DYNAMICS OF LARGE PARTICLES IN A VON KÁRMÁN SWIRLING FLOW

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Abstract We study the dynamics of large particles in a turbulent von Kármán swirling flow, tracking the particles in the whole volume. We observe a transition with increasing particle diameter in the dynamics from homogeneous toward inhomogeneous sampling of the apparatus. Large particles tend to avoid the center of the flow, an effect almost insensitive to the Reynolds number or inertia of the particles. Studying the Lagrangian position power spectrum, we observe three distinct regimes. The observed slopes can be qualitatively understood in the framework of Brownian motion in a double well potential.

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The turbulent dynamics of material particles, whose sizes are much greater than the Kolmogorov scale and which are not necessary neutrally buoyant, is a complex matter. Furthermore, this is a very challenging topic since this situation happens as much in every-day life as in industrial processes: how rocks are advected by a river, how winds can affect a weather balloon or even how solid subtracts move in an industrial mixer?

We choose to study a von Kármán swirling flow. Two counter-rotating disks, with straight blades, produce a highly turbulent flow in a squared vessel filled with water. This confined flow has a strong mean flow presenting differential rotation in the azimuthal direction and meridian recirculations with fluctuation level around 30% (figure 1). This flow is anisotropic at large scale and homogeneous only in a small region in the center of the apparatus. The integral length scale is approximately 3 cm. The propellers are used at rotating frequencies ranging from 2 to 4 Hz, giving Reynolds numbers based on the Taylor micro-scale $R_\lambda = [300 - 500]$ and Kolmogorov scales $\eta = [38 - 22]\mu\text{m}$.

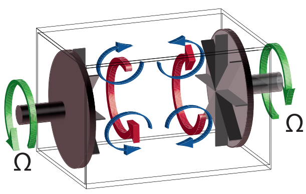

Figure 1. Sketch of the mean flow in a von Kármán square vessel produced by two counter-rotating disks. The red arrows stand for the counter-rotating cells and the blue ones for the meridian recirculations.

To study the dynamics of the particles, we track them in the whole volume with two high speed cameras. We use the same tracking techniques as in [1]. As opposed to classical studies of Lagrangian turbulence which focussed on the fastest scales of the motion, we performed both short and long experiments varying the sampling frequency to resolve both the fast and slow time scales of the particles motion. We can then compute the fluctuations of velocity and acceleration, their probability density functions and their auto-correlation functions.

We study the dynamics of particles with diameters ranging from 6 to 24 mm and two cases of buoyancy: heavy and light particles with difference of density from neutrally buoyant of around 10%.

The probability density function of the axial position (figure 2.a) sheds light on an effect of size on the exploration of the vessel by the particles. Indeed, the smaller particles sample the whole volume homogeneously. In contrast, above a certain diameter, the particles sample mostly the large scale structures of the flow, in particular the two counter-rotating cells (figure 2.a and figure 1). The Reynolds number, as long as the flow is still turbulent, has no effect on the sampling. Besides, the sampling is slightly modified by the density but still happens for the two densities we used. We also explore the case of neutrally buoyant particles (practically, we use the heavy particles described above in a glycerol-water solution) with a viscosity height times that of water; sampling was also observed in this situation.

SLOW DYNAMICS

Looking closely at the trajectories of one large particle in the vessel, we can observe that the particle is trapped in one counter-rotating cell for a certain time (figure 1). Then, when the particle undergoes an axial velocity strong enough, it moves to the opposite cell. The excursion from one cell to another is really brief, the particle does not stay in the center

