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# Effect of the instantaneous turbulent flow structures on the particle distribution near the wall of a channel

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## HIGHLIGHTS

- We analyzed databases of simulations of the turbulent flow in a channel.
- Particles with different inertia were tracked using the dilute phase approximation.
- A pair of vortices is associated with large fluctuations of the wall shear stress.
- These events produce large fluctuations of particle concentrations near the wall.
- We quantified these fluctuations using a conditional sampling technique.

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## ABSTRACT

We analyzed databases obtained from direct numerical simulations of the turbulent flow in a plane channel at low Reynolds numbers. Particles with different inertia were tracked using the dilute phase approximation. The main objective of this study is the determination of the fluctuations of concentration produced by two types of instantaneous near-wall flow structures. The first type of structure produces extreme negative fluctuations of the wall shear stress ($\tau_w' \ll 0$) and the second type of structures are associated with large positive fluctuations ($\tau_w' \gg 0$). A conditional sampling technique was used to educe the topologies of these two types of flow structures and the corresponding conditional averaged particle concentration fluctuations. The contribution of each type of flow event to the wall shear stress history is about 10% but their contribution to the particle velocity component perpendicular to the wall, in the near-wall region, is about 50% for the flow structures associated to events with $\tau_w' \ll 0$ and about 40% for those with $\tau_w' \gg 0$, indicating that the role of these structures is significant in the particle fluxes from and towards the wall. The flow structures consist in two parallel counterrotating streamwise vortices that, in the case of $\tau_w' \ll 0$, create a flow ejection from the wall between them and in the case of $\tau_w' \gg 0$, produce a sweep towards the wall. These events produce important fluctuations of the particle concentration near the wall, with intensities up to 200% for the flow structure associated with $\tau_w' \ll 0$ and for the largest Stokes number considered ($St = 25$).

## 1. Introduction

Flows that transport small particles, bubbles or drops can be found in many engineering, industrial and environmental situations. The determination of the rates and the mechanisms responsible for the dispersion and deposition on solid surfaces of the dispersed phase has been the topic of many studies because they have important implications in practical problems. Reviews on the topic can be found, for example, in Michaelides [1] and Guha [2].

The determination and analyses of the time-averaged quantities near the wall in turbulent flows provide quantitative information useful for design purposes and to understand the overall interaction of the flow with the wall. The study of the statistics and the dynamics of the instantaneous fluctuations of the wall transfer rates or, for example, of the particle concentration in particulate flows can be considered a step forward in the understanding of the interaction between the flow and the wall. Particularly, it is interesting to detect and to describe the dynamics of the near wall flow structures since they are responsible for the instantaneous fluctuations of the wall transfer rates and of the particle concentrations in particulate flows. Knowing how these structures evolve and interact with the wall provide information that can be used to develop efficient techniques to manipulate the flow in order to obtain a desired modification of the wall transfer rates or of the particle concentration near the wall.

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### Nomenclature

| | |
|---|---|
| $C$ | particle concentration (particles $m^{-3}$) |
| $C_d$ | drag coefficient |
| $L$ | length (m) |
| $d$ | diameter (m) |
| $p$ | pressure (Pa) |
| $Re_\tau$ | Reynolds number, $Re_\tau = u_\tau \delta/\nu$ |
| $St$ | Stokes number, $St = (d_p^2 \rho_p/18\mu)/(\nu/u_\tau^2)$ |
| $t$ | time (s) |
| $u, v, w$ | velocity components ($m\ s^{-1}$) |
| $u_\tau$ | friction velocity, $u_\tau = (\langle \tau_w \rangle/\rho_f)^{1/2}$ ($m\ s^{-1}$) |
| $x, y, z$ | Cartesian coordinates (m) |

*Greek letters*

| | |
|---|---|
| $\Delta$ | increment |
| $\delta$ | channel half width (m) |
| $\delta_{ij}$ | Kronecker's delta |
| $\lambda_2$ | second largest eigenvalue of the velocity gradient tensor |
| $\mu$ | dynamic viscosity (Pa s) |
| $\nu$ | kinematic viscosity ($m^2\ s^{-1}$) |
| $\rho$ | density ($kg\ m^{-3}$) |
| $\tau$ | shear stress (Pa) |

*Subscripts and superscripts*

| | |
|---|---|
| $'$ | fluctuation |
| $+$ | wall scaling |
| $*$ | non-dimensional quantity |
| $i$ | initial |
| $f$ | fluid |
| $p$ | particle |
| $w$ | wall |

