FORMATION OF NEAR-WALL PARTICLE-STREAKS IN PARTICLE-LADEN WALL-BOUNDED TURBULENT FLOWS

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ABSTRACT

In wall-bounded turbulent flows laden with small heavy particles, the turbulence pushes the particles towards the wall, where the particles tend to cluster into streamwise-elongated streaks. We study the process of formation of the particle-streaks, and its relation with the near-wall turbulence, using point-particle Eulerian-Lagrangian large-eddy simulations in a fully-developed turbulent channel flow laden with small heavy particles. In the literature, the formation of the particle-streaks has been generally attributed to the sweeps and ejections associated with the passage of streamwise vortices further away from the wall. However, we show that the sweeps and ejections associated with the passage of the streamwise vortices are not directly associated with the formation of the particle-streaks. We show that the formation of the particle-streaks is closely related with the fluid streaky-pattern close to the wall. We present a new characterization of the fluid-streaky pattern in terms of its streamlines, and show that the formation of the particle-streaks is slow process of collection associated with the convergence of these streamlines into a few "baselines". These "baselines" have a very good correlation with the particle-streaks. They both have an extremely-long life, and once formed they remain roughly in the same position for a long time.

INTRODUCTION

In wall-bounded turbulent flows laden with small heavy particles, the turbulence pushes the particles towards the wall. This leads to a high particle-concentration very near the wall, where the particles tend to cluster into streamwise-elongated streaks. This particle-clustering can affect significantly the performance of numerous industrial processes, like: catalytic reactors, risers and downers, coal combustors, pneumatic conveying, etc. (Portela and Oliemans, 2005).

Particle-streaks have been observed by several authors, both experimentally and in numerical simulations (e.g., Rashidi *et al.*, 1990; Eaton and Fessler, 1994; Niño and Garcia, 1996; Rouson and Eaton, 2001). However, the mechanisms for their formation, and how they interact with the turbulence structure, are still poorly understood. Essentially, there exist two phenomena: (i) the accumulation of particles near the wall, and (ii) the formation of the particle-streaks. The accumulation of particles near the wall can be understood in terms of the turbophoresis: the pushing of particles towards regions of low turbulence intensity. The turbophoresis is due to the gradient in the particle-velocity fluctuation associated with a gradient in the fluid turbulence intensity, and it can be understood using a simple balance of momentum in the direction normal to the wall: similarly to the Reynolds-stresses for the fluid, a gradient in the particle-velocity fluctuation results in a net force in the opposite direction. This force pushes the particles towards the wall until is balanced by an opposing gradient in the particle-concentration, leading to a high concentration of particles near the wall (Young and Leeming, 1997; Portela *et al.*, 2002). However, this only explains the high accumulation of particles near the wall in an average-sense, and it does not explain how/why the elongated particle-streaks are formed.

The particle-streaks are closely related with the preferential concentration of the particles in the low-speed fluid-streaks near the wall (e.g., Eaton and Fessler, 1994; Niño and Garcia, 1996; Rouson and Eaton, 2001). Since the formation of the fluid streaky-pattern near the wall is closely related with the sweeps and ejections promoted by the passage of streamwise vortices further away from the wall, by extension, in the literature the formation of the particle-streaks has been also generally attributed to the passage of the streamwise vortices. For example, Marchioli and Soldati (2002) revised the existing literature, and, building on previous observations that sweeps/ejections are closely associated with the motion of the particles towards/away from the wall, they attributed both the high particle-concentration near the wall and the occurrence of the particle-streaks to a sequence of events associated with the passage of the streamwise vortices, closely linked to the dynamics of the turbulence structure near the wall. However, as mentioned above, the accumulation of particles near the wall can be understood using simple momentum-averaging concepts, akin to the Reynolds-averaging for single-phase flows,

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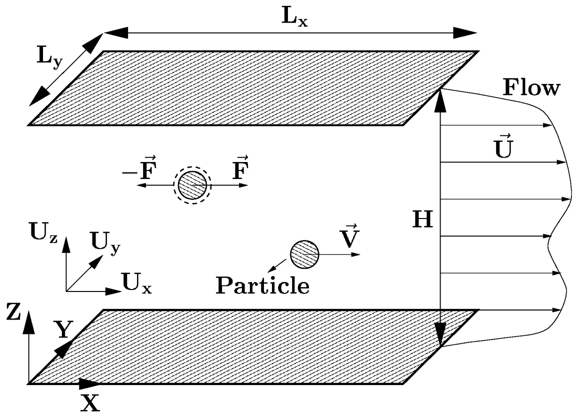

