INERTIAL EFFECTS ON NON-SPHERICAL PARTICLE ROTATION IN TURBULENT CHANNEL FLOW

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Abstract We investigated the rotation of non-spherical particles (rod-like and disk-like) in turbulent channel flow with focus on inertial effects. A direct numerical simulation (DNS) with an Eulerian-Lagrangian approach was performed. A wide range of particle aspect ratios, λ, ranging from 0.01 to 50 were considered for Stokes numbers *St* equal to 1 and 30. In the particle reference frame, statistical results reveal the importance of shape effect on the particle rotation. The rods ($\lambda > 1$) are spinning (rotation about their symmetry axis) more than tumbling (rotation about other axes) whereas disks ($\lambda < 1$) behave oppositely. With increasing particle inertia, i.e. higher *St*, the preferential tumbling of the disks and the spinning of the rods are reduced. We ascribe these observations to the varying degree of alignment of the particle symmetry axis with the fluid vorticity vector.

INTRODUCTION

Suspensions of solid particles in turbulent flows are commonly found both in nature and industry. In many real applications, such as biomass combustion and dispersion of air pollutants, the particle shape is usually non-spherical. From earlier studies [1-4] it is known that the shape of a non-spherical particle is of crucial importance for the particle rotation and orientation, which in turn will influence the forces and torques from the carrier fluid on the particles, and ultimately also the trajectories of the individual particles. To the authors' best knowledge, however, the effects of particle inertia on the particle orientation and rotation in a turbulent flow field have not yet been carefully examined and fully understood. The objective of the present work is therefore to explore the inertia effects on the rotation of non-spherical particles in a turbulent channel flow by means of DNS.

RESULTS AND DISCUSSION

A direct numerical simulation was performed at a frictional Reynolds number 180 based on the channel half-width h and the wall friction velocity u_τ. We consider a dilute suspension of non-spherical particles in which one-way coupling can be justified. The numerical method used for the integration of the Navier-Stokes equations and the scheme for tracking of ellipsoidal point-particles are adopted from Mortensen et al. [3] and Zhao et al. [5] and extended here to include not only prolate spheroids with aspect ratio $\lambda > 1$ as in [3], [5], but also oblate spheroids with $\lambda < 1$. The translational motion of a spheroidal particle is governed by Newton's 2nd law of motion expressed in the inertial reference frame $x_i = < x, y, z >$ in which also the turbulent flow field is computed. The rotational motion is governed by Euler's equation which is formulated in a particle frame $x'_i = < x', y', z' >$ with its origin in the mass center and the coordinate axes aligned with the principal directions of inertia of the spheroid.

We considered a thin bin surrounding the channel center at $z^+ = 180$ and computed particle statistics from 50 samples gathered in the time window $7200 < t^+ < 9000$. The total angular velocity ω is decomposed along the three principal axes into *spinning* and *tumbling* components, as shown in Figure 1. Rod-like particles ($\lambda > 1$) spin about their symmetry axis (z') more than they tumble, whereas disk-like particles ($\lambda < 1$) tumble more than they spin. These results for St = 1 are qualitatively consistent with recent numerical and experimental observations for non-inertial particles in homogenous isotropic turbulence (HIT) by Parsa et al. [1]. For the more inertial particles with St = 30, however, the preferred spinning ($\lambda > 1$) and tumbling ($\lambda < 1$) are dramatically reduced.

The particle rotation in the core region of the channel is mainly caused by the fluctuations of the fluid vorticity. We therefore examined the alignment between the particle symmetric axis and fluid vorticity vector in Figure 2. Firstly, we can see that the rods prefer to orient with theit major axis aligned with the fluid vorticity vector, whereas disks orient themselves with the symmetry axis aligned orthogonally to the vorticity. This explains why spinning is the preferred mode of rotation for rods and tumbling the prefered mode for disks. Similar observations for inertia-free particles in HIT were recently reported by Gustavsson et al. [4]. From the present results we also learned that inertia tends to suppress this preferential alignment. It is remarkable, however, that the actual aspect ratio of a rod-like particle doesn't seem to matter as long as $\lambda >> 1$. Similary, a disk-like particle exhibits similar orientations for $\lambda = 0.33$ and 0.01. This explains why the preferred mode of rotation, as shown in Figure 1, becomes independent of particle aspect ratio for sufficiently long rods and for sufficiently flat disks.