*Special symbols*

| | |
|---|---|
| $<>$ | averaged value |
| $\|\|$ | absolute value |

Particle dispersion in isothermal turbulent plane channel flows has been analyzed using direct numerical simulations (DNS) [3–10]. The effect of heat transfer between the particles and the fluid is considered by Arcen et al. [11]. The assumption that the particles do not affect the flow (i.e. the dilute phase approximation) is usually considered in DNS although there is experimental [12,13] and numerical [7,8] evidence that even small volume fractions of particles affect the flow, especially in the near-wall region. It is known that particles in wall-bounded turbulent flows tend to accumulate near the wall. This phenomenon, often referred as "turbophoresis" [1], is produced by the larger turbulence intensity in the buffer layer than in the viscous sublayer. The accumulation of particles near the walls can be also understood considering that the particle fluxes towards the wall are more efficient than the particle fluxes away from the wall. This produces the progressive accumulation of particles near the wall from an initially uniform distribution of particles until a statistically steady state for the particles quantities is reached [6].

Marchioli and Soldati [4] found that there is a strong correlation between sweep events and particle fluxes towards the wall and between ejection events and particle fluxes out from the wall. They classified the sweeps and ejections as coherent following the criteria of Lombardi et al. [14] for which an event is considered coherent if, instantaneously and locally, $u'v'$ at different distances from the wall belongs to the same quadrant. The inspection of instantaneous flow fields and particle concentration distributions near the wall indicated the influence of single individual streamwise vortices on the particle fluxes from and to the wall. A similar quadrant analysis technique was used by Vinkovic et al. [9] to study the interaction between the particle fluxes away from the wall and ejections.

Picciotto et al. [5] investigated the preferential location of particles within the viscous sublayer ($y^+ < 5$) in the four topological regions in the *QR* plane defined by the flow classification scheme proposed by Chong et al. [15]. They found that particles tend to concentrate in quadrants III and IV corresponding to convergence flow regions. However near wall sweeps belong to the IV quadrant but the ejection-like events do not possess a clear classification in the *QR* plane, so with this approach it is difficult to associate the fluctuations of concentration of particles with ejections. These authors also showed that the probability density function (pdf) of the wall shear stress ($\tau'$) evaluated at the particle locations has a slightly different distribution of the positive (≈60%) and negative (≈40%) events in comparison with that of the pdf of the wall shear stress evaluated at every location on the wall (≈57% are positive events and ≈43% negative) to indicate that particles tend to accumulate in the low speed streaks (i.e. in the negative events of $\tau'$). The inspection of instantaneous flow fields with the particle distribution in the viscous sublayer ($y^+ < 5$) indicated that high speed streaks correspond to short term accumulation regions and low speed streaks to long term accumulation regions.

Dritselis and Vlachos [7,8] used a conditional sampling technique based on the detection of single individual streamwise vortices, using the $\lambda_2$ criterion [16], to determine the effect of the particles on the sizes and properties of these coherent flow structures. These authors found that in general the particles tend to decrease the streamwise vorticity and the size of the single streamwise vortices.

Recent DNS [10] have shown that inertial particles tend to accumulate in the low speed streaks and they are aggregated in filamentary structures with typical streamwise lengths between 500 and 1000 wall units. For particles with low inertia the typical transverse distance of these aggregates is determined by the spanwise correlation length of the wall-normal velocity, while heavier particles display larger separations.

In this study we analyze DNS of particle-laden channel flow to put face on the flow structures responsible for the strong particle fluxes from and towards the wall and to quantify the contribution of these flow structures on the overall particle fluxes. Particles with different inertia have been considered and the effects of the instantaneous large-scale flow structures on the particle distribution near the wall are analyzed using a conditional sampling technique. The original aspect of this study is that we focus our attention in the flow structures responsible for the extreme fluctuations of the wall shear stress. These structures can be considered as strong flow events in the near-wall region. We show, additionally to the observations of previous studies based on the inspection of instantaneous flow fields and conditional sampling techniques focused on the detection of individual single streamwise vortices, that these events consist in a pair of counter-rotating vortices that contributes importantly to the particle fluxes towards and from the wall. In particular, although these flow structures explain only about 20% of the history of the wall shear stress, they are responsible for most of the particle velocities perpendicular to the wall within the viscous sublayer.

## 2. Physical and mathematical model

Fig. 1 shows the coordinate system and the computational domain, which model an infinite channel along the *x* and *z* directions. The flow, which is driven by a constant pressure gradient, is assumed to be hydrodynamically fully developed. The two walls of