Figure 1: Particle-laden channel flow.

and it does not require a particular dynamics for the near-wall turbulence structure. Furthermore, the particle-streaks are very elongated and have a very-long life-time, whereas the streamwise vortices are much shorter and have much smaller time-constants. This makes it difficult to understand how the streamwise vortices could be directly responsible for the formation and maintenance of the particle-streaks.

In this work, we study the process of formation of the particle-streaks, and its relation with the near-wall turbulence structure, using point-particle Eulerian-Lagrangian large-eddy simulations in a fully-developed channel flow laden with small heavy particles. Similarly to previous authors, we observed the movement of the particles towards/away from the wall promoted by the sweeps/ejections associated with the passage of strong streamwise vortices. However, we show that this normalwise velocity of the particles does not play a direct role in the formation of the particle-streaks. We show that the formation of the particle-streaks is a slow process of collection due to a local interaction with the fluid streaky-pattern.

First, we briefly present the numerical method and the parameters used in the simulation. Then, we present an alternative characterization of the fluid streaky-pattern, in terms of its streamlines. We show that the streamlines converge into a few "baselines" and that this convergence can explain the formation of the particle-streaks. Finally, we compare simulations in which the normalwise velocity of the particles is suppressed with the full-simulations, and show that the process of formation of the particle-streaks is essentially the same in both cases.

NUMERICAL SIMULATION

The situation under consideration is sketched in figure 1. We use a standard point-particle Eulerian-Lagrangian simulation, which is adequate, provided that the particles are significantly smaller than the relevant flow scales (Portela and Oliemans, 2001). In this approach, the interaction between the particles and the fluid is considered through a force applied at the center of the particle. Since the volume-fraction of particles is very small, the effect of the particles on the continuity equation is neglected. The interaction between the particles and the fluid is felt through an exchange of momentum: the Navier-Stokes equation contains an extra particle-forcing term, and is solved together with the equation of motion of each particle.

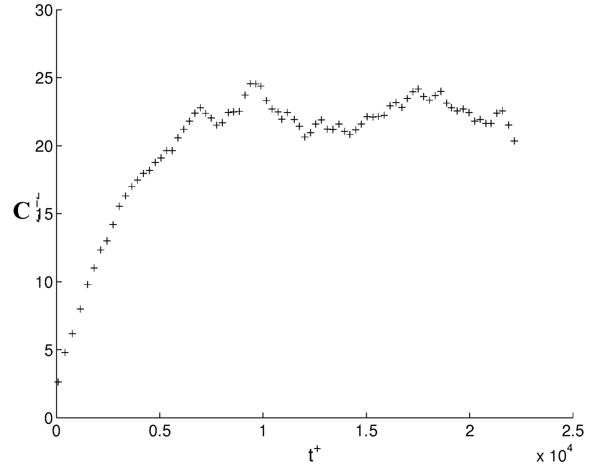

Figure 2: Time-evolution of the particle-concentration very close to the wall ($Z^+ = 2$), normalized by the average particle-concentration in the channel.

For the numerical solution we use a standard two-step predictor-corrector solver for incompressible flows. The flow is driven by a pressure gradient imposed along the streamwise direction, and we impose periodic boundary conditions both in the streamwise and spanwise directions. The particles are tracked using a second-order Adams-Basforth scheme, with elastic bouncing (specular refection) at the walls. Details of the numerical method can be found in Portela and Oliemans (2003).

We performed two types of simulations: (i) one-way coupling, where the influence of the particles on the flow is neglected, and (ii) two-way coupling, where the back-forcing of the particles on the fluid is taken into account. In both cases, we used linear (Stokes) drag for the force acting on the particles, and did not consider gravity and inter-particle collisions. Te use of Stokes drag is justified when we have small heavy particles (Maxey and Riley, 1983), which is our case. In order to focus on the particle-fluid interaction mechanisms that lead to the formation of the particle-streaks, we did not consider gravity and collisions. However, we should note that for large particle-concentrations inter-particle collisions play an important role, leading to a significant reduction in the particle-concentration near the wall and to weaker particle-streaks (Li *et al.*, 2001; Yamamoto *et al.*, 2001).

