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Direct Numerical Simulation of inertial particle accelerations in near-wall turbulence: comparison with experiments

Lavezzo[a], V., Soldati[a], A., Gerashchenko[b], S., Warhaft[c], Z., Collins[c], L.
[a] Università degli Studi di Udine – Udine – Italy
[b] California Institute of Technology – CA- USA
[c] Cornell University – Sibley school of Mechanical and Aerospace Engineering – Ithaca – NY-USA
and International Collaboration for Turbulence Research (ICTR)

Direct Numerical Simulation and Lagrangian Particle Tracking technique are used to study particle acceleration in a turbulent channel air flow. Recent experiments in a turbulent boundary layer (Gerashchenko et al. 2008) revealed surprising trends for inertial particle accelerations in the near-wall region with respect to homogeneous and isotropic turbulence. The objectives of the present study are (i) to validate our code against the experiments and (ii) to gain further insight into the findings by Gerashchenko and co-authors. Qualitative and quantitative agreement are found in the mean and rms profiles of particle acceleration.

1. Introduction

Particle acceleration in turbulent flows can be considered a key issue for many environmental and industrial applications e.g. cloud formation, atmospheric transport, combustion systems etc. It is thus, important to understand the nature of the acceleration since it affects the collision rate, the dispersion of droplets or particles in the carrier fluid.

Many experimental and numerical studies on particle acceleration can be found in literature, but most of them deal with homogeneous and isotropic turbulence rather than wall-bounded flows which represent the objective of the present work. Previous studies focus mainly on the effect of inertia on particle acceleration and the relationship between acceleration and fluid coherent structures. It has been found that particle acceleration is an intermittent phenomenon affected by the filtering and sampling exerted by the particles on the turbulent flow field. Ayyalasomayajula et al. (2008) studied by means of Lagrangian tracking inertial particle acceleration in isotropic turbulence created with two-dimensional array of potential-flow vortices. They found that the coupling between sampling and filtering exerted by the particles on the fluid flow affects particle acceleration. In particular, the acceleration variance was found to be decreasing with increasing inertia and the pdfs tails narrower.

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Similar results have been obtained by Bec et al., (2006) who found that for small St number particles (St<<1) the acceleration coincides with fluid acceleration and the net effect of inertia is a reduction of the acceleration rms due to preferential accumulation. This latter doesn't affect the large Stokes number particle acceleration which, on the contrary, is suppressed by the low-pass filter action exploited by the particles on the fluid velocity. The same argument is used by the authors to explain the inertia dependence of the acceleration pdf tails, which become more skewed as the St number increase.

Recent experiments in a turbulent boundary layer (Gerashchenko et al. 2008) revealed surprising trends for inertial particle accelerations in the near-wall region. In particular, acceleration variance was seen to increase with increasing inertia, contrary to what is found in isotropic turbulence.

To gain further insight into these findings we perform Direct Numerical Simulations (DNS) of a horizontal channel flow with suspended inertial particles tracked in the Lagrangian frame of reference. The DNS parameters have been chosen to match those of the experiment, based on boundary layer scaling. Three swarms of particles with different Stokes numbers (0.8, 1.6 and 10.7) have been simulated. Results for the mean and rms profiles of particle acceleration are in good agreement with the experimental findings. A coupling between shear and gravity is considered the cause of high variance for high Stokes number particles in proximity of the wall, as it will be discussed in the following sections.

2. Methodology

Navier Stokes equations are solved using a pseudo-spectral Direct Numerical Simulation. Particles are dispersed in a Poiseuille turbulent air flow assumed to be incompressible and Newtonian (ρ_f= 1.2 Kg m^{-3} , ν= 1.5 10^{-5} m^2 s^{-1}). The domain, visible in Figure 1, is an horizontal channel bounded by two infinite parallel walls of length $4\pi h$ in the streamwise (x) direction, $2\pi h$ in the spanwise (y) direction and 2h in the wall-normal (z) direction where h is equal to 0.04 m or 300 wall units. The domain has been discretized with 256 x 256 x 257 nodes. Periodic boundary condition is imposed in the streamwise and spanwise direction whilst no-slip boundary condition is enforced at the upper and lower wall. Details of the numerical method can be found in some of our previous works (Marchioli et al, 2007, Picciotto et al, 2005).

For a better comparison with the experimental work by Gerashchenko et al. (2008), we chose the parameters for the simulation accordingly. In Table 1 the parameters for the fluid flow are summarized. The shear velocity has been chosen equal to u_τ=0.112 m/s. The shear Reynolds number based on the channel half height h and the shear velocity $u\tau$ thus, becomes $Re_\tau = u_\tau h/\nu = 300$.

Table 1: Simulation parameters used to match the fluid flow in the experimental work by Gerashchenko et al. (2008)

	ρ_f [Kg/m^3]	ν [m^2/s]	$u\tau$ [m/s]	Height [m/s]	$Re\tau$
DNS	1.2	1.5E-05	0.112	H=0.04	300
Gerashchenko 2008	1.2	1.5E-05	0.117	δ=0.06	470

We can observe that the Reynolds number is slightly lower than the two employed in the experiments, but it has been seen (Marchioli et al. 2007) that it has little effect on particle behavior and that particle timescale normalized to wall variables may be used as the representative Stokes number.

