THE SLIP DIRECTION OF LARGE-SIZE PARTICLES IN TURBULENT FLOWS

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Abstract Direct numerical simulations are used to investigate the dynamics of a large spherical particle suspended in a developed homogeneous turbulent flow. A definition of the direction of slip is introduced and used to construct the mean fluid velocity profile around the particle. One observes that the carrier flow turbulence is calmed down in the wake of the particle.

Many industrial processes and natural phenomena involve the suspension of finite-size particles in a turbulent flow. When the particles are much smaller than the Kolmogorov dissipative scale η of the carrier flow, their dynamics can be written in terms of a Newton equation that can account for low-order corrections due to their finite size [5]. However, only little is known about the motion of particles with sizes exceeding η. In that case one has generally recourse to ad-hoc models in which the drag and lift coefficients are estimated empirically (see, e.g., [2]). Current developments of experimental tracking techniques and of computational power have given a strong revival to such long-lasting questions (see [6, 1] for recent reviews). One of the main difficulties in analysing finite-size particle dynamics is to distinguish the slipping motions from the sweeping by the turbulent eddies that are larger than the particle. For very small particles, the fluid flow remains almost uniform on scales of the order of the particle size and one can then introduce a fluid velocity at the particle position. This notion looses sense for large particles where the outer turbulent fluctuations and the flow modifications by the particle occur on comparable length scales. Disentangling them becomes then indispensable.

In this work, we suggest a first step in order to tackle this issue. For this, we make use of direct numerical simulations using a pseudo-spectral method with immersed boundaries to impose the right no-slip boundary conditions at the particle surface. This approach was used in [3] to study the dynamics of neutrally buoyant particles with sizes of the order of η. We report here results on larger particles with diameters $D_{\rm p} = 16$, 32, and 64η in a statistically stationary homogeneous isotropic flow with $R_\lambda \approx 160$ integrated on 1024^3 grid points. Figure 1(a) shows a typical snapshot of the simulation.

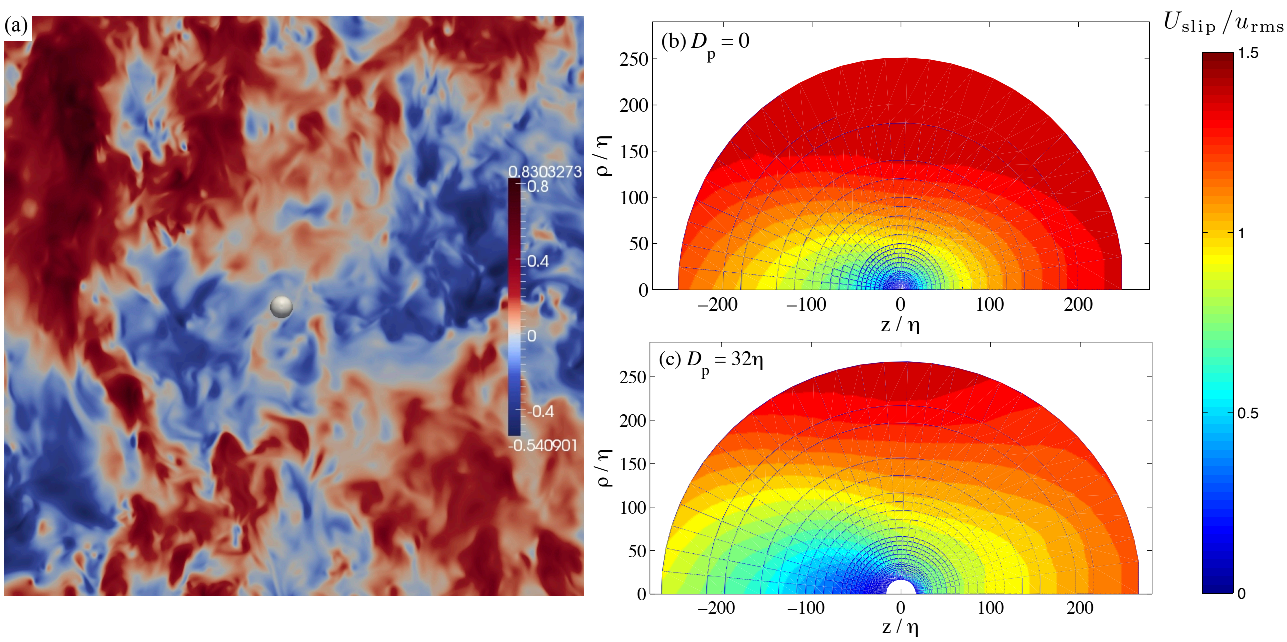

Figure 1. (a) Snapshot of the turbulent velocity amplitude in a slice passing through the center of the particle. (b) and (c) Average difference between the fluid and the particle velocities in the direction of the particle relative motion (see text for definition) for a tracer (b) and for a particle with diameter $D_p = 32\eta$ (c).

