EFFECT OF TURBULENT FLUCTUATIONS ON THE DRAG FORCE AND BOUNDARY LAYER OF A TOWED SPHERE

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Abstract The impact of turbulent fluctuations on the forces exerted by a fluid on a towed spherical particle is investigated by means of high-resolution direct numerical simulations. The measurements are carried out using a novel scheme to integrate the two-way coupling between the particle and the incompressible surrounding fluid flow maintained in a high-Reynolds-number turbulent regime. The main idea consists in combining a Fourier pseudo-spectral method for the fluid with an immersed-boundary technique to impose the no-slip boundary condition on the surface of the particle. Using this method it is shown that the average drag force increases as a function of the turbulent intensity and the particle Reynolds number. This increase is significantly larger than predicted by standard drag correlations based on laminar upstream flows. It is found that the relevant parameter is the ratio of the viscous boundary layer thickness to the dissipation scale of the ambient turbulent flow. The drag enhancement can be motivated by the modification of the mean velocity and pressure profile around the sphere by small scale turbulent fluctuations.

INTRODUCTION

The transport of particles in a turbulent flow is important in many natural and industrial settings. Those particles can be modeled by a point particle approach if their diameter is much smaller than the Kolmogorov scale and if they have a vanishing Reynolds number. However, recent experimental work showed that the dynamics of finite-size particles (particles with diameters larger than the Kolmogorov scale) is not well described by such models [3, 6, 5]. Significant size effects have been for instance measured in the acceleration statistics of such particles.
A key ingredient of the finite-size models mentioned above are drag correlations, which determine the forces on a sphere based on its velocity difference with the fluid. All those drag correlations are empirical formulas fitting experimental and numerical measurements of the drag experienced by a sphere in a *laminar* upstream flow. However, the question whether or not turbulent fluctuations eventually present in the carrier flow modify those drag correlations is an open issue, which has been under discussion for more than forty years. Another challenging requirement to improve models for the dynamics of finite-size particles in turbulent flows is to get a precise understanding on how the carrier flow is modified in the vicinity of the particle in situations where such effects occur on scales which are comparable to the active scales of the surrounding turbulence.

Figure 1. Turbulent wake of a particle located at the left side of the simulation box at $Re_\mathrm{p} = 400$ (defined with the mean flow U_c). The advected flow is turbulent with $I = 0.14$ (volume rendering of high-vorticity isosurfaces).

NUMERICAL METHOD

In this work we use high-resolution direct numerical simulations to conduct a wind tunnel experiment where a fixed spherical particle is placed either in a homogeneous or turbulent upstream flow. The principle flow configuration is depicted in Fig. 1. The idea of our approach is to combine a standard pseudo-Fourier-spectral with a penalty method. The former is well adapted to incompressible homogeneous and isotropic turbulence, has a high degree of accuracy, and has shown good performances on massively parallel supercomputers. No-slip boundary conditions are implemented by an immersed boundary and a penalization strategy called "direct-forcing" method. More details can be found in [2].
We benchmark the accuracy of the method by measuring for example the drag C_D on the particle in the numerical wind tunnel experiment. The Reynolds number is varied by changing either the particle diameter d or the viscosity of the fluid. Data compare well to Schiller and Naumanns's [4] empirical formula $C_D^{\mathrm{SN}} = (24/Re_\mathrm{p})(1 + 0.15Re_\mathrm{p}^{0.687})$. The convergence of the drag coefficient can be quantified by looking at the relative error $(C_D - C^{\mathrm{SN}})/C^{\mathrm{SN}}$ as a function of the number of grid points on the diameter of the particle. We find that the coefficients converge with an exponent

