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Dynamics of single, non-spherical ellipsoidal particles in a turbulent channel flow

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HIGHLIGHTS

- Eulerian–Lagrangian with Euler rotational equation represents particle dynamics.
- Technique developed is applicable to any regular isotropic non-spherical particle.
- Ellipsoidal particles display a transition from one orientational state to another.
- Particle orientation is affected by the shear rate, particle inertia and shape.

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ABSTRACT

Using disk, spherical and needle-like particles with equal equivalent volume diameters, the orientational dynamics of non-spherical particles is studied in a turbulent channel flow. An Eulerian–Lagrangian approach based on large eddy simulation with a dynamic sub-grid scale model is used to predict a fully developed gas–solid flow at a shear Reynolds number $Re_{\tau}=300$. Particle shape and orientation are accounted for by the coupling between Newton's law of translational motion and Euler's law of rotational motion, both in a Lagrangian framework. The particle shapes are simulated using the super-quadrics form, with the dynamically relevant parameters being the particle aspect ratio, equivalent volume diameter and response time. The translational and orientational behaviour of single particles initially released at three different locations in the wall-normal direction are monitored, with analysis showing a clear distinction between the behaviour of the different particle shapes. The results show that turbulent dispersion forces non-spherical particles to have a broad orientation distribution. The orientational states observed include periodic, steady rotation, tumbling, precessing and nutating. Velocity gradient, aspect ratio and particle inertia all have an effect on the alignment of the particle principal axis to the inertial axes. Unlike spherical particles, the disk and needle-like particles display a transition from one orientational state to another, especially when their initial position is in the near-wall region, with the frequency of this transition highest for the disk-like particle. Overall, this study leads to an improved understanding of the significance of shape on particle behaviour which is of relevance to many practical flows.

1. Introduction

Non-spherical particles suspended in a wall-bounded turbulent flow display varying linear (position and velocity) and rotational (orientation and rotation) attributes under the action of the velocity gradient. Understanding these dynamic attributes is important in many areas of science and engineering, and in many practical applications. For example, their importance spans the fundamental properties of turbulence and the rheological properties of suspensions, with relevant applications ranging from the deposition of aerosols in respiratory organs, the distribution of cellulose fibres in the paper and pulp industry, the motion of red blood cells travelling through blood vessels, and ice crystal dynamics in clouds, to name but a few. Of particular interest here are flows of relevance to nuclear reactor operations, where corrosion products can be transported into the reactor core by the cooling fluids, and in some cases are deposited on the outside of the fuel pins in the form of CRUD (an acronym for Chalk River unidentified deposit or corrosion residual unidentified deposit). Individual particles are small, of the order of 0.1–2.0 μm, but these agglomerate into larger particles giving rise to

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a wide range of sizes and morphologies, varying from needle-like, through near-spherical to platelets or flakes (Hazelton, 1987). Particles suspended in a turbulent fluid undergo mean motion due to the mean fluid velocity and random motion due to the fluctuating component of that velocity. For non-spherical particles, their motion is then a combination of translation and rotation due to the anisotropy of their shape and orientation.

The first step in understanding non-spherical particle behaviour is to track the trajectory and orientation of single particles in a given flow field. Starting with the work of Jeffery (1922) on the behaviour of a single ellipsoid in viscous shear flows, analytical studies on isolated anisotropic particles in steady and unsteady laminar flows are available in the literature. In his formulation for the resistance force and torque on ellipsoids in uniform shear flow under Stokes conditions, Jeffery (1922) showed that the axis of symmetry of a spheroid performs a periodic motion on a closed orbit, the so-called “Jeffery” orbit. He concluded that the final state of a spheroid depends on its initial orientation, with the spheroid's motion being that which results in the minimum average dissipation of energy. Brenner, in a series of publications, e.g. (Brenner, 1963, 1964), expanded Jeffery's analysis to arbitrary flow fields, however, both Jeffery's and Brenner's works are in the absence of fluid and particle inertia. Many researchers have subsequently extended these works to study non-spherical particle suspensions in more general terms, including inertial effects and turbulent flow regimes. For example, Karnis et al. (1963, 1966) observed that at large Reynolds number, inertial effects become significant, making the non-spherical particles exhibit behaviour different from Jeffery's theory. They reported that neutrally buoyant particles in a Newtonian fluid move towards the region of maximum energy dissipation, although with insignificant change in the particle rotation.

Following growing interest in the subject, physical modelling and different numerical modelling approaches have been used to study the motion of non-spherical particles in various flow fields, with an extensive literature having been produced. Carlsson et al. (2006) used as charge-coupled device to analyse the velocity and orientation of fibres suspended in a shear flow moving over a solid wall. Holm and Söderberg (2007) applied an index-of-refraction matching method, together with particle tracking techniques, to study the influence of the near-wall shear stress on fibre orientation with different fibre aspect ratios and concentrations. Dearing et al. (2012) applied and validated a comprehensive methodology based on simultaneous single camera, two-phase PIV measurements to obtain fibre orientation and distribution, as well as flow field data, in a turbulent pipe flow. Hakansson et al. (2013) observed fibre streaks using a camera, and measured flow velocity profiles using laser Doppler velocimetry, in their experiments which used fibre suspensions in a turbulent half-channel flow. All these works have demonstrated that fibres accumulate in the near-wall region, preferentially concentrating in regions of low-speed velocity streaks, and tend to align with the mean flow direction.