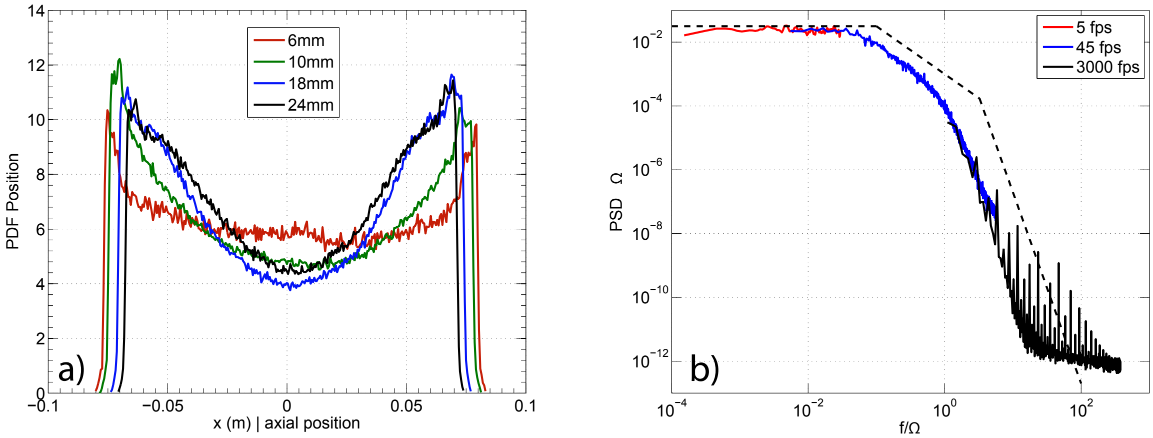

Figure 2. a) Probability density function of the axial position showing the transition to sampling with particles diameter in the vessel. This experiment is done with a Reynolds number based on the Taylor micro-scale equal to 400, with 4 different particles diameters, of density $d = 1.14$. The propellers are 18 cm apart and the axial direction is the rotation axis. **b)**: Power spectral density of the axial position x reconstructed from the 3 same experiments with recording speed of 5, 45 and 3000 frames per second. Ω is the propellers frequency and is used to rescale the spectra. The particle diameter is 18 mm and the sphere samples the flow inhomogeneously.

of the apparatus. Then the particle is trapped again in one cell, until another fluctuation is strong enough to send it to the opposite cell.

Furthermore, if the particle is trapped in one structure, one can wonder how much time it stays there, and look at the escape times from both structures. The escape times distributions in our experiments follow an exponential decay. We could compute this distribution thanks to the long-time signal of the axial position of the particles, obtained by experiments recorded at low speed.

Besides, taking advantage of having both slow speed and high speed measurements, we construct spectra over a large range of frequency (figure 2.b). This spectrum presents several regimes: at low frequency the energy is equally distributed, then there is a first slope, followed by a steeper one, and at higher frequency we see noise. The plateau is due to the fact that the particle is confined in the vessel. The high frequencies slope, probably affected by the large diameter and/or the sampling, is steeper (ranging from -5 to -6), but still close to a turbulence spectrum, which presents a -4 slope (leading to -2 for the velocity spectrum). We believe that the intermediate slope (-1.5), which appears with the sampling, is a signature of this phenomena. This milder slope is due to oscillating motions of the particles from one large structure to the other. This dynamics happens because the particles, especially the large ones, are very sensitive to the large scale structures of the flow. For the smaller particles, which sample the flow homogeneously, the spectrum presents only a low frequency plateau followed by a cut-off with a slope equal to -4.

DISCUSSION

We study the motion of large particles in a turbulent swirling flow and the effect of particles size on their dynamics. Large particles do not sample the flow homogeneously, tending to be trapped in large scale structures. We observe a transition toward sampling as we increase the particle diameter, independently of Reynolds numbers, densities and viscosities.

The experimental observations can be qualitatively understood in the framework of Langevin equations. The dynamics is very similar to the motion of a Brownian particle moving in a double potential, set into motion by a coloured noise [2]. Indeed, a potential of the form $V(x) \sim ax^4 - bx^2$ can reproduce nicely the probability density functions of the axial position of the particles seen in figure 2.a. The spectrum from this model presents a low frequency plateau followed by a -2 slope, and a -4 slope, very similar to the experimental spectra. The escape times from this model have an exponential PDF, which is also observed in the experiments.

References

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