. Preliminary statistics on fluid velocity have shown that a slight reduction on the mean fluid velocity is present if collisions are taken into account. Even if this result is consistent with those obtained in the literature (Li et al., 2001, Nasz and Ahmadi, 2007) on the mean fluid velocity and turbulent intensities modifications due to collision effects, further investigations will be performed.

3.2 Particle statistics

The issue addressed in this section is: how is particle energy affected by collisions and which is the energy associated with colliding particles? We'll try to answer this question by comparing the statistics on particle kinetic energy, collision angle and particle relative velocity obtained from simulations considering one-way coupling, two-way coupling with and without collision.

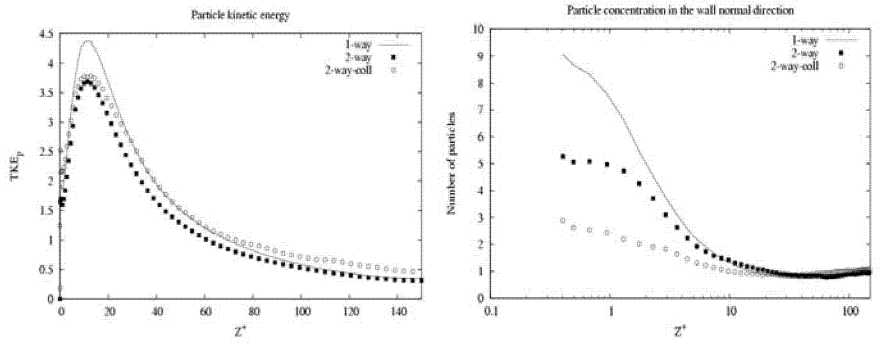

Figure 2: --Left--Particle kinetic energy profile; --Right--Particle concentration profile. One-way coupling (Line), Two-way coupling with and without collisions (Symbols) Half of

Figure 2 (Left) shows particle kinetic energy profiles. Values are averaged in both space (over the streamwise and spanwise directions) and time (over the entire time span available for each simulation). We can notice that the energy associated with particles in the two-way coupled simulations is higher if collisions are taken into account. Since other forces are neglected, the only force that can influence the motion of particles is the Stokes drag, and in particular the relative velocity between the fluid and the particle. The one-way coupled simulation shows a higher particle energy due to the higher particle concentration at the wall as visible in Figure 2 (Right).

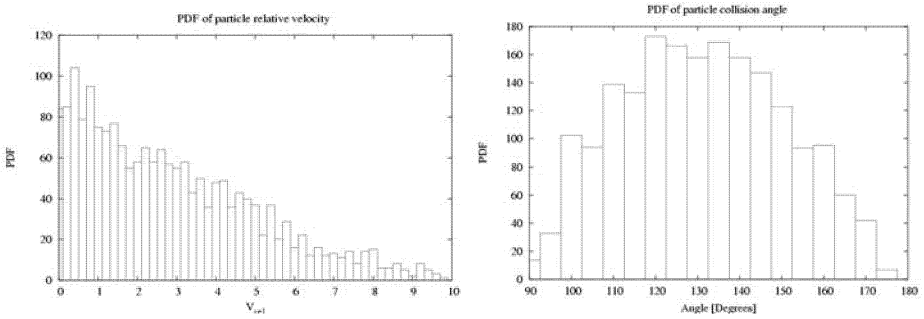

Figure 3: --Left --PDF of the relative velocity of the colliding particles: --Right--PDF of

To have a better insight on the energy associated with the colliding particles the PDF of the relative velocity between each colliding couple has been calculated, as visible in Figure 3 (Left). We can notice that most of the collisions occur between particle pairs characterized by almost the same velocity. A peak is indeed visible in correspondence to low relative velocities. This result is quite surprising since two different collision types were expected: high energy collisions characterized by a high relative velocity between two particles and low energy collisions. The first type might appear when a particle coming from the center of the channel collides with particles already segregated at the walls. The second refers to collisions between particles already accumulated either at the channel walls or at the edges of the vortices moving one in front or close to the other.

In this view the collision angle can help to characterize the type of collision and disclose the collision dynamics. In Figure 3 (Right) the PDF of the collision angle is shown. Most of the collisions are characterized by an angle of 130 degrees which corresponds to particles close to each other confirming that the collisions are mostly of the low energy type. Indeed, if the collision is of the first type, the collision angle would be close to 90 degrees.

4. Conclusions

This paper addresses the issue of energy modification in a developed turbulent boundary layer due to particle-particle and particle to fluid interactions under one-way and two-way coupling assumptions.

It is well known from the literature that particles tend to segregate at the channel walls. In this region the e

ffect of the dispersed phase on turbulence is no longer negligible and the dilute flow assumption is not valid locally. Simulations with one-way coupling and two-way coupling between particles and fluid were performed to investigate on energy modi

cation both on the fluid and on the particles. Particle-particle interactions have been also considered in the two-way coupled simulation.
Mean velocity profiles of the fluid velocity have shown almost no differences between the one-way and the two-way approach without collisions as found in many previous studies.
The two-way coupled simulation considering collisions has shown higher particle kinetic energy with comparison to the simulation without inter-particle collisions. The one-way coupled simulation exhibits the highest particle kinetic energy due to the higher particle concentration at the walls.
Most of the collisions are characterized by low relative velocity between the two colliding particles and a collision angle close to 130 degrees. This confirms that the colliding particles are those already segregated either at the channel walls or at the vortex edges.

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