Direct numerical simulation (DNS), in particular, has been used to study many aspects of these flows. Feng et al. (1994), for example, used DNS to investigate the motion of neutrally and non-neutrally buoyant circular particles in plane Couette and Poiseuille flows, with qualitative agreement recorded against results obtained from experimental measurement and perturbation theories. Others have studied the statistics, dispersion and deposition of ellipsoidal particles in turbulent channel flow using DNS. A wide range of classes of prolate spheroids have been considered using this approach, with the particles characterised by their different elongation (quantified by the particle aspect ratio, λ) and inertia (quantified by a suitably defined particle response time, τ_p^+), and transported in flows with different levels of turbulence (quantified by the shear Reynolds number, Re_τ) (Zhang et al., 2001; Mortensen et al., 2008a; Marchioli et al., 2010). Here, the particle response (or relaxation) time, τ_p, is the response of the particle to the perturbations produced by the underlying turbulence, and the flow Reynolds number. The particle Stokes number, St, is then ratio of the particle response time, τ_p, to a characteristic time of the flow, τ_f. When the particle relaxation time is made dimensionless using wall variables, the resulting particle Stokes number is given by $St = \tau_p^+ = \tau_p/\tau_f$, where $\tau_f = \nu/u_\tau^2$, ν is the fluid kinematic viscosity and u_τ is the shear velocity. The shear Reynolds number $Re_\tau = hu_\tau/\nu$, with h the channel half-height. These authors (Zhang et al., 2001; Mortensen et al., 2008a; Marchioli et al., 2010) observed that, similar to spheres, prolate spheroids accumulate in the viscous sub-layer and preferentially concentrate in regions of low-speed fluid. They also tend to align with the mean flow direction, particularly very near the wall where their lateral tilting is suppressed. Tian et al. (2012) also used commercial CFD software to study low Reynolds number flows, reporting that the flow shear rate, the particle aspect ratio, different equivalent sphere sizes and the particle-to-fluid density ratio all significantly affect the transport and deposition of regular non-spherical particles. These authors also reviewed four frequently encountered equivalent sphere prescriptions used in the literature. Of the four, earlier work (Zhang et al., 2001; Mortensen et al., 2008a; Marchioli et al., 2010) only applied the equivalent Stokes sphere developed by Shapiro and Goldenberg (1993), and did not consider platelet-like particles ($\lambda < 1$). They also adopted Jeffery and Brenner's model for the general hydrodynamic forces and torques acting on an ellipsoidal particle in an arbitrary flow field. The Jeffery method is, however, limited to ellipsoidal particles with particle Reynolds numbers $Re_p \sim O(1)$, where $Re_p = |\mathbf{u}_f - \mathbf{v}| d_{ev}/\nu$ (for volume equivalent diameter, d_{ev}, and particle slip velocity ($\mathbf{u}_f - \mathbf{v}$)), and there remains continued interest in the dynamics of finite Reynolds number particles beyond the Stokesian regime. In addition, the dynamics of even the simplest non-spherical particles is often not well understood.

The lattice Boltzmann method has also been applied to study the effect of inertia and initial orientation on the dynamics of ellipsoidal particles suspended in shear flow (Ding and Aidun, 2000) and in Couette flow (Qi and Luo, 2002, 2003), with different states found depending on the Reynolds number range and the particle shape. Here, the shear Reynolds number is defined as (Huang et al., 2012) $Re_\tau = 4Gd^2/\nu$, where $G = 2U/N_y$ is the shear rate, d is the length of the semi-major axis of the particles, U is the velocity of the moving wall and N_y is the number of nodes along the velocity gradient direction. Qi and Luo (2002, 2003) identified the following modes for $Re_\tau < 467$: tumbling, precessing and nutating, log rolling and inclined rolling for a prolate spheroid; and for an oblate spheroid, log rolling and inclined rolling as Reynolds number increases. Huang et al. (2012) considered $0 < Re_\tau < 700$, beyond the range studied by Qi and Luo (2002, 2003), and reported seven rotational transitions and eight steady or periodic modes, with the modes identified by Qi and Luo (2002, 2003) a subset of these. Glowinski et al. (1999) and Glowinski et al. (2001) introduced the distributed Lagrange multiplier/fictitious-domain (DLM/FD) method for the numerical simulation of neutrally buoyant particles in a two-dimensional Poiseuille flow, later extending (Pan et al., 2008) the method to non-spherical particles and performing DNS of the motion of neutrally buoyant ellipsoids in a three-dimensional Poiseuille flow. In this work they investigated the orientational and rotational behaviour of an ellipsoid at Reynolds numbers up to 80, and found its rotation exhibits distinctive states depending on the Reynolds number range and particle shape. Yu et al. (2007) also studied the rotation of a single spheroid in a planar Couette flow at moderate Reynolds number, with $Re_\tau < 256$, using the DLM/FD method, identifying an extra mode for the oblate spheroid, i.e. the motionless mode, in addition to those noted by Qi and Luo (2003), and finding that the orbital behaviour of the prolate spheroid is sensitive to its initial orientation.