We used an uniform grid in the periodic (streamwise and spanwise) directions and an hyperbolic-tangent grid-stretching in the normalwise direction. For the results presented here, with a Reynolds number based on the wall-shear velocity, u_τ, and the channel height, H, equal to $Re_\tau = 500$, we used a high-resolution LES with the standard Smagorinsky model and Van Driest wall-damping, with 64 grid-points in the periodic directions and 48 grid-points in the normalwise direction ($\Delta X^+ = 39$, $\Delta Y^+ = 15$, $\Delta Z^+ = 4$ at the wall and $\Delta Z^+ = 13$ at the center)[1]. We also performed a few DNS simulations at a lower Reynolds number ($Re_\tau = 360$) and observed essentially the same behavior described here. The domain of the simulation is equal to $L_x = 5H$ in the streamwise direction and $L_y = 2H$ in the spanwise direction. In order to check

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[1] Throughout this paper, the superscript $^+$ is used to denote a quantity in wall units; i.e., non-dimensionalized using the wall-shear velocity, u_τ, and the kinematic viscosity, ν.

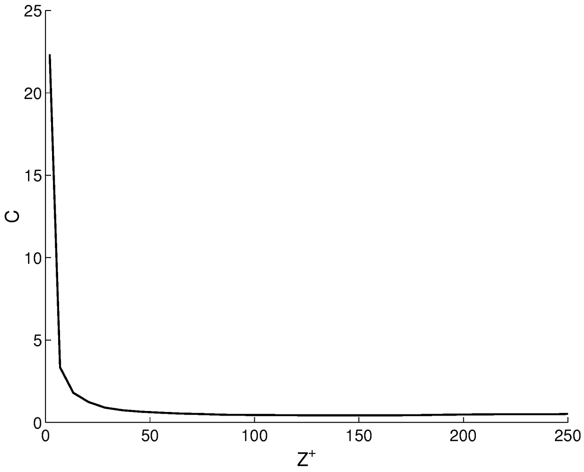

Figure 3: Statistically-steady particle-concentration profile (normalized by the average particle-concentration in the channel).

any possible influence of the domain in the results, we performed also a few simulation with $L_x = 10H$ and $L_y = 4H$, and obtained similar results.

We used a total number of particles $N_p = 4 \times 10^5$, with $D_p/H = 1 \times 10^{-3}$ and $\rho_p/\rho = 8000$, where D_P is the particle diameter, ρ_p is the density of the particles and ρ is the density of the fluid. This corresponds to $D_p^+ = 0.5$, and to a particle relaxation-time $T_p^+ = 111$. The particle volume and mass fractions are, respectively, $\phi_v \approx 2 \times 10^{-5}$, $\phi_m \approx 0.16$. Typically, for this mass fraction two-way coupling effects are small, even though not negligible (Portela *et al.*, 1999). Here, we focus mainly on the one-way coupling simulations, and how the turbulence structure determines the formation of the particle-streaks.

The average length and time Kolmogorov-scales can be estimated from the average dissipation as $L_k^+ \approx 2$ and $T_k^+ \approx 4$. This shows that the particles are smaller than L_k and that the particle relaxation-time is much larger than T_k. In this case, the use of a high-resolution LES ensures that the particles are significantly smaller than the grid, and, since they are driven mostly by the large turbulence-scales, with a characteristic time of the same order or larger than the particle relaxation-time, the effect of the subgrid scales is negligible (Portela and Oliemans, 2001 and 2002).

RESULTS

The simulations were started without particles. After a statistically-steady state is reached, the particles where introduced in the flow with a randomly-uniform distribution. After their introduction, the number of particles remains constant. When one particle leaves the domain, it is re-introduced with the same velocity at the opposite side.

Due to the turbophoresis, the particles are pushed towards the wall, and the concentration there keeps increasing in time, as shown in figure 2. As shown by Portela *et al.* (2002), this process is quite slow and it takes an interval of time $\Delta t^+ \approx 7500$ until a statistically-steady particle-concentration is reached. This time corresponds, roughly, to a "developing-length" of about $300H$ (i.e., it corresponds to a distance of about 300 channel-heights, when travelling with the bulk velocity in the channel). The statistically-steady concentration is shown in figure 3, where we can see the large increase in particle-concentration near the wall.