Three sets of 320,000 particles characterized by different diameter have been released into the air flow. As for the fluid we matched particle parameters with those employed by Gerashchenko and co-authors as visible in Table 2. The Stokes number, calculated as the ratio of the particle response time $\tau_p = Dp^2\rho_p/18\nu$ to the flow characteristic timescale $\tau_f = \nu/u^2_\tau$ has been set equal to $St = \tau_p/\tau f$ 0.80, 1.60 and 10.7. Since the particle density ρ_p is much higher than the one of the fluid, the equation for particle motion reduces to a balance of the Stokes drag and gravity.

Table 2: Particle parameters used in the simulation in comparison with the experimental work by Gerashchenko et al. (2008)

	ρ_p [Kg/m^3]	D_p [μm]	τ_p^+=St
DNS	1000	18.4	0.80
		26.1	1.60
		67.6	10.7
Gerashchenko 2008	1000		0.80
			1.60
			10.7

The assumptions for particle modeling are: (i) particles are point-wise (ii) non-deformable, (iii) rigid and spherical. The effect of particles on the fluid is neglected so one-way coupling is assumed between the dispersed and the carrier fluid.

The time step used for both fluid and particle advancement has been chosen equal to 1/10 the smaller particle response time equal to $\Delta t = 1 \cdot 10^{-4}$s in order to satisfy the Nyquist sampling criterion to accurately follow curved trajectories. The particles are randomly distributed in the domain at the beginning of the simulation, with a velocity equal to the fluid velocity at particle position.

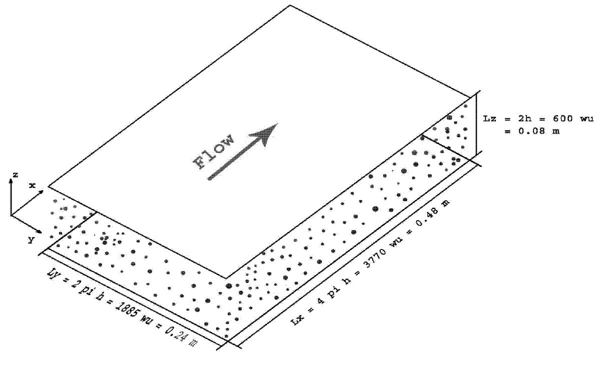


Figure 1: Channel geometry

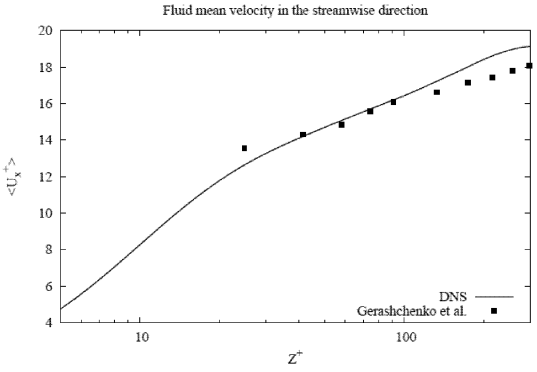


Figure 2: Fluid mean velocity, streamwise component. Half of the channel is considered for visualization. Lines are DNS results, symbols the experimental values.

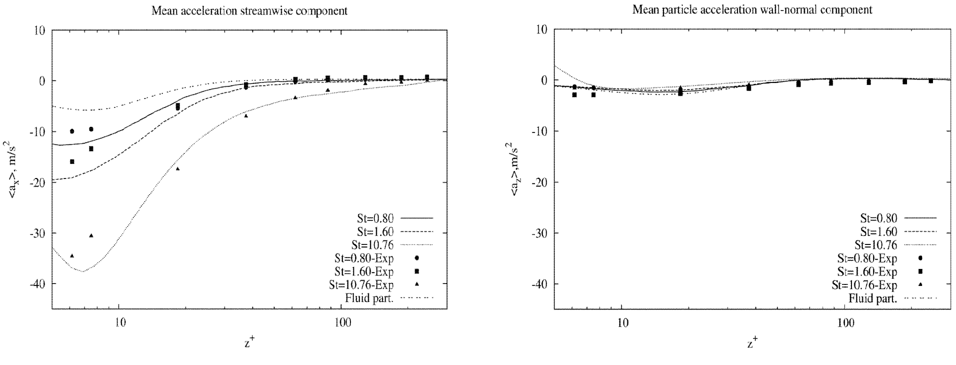
3. Results

In this section results of the comparison between the experimental work of Gerashchenko et al. (2008) and the present simulation are presented. Before going into detail on particle acceleration it is useful, for the following discussion, to compare the two flows in which particles have been dispersed.

