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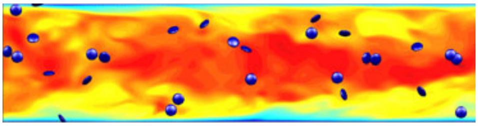
Disks aligned in a turbulent channel



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Anisotropic particles are suspended in a wide range of industrial, environmental and biological fluid flows. The orientations of these particles are sometimes randomized by turbulence, but often they are brought into preferential alignment by the fluid flow. In a recently published study, Challabotla, Zhao & Andersson (*J. Fluid Mech.*, vol. 766, 2015, R2) performed the first numerical simulations of inertial disks in a turbulent channel flow. They find that disks can be made to preferentially align either parallel or perpendicular to the wall depending on the particle density. Particle shape also affects alignment, particularly for lower density particles, and the alignment of disks is quite different from the alignment of fibres.

Key words: channel flow, particle/fluid flow, turbulence simulation

1. Introduction

We see anisotropic particles carried by turbulent fluid flows all around us. The particles could be snowflakes or leaves blowing in the wind. They could be ice crystals in clouds that produce sundogs or seeds with shapes adapted by evolution to enhance their dispersal. Non-spherical particles also play important but less noticed roles in our lives. Paper is made using turbulent suspensions of wood fibres (Lundell, Söderberg & Alfredsson 2011); the lowest trophic levels of the largest ecosystem on the planet are dominated by plankton of a wide variety of shapes (Guasto, Rusconi & Stocker 2012; Byron *et al.* 2015); and the disk shape and deformability of red blood cells play a critical role in the human circulatory system (Chien 1987).

A natural expectation might be that turbulence will randomize the orientation of these particles so that simple rotationally averaged models can describe light scattering by particles, rheological properties of a suspension or the rotation rates of particles. But even in isotropic turbulence, it is found that particles become aligned by fluid velocity gradients and this alignment results in particle rotation rates up to three times smaller than that predicted by rotationally averaged models (Shin & Koch 2005; Parsa *et al.* 2012).

Particles occur in a wide variety of shapes, but many of them can be accurately modelled by effective ellipsoids (Bretherton 1962). An axisymmetric ellipsoid, (or spheroid) can be specified by a single aspect ratio, λ, defined as the ratio of the dimension along the symmetry axis to a perpendicular dimension: $\lambda = 1$ is a sphere,

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$\lambda > 1$ is a prolate spheroid or fibre and $\lambda < 1$ is an oblate spheroid or disk. Fibres have received most of the attention from researchers working on anisotropic particles in turbulence. The reason for this prejudice against small aspect ratios is not entirely clear, but factors involve the industrial importance of fibre flows, the theoretical convenience of slender body theory, and the experimental convenience of imaging nearly one-dimensional objects.

Disks have recently climbed into the limelight as researchers realized that the rotation and alignment of disk-shaped particles provide a challenging test case for stochastic models of the velocity gradient tensor (Chevillard & Meneveau 2013) as well as for analytic models of particle rotation rates (Gustavsson, Einarsson & Mehlig 2014). Experiments have recently been able to measure rotations of three-dimensional printed particles that rotate like disks and whose orientation can be accurately measured with multiple cameras (Marcus *et al.* 2014).

2. Overview

Recently, Challabotla, Zhao, & Andersson have presented a groundbreaking numerical study that explores the rotation and alignment of inertial disk-shaped particles in a turbulent channel flow (Challabotla, Zhao & Andersson 2015). This has been a very fruitful system in the study of fibres in flows (Mortensen *et al.* 2008; Marchioli, Fantoni & Soldati 2010), but the dynamics of disks in wall-bounded shear flow has not previously been explored. Challabotla *et al.* (2015) use a point particle model similar to those that have been widely used for spherical particles in turbulent flows (Balachandar & Eaton 2010). When spherical particles are sufficiently small, their equation of motion can be accurately approximated with a simple Stokes drag force. The equivalent model for ellipsoidal particles requires a resistance tensor to find the drag force vector from the particle orientation and its relative velocity with the fluid. Modelling the orientation requires integrating the torques on the particle produced by the fluid velocity gradients. Challabotla *et al.* (2015) provide a clear and compact guide for implementing this anisotropic Stokes drag model. This model does not include fluid inertia effects, but is a good approximation in many systems of interest where particles are small and their density is large compared with the fluid density.

A snapshot of disks moving in the channel flow simulated by Challabotla *et al.* (2015) is shown in figure 1. The most striking feature is the preferential orientation of the disks near the walls where the disks' symmetry axes align in the spanwise direction. In the centre of the channel, particles are more randomly oriented. This image is for heavy particles whose response time, τ_p, is much longer than the fluid viscous timescale, τ_ν; so the Stokes number is relatively large, $St = \tau_p/\tau_\nu = 30$. At lower $St = 1$, they observe a very different alignment with the symmetry axis of the disks in the wall normal direction. None of their simulations find disks preferentially aligned in the streamwise direction which is the orientation chosen by fibres (Mortensen *et al.* 2008; Marchioli *et al.* 2010).