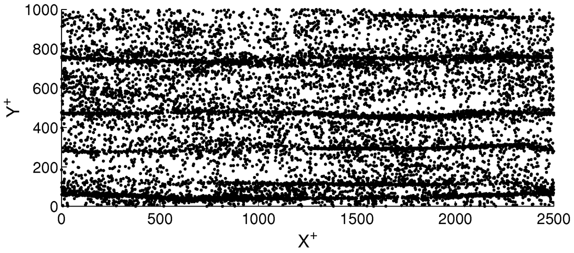

Figure 4: Snapshot of the distribution of the particles in a plane very close to the wall ($Z^+ = 2$).

The concentration very near the wall is far from uniform and the particles organize themselves into streamwise-elongated streaks, as shown in figure 4. As observed previously by several authors, these particle-streaks are closely related with the preferential concentration of the particles into the low-speed fluid-streaks, as shown in figure 5. As mentioned in the introduction, since the formation of the fluid streaky-pattern is closely related with the sweeps and ejections promoted by the passage of streamwise vortices further away from the wall, by extension, in the literature the formation of the particle-streaks has been also generally attributed to the passage of the streamwise vortices. This lead us to look for an association between the passage of the streamwise vortices and the gathering of the particles into the elongated streaks. We found that the passage of strong streamwise vortices leads to the local resuspension and deposition of the particles (Portela and Oliemans, 2003). However, we did not find any association between the passage of the vortices and the formation and maintenance of the particle streaks.

Actually, it is difficult to understand how the streamwise vortices could be directly responsible for the formation and maintenance of the particle-streaks, since both structures have very different length and time scales. The particle-streaks are extremely long (here, they occupy the entire streamwise-length of the domain, $L_x^+ = 2500$), take a long-time to be formed (here, the formation-time of the particle-streaks is $\Delta t^+ \approx 1000$), and once formed they have an extremely-long life, remaining essentially in the same position almost indefinitely (see figure 9). On contrary, the streamwise vortices have a short-length (of the order of 100 wall-units), can be formed and disappear rather quickly, and do not remain in the same spanwise/normalwise position for very-long times (e.g., Portela, 1997). This lead us to look for other possible mechanisms for the formation of the particle-streaks, not directly associated with a particular dynamics of the streamwise vortices.

Usually, the fluid streaky-pattern is characterized in terms of the pattern of the elongated low-speed regions (e.g., Jimenez *et al.*, 2004). Here, we explore a new characterization, using the streamlines of the velocity field in the plane parallel to the wall. As shown in figure 6, these streamlines tend to converge. This convergence requires a long streamwise-length, but, eventually, the streamlines converge into a few "baselines", as shown in figure 7, where the periodicity of the velocity field was used in order to construct a long domain (we checked the sensitivity of the results to the streamwise and spanwise lengths of the actual domain of the simula-

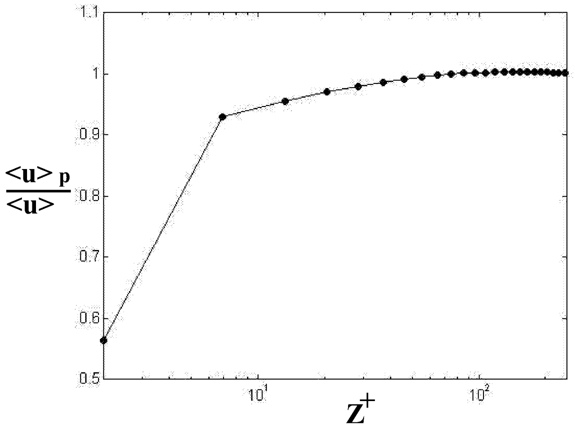

Figure 5: Average streamwise-velocity at the position of the particles, divided by the average streamwise-velocity of the fluid, as a function of the distance to the wall.

tion, and similar results are obtained with $L_x = 10H$ and $L_y = 4H$). These "baselines" have a very-good correlation with the particle-streaks; essentially, a one-to-one correlation, as shown for a particular snapshot in figure 8. Furthermore, once formed, both the "baselines" and the particle-streaks have an extremely long-life and remain roughly in the same position. This is illustrated in figure 9, which shows two snapshots of the particle-streaks and "baselines", separated by an interval of time $\Delta t^+ \approx 1000$.