In Figure 2 the mean fluid velocity profile in the two cases is presented. Good agreement is found close to the wall, while a slight deviation is present at the center of the channel. This was expected, since the flow in the simulation is bounded by an upper wall while a free stream boundary can be considered in the experiments. Since the two flows compare well to each other in terms of velocity we can consider half of a channel a good approximation of a turbulent boundary layer and expect a good agreement also on particle behavior.

In Figure 3 the mean acceleration profiles for three Stokes number particles are shown. Statistics are taken over a time interval of 20,000 time steps i.e. 600t+, starting at 35 t+, which corresponds to few larger particles response times. In the streamwise direction, Figure 3(a), good agreement between the DNS results and the experiments is observed. Slight discrepancies for Z+ < 10 can be the result of either difficulties in the measurements close to the wall or the presence of boundaries on which the particles are bouncing in the simulation. Very good agreement is found also in the wall-normal direction as visible in Figure 3(b). The highest Stokes number particles (St = 10.7) deviate from the experimental values for Z+ < 7 wall units as the result of an higher number of particles that decelerate, reach the wall due to inertial and gravitational effects and then bounce giving rise to a wall normal acceleration.

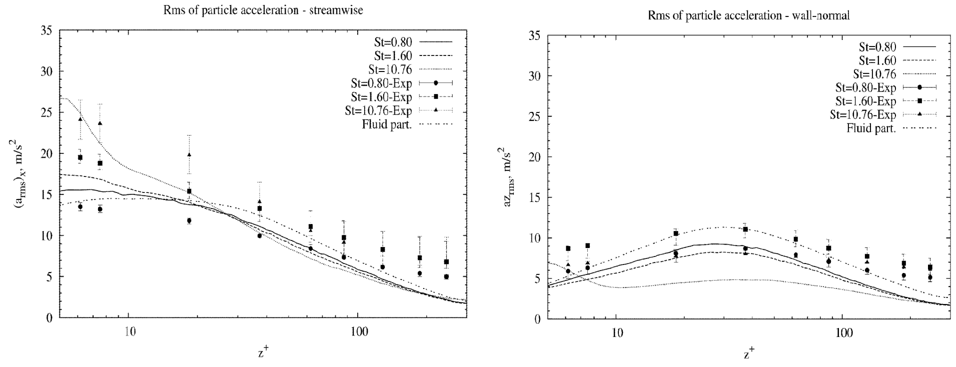
Comparing high order statistics it is possible to observe that experimental and simulation values compare well from a qualitative view point while quantitatively slight differences are present. This can be associated to the different fluid velocity faced by



(a) (b)

Figure 3: Mean particle acceleration in the streamwise (a) and wall-normal (b) direction. Symbols are the experimental values, lines the simulation results.

the particles in the two flows, as previously described. DNS results, indeed show lower values in correspondence to the channel core, as visible in Figure 4(a), where the streamwise component of the rms of particle acceleration is plotted against the wall-normal direction. The same trend can be observed also in the wall-normal direction (Figure 4b) with the experimental values shifted upwards with respect to the DNS ones. Furthermore we can notice that in the streamwise direction, in correspondence to the wall, the variance is varying with Z+. In particular its value is increasing with increasing Stokes number as described by Gerashchenko and co-authors. This result confirms the difference of a wall shear flow from homogeneous and isotropic turbulence where a decrease in acceleration variance is observed with increasing Stokes number as described in Bec at al.(2006). It is, thus clear that the presence of a wall affects particle behaviour and the reasons can be found in the coupling between the shear and the gravity force, but this is still under investigation.



(a) (b)

Figure 4: Rms of particle acceleration in the streamwise (a) and wall-normal (b) direction. Symbols are the experimental values, lines the simulation results.

4. Conclusions

Direct Numerical Simulation and Lagrangian particle tracking techniques have been used to study particle acceleration in a turbulent horizontal channel air flow. The motivation for this work comes from the results on particle acceleration obtained by Gerashchenko and co-authors (2008) in a turbulent boundary layer. They found an acceleration variance increasing with increasing Stokes number which was in contrast with previous studies in homogeneous and isotropic turbulence. For a better comparison the parameters used in the present simulation have been chosen equal to the ones employed in the experiments. Three sets of particles have been released in the turbulent flow to evaluate the effect of inertia on particle acceleration.

Two main conclusions can be drawn (i) our code can be considered reliable to solve the flow in a turbulent boundary layer and (ii) we confirm the findings of Gerashchenko and co-authors on acceleration variance.

A good agreement on the velocity profile in the two flows has been observed apart away from the wall where the different boundary conditions play an important role. Mean and Rms profiles of particle acceleration showed good agreement between experiments and simulation. In particular even if the results in the rms profile show a deviation from the experiments in quantitative terms, the trend has been correctly captured. The high Stokes number particles show a higher variance in correspondence to the wall, thus confirming the experimental findings. Reasons for this increase are still under investigation, but it is reasonable to think it is due to a coupling between shear and gravity forces. To confirm this hypothesis further simulations in absence of gravity are currently running.

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