The interaction of preferentially oriented particles with the mean and fluctuating velocity gradients produces fascinating rotation statistics. Heavy particles ($St = 30$) have a mean rotation that is almost equal to the mean fluid rotation, while light particles have a smaller rotation that is strongly dependent on particle shape. The fluctuating rotation rates show even more complex behaviour which reveals an important feature of anisotropic inertial particles: the rotational response time of particles can be quite different than their translational response time.

To understand these observations conceptually, the authors turn to the large body of work on the motion of anisotropic particles in simple shear flow where neutrally

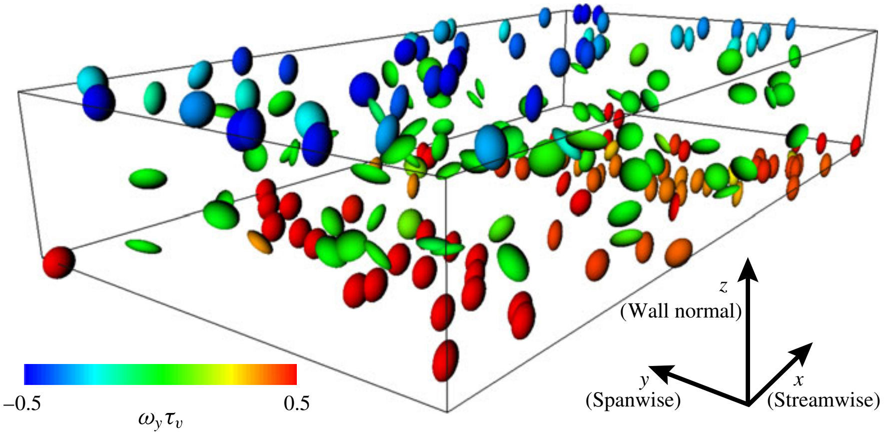

FIGURE 1. Disks in a turbulent channel flow showing the preferential orientation near the wall. Data are the same as Challabotla *et al.* (2015, figure 1(*b*)). The mean velocity is in the x (streamwise) direction, the flow has periodic boundary conditions in the y direction, and no-slip boundary conditions at the upper and lower walls (z direction). The particles have aspect ratio 1/3 and Stokes number 30. Particle colour encodes the spanwise component of the particle angular velocity, ω_y.

buoyant spheroidal particles undergo periodic motions called Jeffery orbits. The preferential alignment of the low-Stokes-number particles in the wall-normal direction can be understood simply by considering the Jeffery orbits of a disk in simple shear flow. Disk-shaped particles in orbits that bring their symmetry axis near the wall-normal direction will spend a long time in this orientation before tumbling, which leads to the observed orientation. The alignment of the high-Stokes-number particles is controlled by particle inertia. The alignment seen near the walls in figure 1 matches the steady state alignment observed in earlier work on disks in simple shear, where the symmetry axis aligns parallel to the flow vorticity. Turbulence competes with alignment by the mean shear so this preferential alignment diminishes toward the centre of the channel where the mean shear becomes small.

3. Future

These important results on the alignment and rotation of inertial disks in turbulent shear flow suggest several promising research directions. The authors observe that both rods and disks have a preferred alignment with a long axis in the streamwise direction. In isotropic turbulence, it has been found that rods and disks align with a long axis in the direction of maximum fluid stretching defined by the Cauchy–Green strain tensors (Marcus *et al.* 2014; Ni, Ouellette & Voth 2014). Consideration of the mean and fluctuating stretching fields may provide additional insights into particle alignment.

Another interesting subject for future work is the instantaneous spatial distribution of particle orientations. For neutrally buoyant particles, the instantaneous orientation should be a nearly continuous field whose rich topology has begun to be explored (Szeri 1993; Wilkinson, Bezuglyy & Mehlig 2011). The addition of particle inertia introduces the possibility of caustics in the orientation field (Gustavsson *et al.* 2014; Siewert, Kunnen & Schröder 2014*b*), which can strongly affect collision probabilities.

Attempts to reproduce the gravity-free numerical results from Challabotla *et al.* (2015) in the laboratory will face the challenge that even quite small inertial disks show effects from gravitational sedimentation. But this raises opportunities as well. The behaviour of sedimenting anisotropic particles is significantly richer than the gravity-free case including phenomena such as sedimentation instabilities (Guazzelli & Hinch 2011) and alignment of particles by inertial torques (Siewert *et al.* 2014*a*).

Some key fundamental phenomena in the behaviour of anisotropic particles in turbulent flows have now been identified, but much of the parameter space remains to be explored. Some of the most pressing applications involve dense suspensions, sedimentation and deformability of anisotropic particles in turbulence. Our deepening understanding of foundational cases such as rigid disks in channel flow is essential for the development of predictive models of the complex turbulent suspensions all around us.

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