In order to investigate the interaction between the particle and the surrounding flow, we have stored with a sufficiently high frequency the velocity field in several concentric shells around the spherical particle. The idea is then to evaluate the slip direction on each of these shells and at each time. On the shell of radius r, we define the direction of motion $\vec{e}_r$ as

$$\vec{e}_r(t) = \vec{\Phi}_r(t)/|\vec{\Phi}_r(t)|, \quad \text{where } \vec{\Phi}_r(t) = \int_{\mathcal{S}_r} \left(\vec{u}(\vec{x},t) - \vec{V}_{\rm p}(t)\right) \cdot \vec{n}\, {\rm d}\vec{S}, \qquad (1)$$

where $\vec{u}$ and $\vec{V}_{\rm p}$ are the fluid and the particle velocity, respectively, $\vec{n}$ is the vector normal to the shell $\mathcal{S}_r$ of radius r

centered on the particle. In other words, we perform on each shell an average of the direction weighted by the fluid mass flux. This choice is physically motivated as the fluid enters such a shell upstream and exits in the wake. If the particle was moving in a laminar flow, the direction $\vec{e}_r$ would be, by symmetry, independent of r and exactly aligned with this motion. When the particle creates a wake in an unsteady flow, the direction $\vec{e}_r(t)$ depends on both time and r.

Once the direction $\vec{e}_r$ is evaluated, one can project on it the velocity difference $\vec{u} - \vec{V}_\mathrm{p}$ and perform a time average to define the average slipping velocity profile

$$U_\mathrm{slip}(\rho, z) = \left\langle \left(\vec{u}(\vec{x}, t) - \vec{V}_\mathrm{p}(t)\right) \cdot \vec{e}_r \right\rangle, \quad \text{with } z = \left(\vec{x} - \vec{X}_\mathrm{p}(t)\right) \cdot \vec{e}_r \text{ and } \rho = \sqrt{\left(\vec{x} - \vec{X}_\mathrm{p}(t)\right)^2 - z^2}. \tag{2}$$

$\langle\cdot\rangle$ designates here the temporal average and $\vec{X}_\mathrm{p}$ the particle center position. The coordinates z and ρ, which are defined at each instant of time, are in the direction of $\vec{e}_r$ and perpendicular to it, respectively. By rotational symmetry around the axis defined by $\vec{e}_r$, the mean profile U_slip depends on z and ρ only and not on the angle. Figures 1(b) and (c) represent the measured average velocity profile for a tracer and a particle with radius $D_\mathrm{p} = 32\eta$. In both cases, the upstream (right) and downstream (left) velocities are clearly asymmetric. Also, when the particle radius increases, one clearly observes the development in the wake of a region (in blue) where the flow is calmed down.

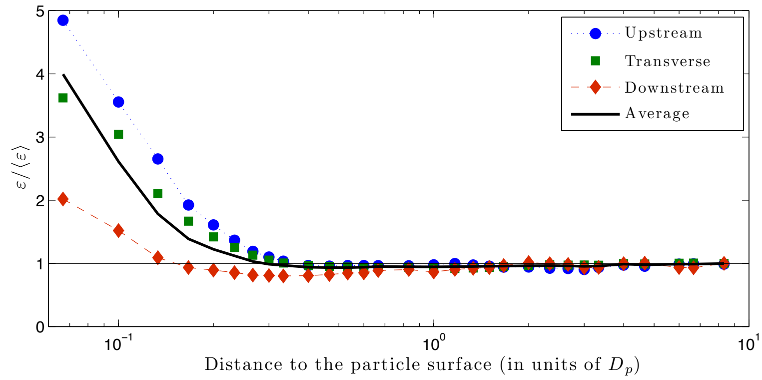

Figure 2. Ratio between the time-averaged kinetic energy ε around the particle and its full turbulent average $\langle\varepsilon\rangle$ as a function of the distance to the particle. The definition of the slip direction $\vec{e}_r$ allows one to distinguish between its behaviour upstream and downstream.

The weakening of turbulence in the particle wake can also be observed when we measure the rate of turbulent kinetic energy dissipation rate ε around the particle. Using again the definition (1) of the slip direction, this rate can be measured either upstream or downstream. As seen in Fig. 2, the behaviours of ε in the upstream and transverse directions are very close to each other. They tend back to its average value $\langle\varepsilon\rangle$ at distances of the order of D_p from the particle. In the wake, the dissipation also tends to the average on comparable scales but before, at smaller distances, it reaches values below the average, showing again that turbulence is there calmed down. Also interestingly, in the particle boundary layer, most dissipation occurs upstream and on the edges. The downstream dissipation is more than twice less than the average.

To conclude, let us stress that our approach might be applied in experiments. Indeed, recent developments make it now possible to simultaneously track the motion of large particles and that of the surrounding fluid [4]. The proposed definition of a slip direction can certainly shed light on the complex interactions between large-size particles and a carrier turbulent flow.

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