The correlation between the particle-streaks and the "baselines", and their long-life, indicates that the formation of the particle-streaks is a slow process of collection due to the gathering of the particles promoted by the converging streamlines. This is further confirmed by simulations in which the velocity of the particles normal to the wall was set to zero. These simulations show that the particle-streaks, and the time it takes for its formation, are quite similar to the actual case (without the suppression of the velocity of the particles normal to the wall). This is illustrated in figure 10, which shows the "baselines" and the particle-streaks formed after $\Delta t^+ \approx 1000$, in a simulation in which the particles are initially random-uniformly distributed and the velocity of the particles normal to the wall is set to zero. This shows that the normalwise velocity of the particles, associated with sweeps/ejections promoted by the passage of the streamwise vortices further away from the wall, does not play a direct role in the formation of the particle-streaks.

The results above were for simulations with one-way coupling, not taking into account the possible modification of the flow by the particles. When the forcing of the flow by the particles is taken into account (two-way coupling), we observe that the particles produce a significant attenuation in the intensity of the streamwise vortices further away from the wall (Portela and Oliemans, 2003). This attenuation tends to make the fluid-streaks close to the wall less wiggly and more elongated. However, it does not produce any significant change in the structure of the "baselines". Since the mechanism of formation of the particle-streaks is associated with the convergence of the streamlines into the "baselines", the process of formation and the behavior of the particle-streaks is essentially the same with one-way and two-way coupling. This is illustrated in figure 11, which shows the particle streaks with one-way and two-way coupling. The similarity between the two cases further supports the idea that the formation of the particle-streaks is a slow process of gathering that is not directly determined by the details of the dynamics of the streamwise vortices further away from the wall. Apparently, for the moderate loadings considered here, the particles can produce a significant attenuation in the streamwise vortices, but the process of formation of the "baselines" appears to be very "robust" and is not significantly affected by the particles.

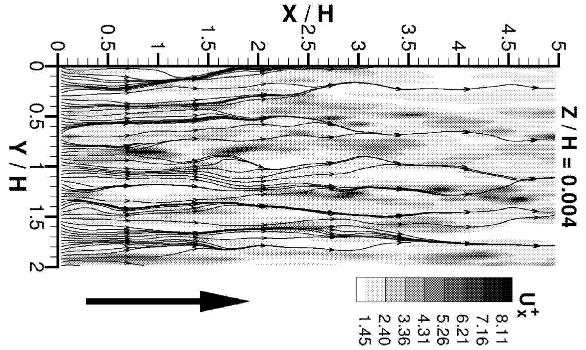

Figure 6: Streaky-pattern of the fluid in a plane very close to the wall ($Z^+ = 2$).

CONCLUSION

In wall-bounded turbulent flows laden with small heavy particles, the turbulence pushes the particles towards the wall, where the particles tend to cluster into streamwise-elongated streaks. The accumulation of particles near the wall is due to the turbophoresis, which pushes the particles towards regions of low turbulence intensity, and it can be understood using simple momentum-averaging concepts, akin to the Reynolds-averaging for single-phase flows.

In the literature, the formation of the particle-streaks has been generally attributed to the sweeps and ejections associated with the passage of the streamwise vortices further away from the wall. However, we show that, even though the passage of strong streamwise vortices leads to the local re-suspension and deposition of particles, the streamwise vortices are not directly associated with the formation of the particle-streaks.

We show that the formation of the particle-streaks is closely related with the fluid streaky-pattern close to the wall: it is a slow process of collection associated with the convergence of the streamlines of the fluid streaky-pattern into a few "baselines". These "baselines" have a very good correlation with the particle-streaks. They have both an extremely-long life, and once formed they remain roughly in the same position for a long time.

The process of formation of the "baselines" and the formation and behavior of the particle-streaks does not appear to be significantly affected by moderate particle-loadings. This further supports the idea that the formation of the particle-streaks does not depend on the details of the dynamics of the streamwise vortices, which are significantly attenuated, even at moderate loadings.