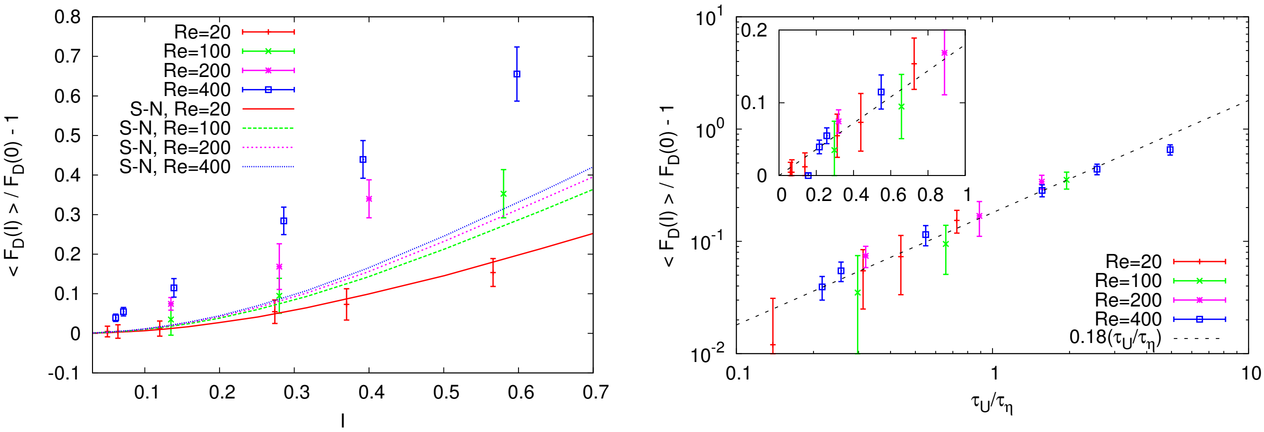

Figure 2. Left: deviations of the mean drag from that obtained with a laminar upstream flow as a function of the turbulent intensity I. Right: same represented as a function of the ratio $\tau_{\mathrm{U}}/\tau_\eta$ where $\tau_{\mathrm{U}} = d/U_c$ is the sweeping time over a distance equal to the particle diameter and $\tau_\eta = (\nu/\varepsilon)^{1/2}$ is the turbulent turnover time associated with the Kolmogorov dissipative scale η.

of -3/2. We propose that this convergence rate is determined by the truncated representation of the velocity field with discontinuous gradient at the surface of the particle.

RESULTS

We now turn to the case when the surrounding flow advects turbulent fluctuations. A large scale forcing is applied to sustain a statistically stationary state. The associated turbulent large-scale intensity is defined as $I = u_{\mathrm{rms}}/U_c$. We have performed four series of numerical simulations corresponding to four different particle Reynolds numbers Re_{p}. They were chosen to cover three different wake configurations: 1) laminar without any recirculation region behind the particle ($Re_{\mathrm{p}} = 20$) - 2) laminar with recirculation region ($Re_{\mathrm{p}} = 100$ and $Re_{\mathrm{p}} = 200$) - 3) turbulent ($Re_{\mathrm{p}} = 400$)

We computed the mean drag, i.e. the force exerted by the turbulent flow on the particle in the stream-wise direction (the averaged perpendicular forces are zero). Results are shown in Fig.2 (Left), where data is normalized to the case without turbulent fluctuations. One finds a clear increase of the stream-wise force on the particle with increasing turbulent intensity. As stated in [1], it is very likely that the drag increase is due to the non-linear dependence of the drag upon the incident fluid velocity (see Schiller-Naumann formula). The prediction of such a model is shown as lines in Fig. 2 (Left). While it gives a rather good approximation of the data at moderate particle Reynolds numbers, it is clearly a too low estimate for $Re_{\mathrm{p}} > 100$.

Another heuristic way to understand the effect of the perturbing turbulence on the drag consists in considering the modification of the amplitude of the typical velocity gradient in the neighborhood of the particle. In the laminar case (when $I = 0$), the velocity field around the particle typically varies over a scale of the order of d. The unperturbed gradient is then $\tau_U^{-1} =\sim U_c/d$. When a background turbulence is added to this flow, the value of the gradient is modified by the typical turbulent gradient $\tau_\eta^{-1} = u_\eta/\eta$ where τ_η is the turnover time associated to the Kolmogorov dissipative scale η. Altogether these considerations imply that the corrections to the drag are expected to be $\propto \tau_\eta^{-1}$, while these forces in the $I = 0$ reference case should be $\propto \tau_U^{-1}$. Such arguments leads to a relative increase $\Delta(I)$ of the drag force acting on the particle $\propto \tau_U/\tau_\eta$. The right-hand side of Fig. 2 shows $\Delta(I)$ as a function of τ_U/τ_η and reveals a rather good collapse of the entire data-set to the curve $\Delta(I) = 0.18\,(\tau_U/\tau_\eta)$, giving support to such phenomenological arguments.

References

[1] P. Bagchi and S. Balachandar. Effect of turbulence on the drag and lift of a particle. *Phys. Fluids*, **15**:3496, 2003.

[2] H. Homann, J. Bec, and R. Grauer. Effect of turbulent fluctuations on the drag and lift forces on a towed sphere and its boundary layer. *J. Fluid Mech.*, (accepted for publication).

[3] Nauman M Qureshi, Mickaël Bourgoin, Christophe Baudet, Alain Cartellier, and Yves Gagne. Turbulent transport of material particles: an experimental study of finite size effects. *Physical Review Letters*, **99**:184502, 2007.

[4] L. Schiller and A. Naumann. über die grundlegenden berechnungen bei der schwerkraftaufbereitung. *Verein Deutscher Ingenieure*, **77**:318, 1933.

[5] R. Volk, E. Calzavarini, E. Leveque, and J.-F. Pinton. Dynamics of inertial particles in a turbulent von Karman flow. *J. Fluid Mech.*, **668**:223–235, 2011.

[6] H. Xu and E. Bodenschatz. Motion of inertial particles with size larger than Kolmogorov scale in turbulent flows. *Physica D: Nonlinear Phenomena*, **237**:2095–2100, 2008.