In this work, we did not explore how/why the "baselines" are formed. However, this new way of looking at the fluid streaky-pattern could be useful in terms of understanding the dynamics of the near-wall turbulence, for both single-phase

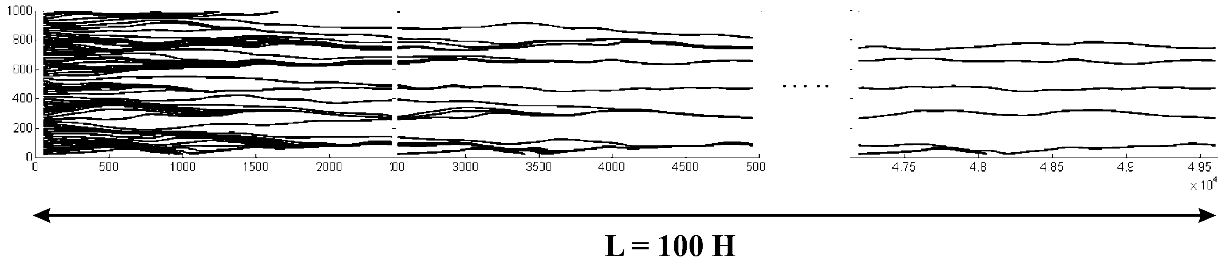

Figure 7: Convergence of the streamlines into a few "baselines", in a plane very close to the wall ($Z^+ = 2$).

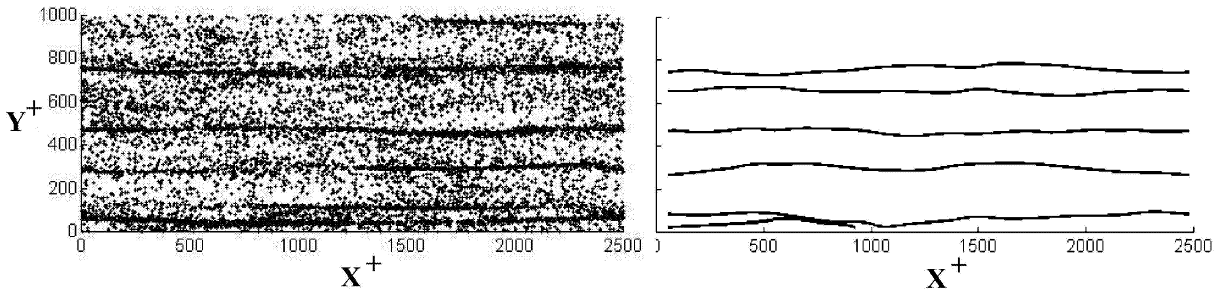

Figure 8: Snapshot showing the correlation between the particle-streaks (left) and the "fluid-baselines" (right), in a plane very close to the wall ($Z^+ = 2$).

and dispersed multiphase flows.

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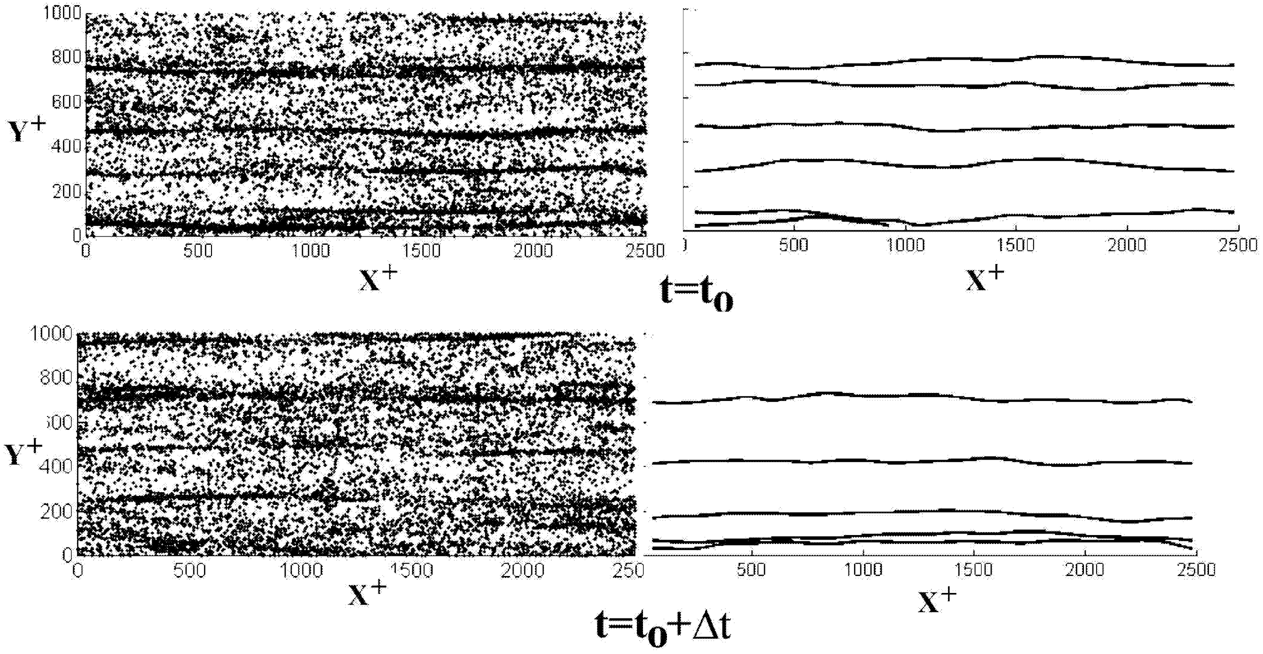

Figure 9: Two snapshots of the particle-streaks (left) and "fluid-baselines" (right), at $t = t_0$ (top) and at $t = t_0 + \Delta t$ (bottom) ($\Delta t^+ \approx 1000$), in a plane very close to the wall ($Z^+ = 2$).

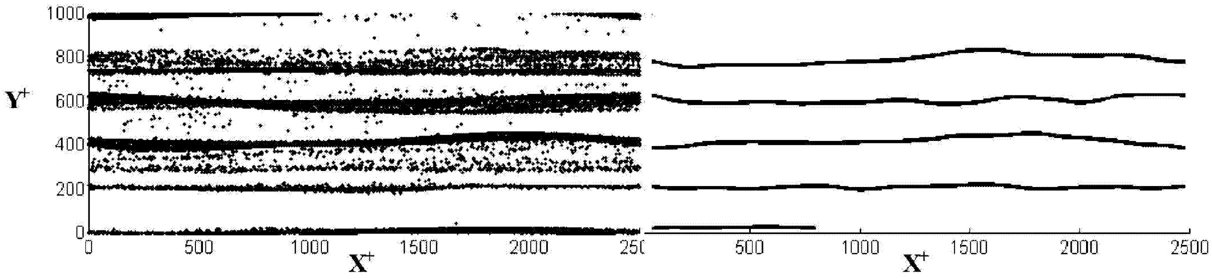

Figure 10: Snapshot of the particle-streaks (left) and "fluid-baselines" (right) at a time $\Delta t^+ \approx 1000$ after the start of the simulation, in a plane very close to the wall ($Z^+ = 2$). The simulation is started with the particles random-uniformly distributed, and during the entire simulation the velocity of the particles normal to the wall is set to zero.

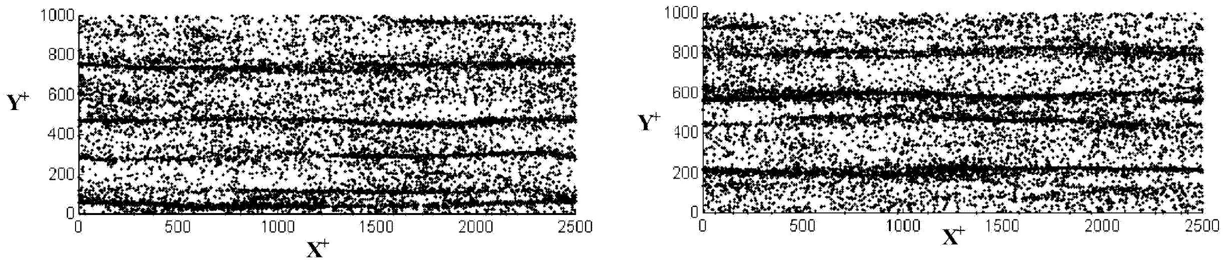

Figure 11: Two snapshots of the distribution of the particles in a plane very close to the wall ($Z^+ = 2$), at the same time after the start of the simulations, with one-way coupling (left) and two-way coupling (right).