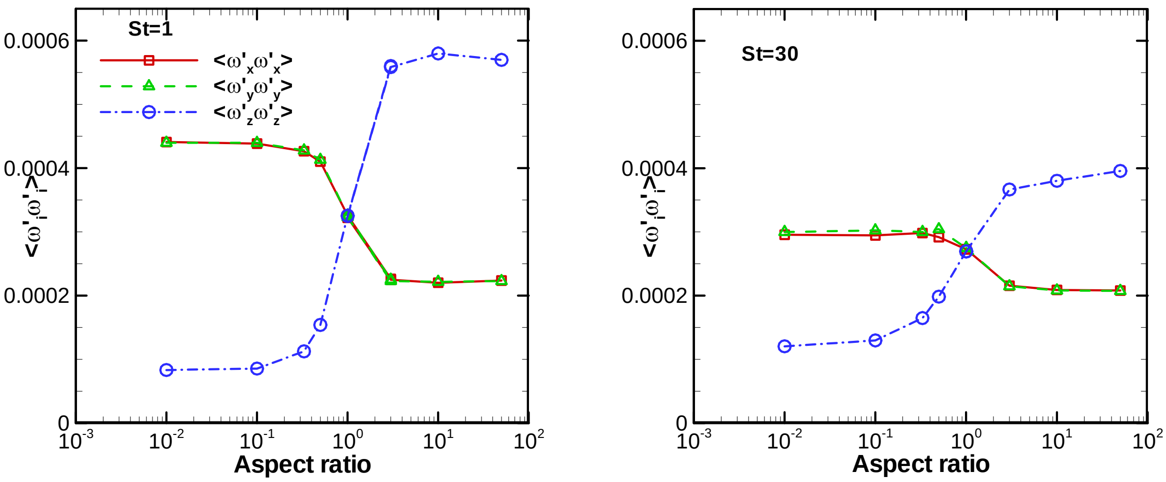

Figure 1. Particle rotation in the particle frame. Inertial particles with Stokes number St = 1 (left) and St = 30 (right).

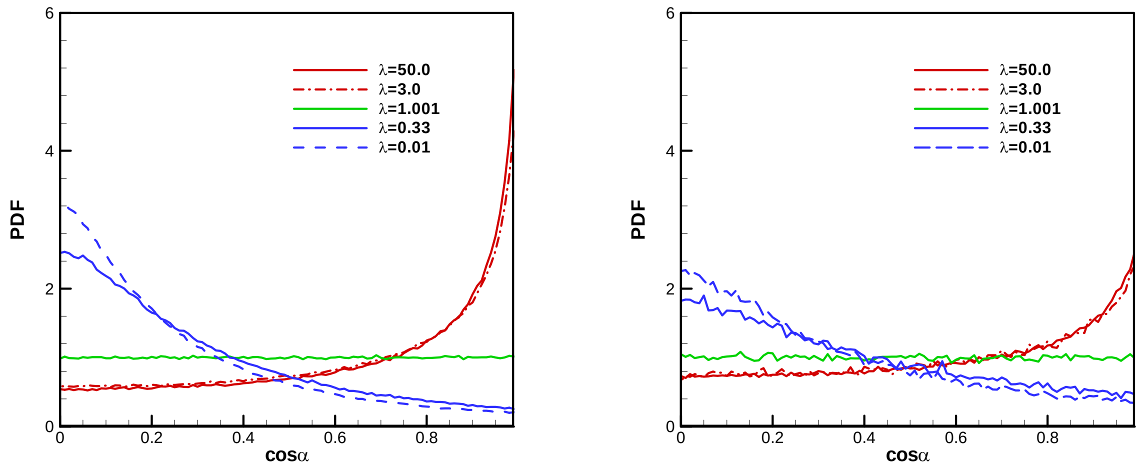

Figure 2. PDF of the alignment of the particle symmetric axis with the fluid vorticity vector in the center of the channel. α is the angle between the z'-axis and the vorticity vector. St = 1 (left) and St = 30 (right).

We have seen that the rotation of spheroidal particles in the channel center closely resembles particle rotation in HIT. The present results have shown that inertia reduces the preferred tumbling of disks as well as the preferred spinning of rods. This abstract is focused on the particle dynamics in the core region of channel where the vorticity field is almost homogeneous and isotropic. Further results from the anisotropic near-wall region will also be presented at the conference in order to demonstrate the dramatic differences between the particle dynamics in near-wall turbulence and the almost homogeneous core region.

References

[1] S. Parsa, E. Calzavarini, F. Toschi, and G. A. Voth, Rotation rate of rods in turbulent fluid flow, Phys. Rev. Lett., **109,** 134501, 2012.
[2] H. Zhang, G. Ahmadi, F.-G. Fan, and J. B. McLaughlin, Ellipsoidal particles transport and deposition in turbulent channel flows, Int. J. Multiphase Flow, **27**, 971–1009, 2001.
[3] P. H. Mortensen, H. I. Andersson, J. J. J. Gillissen, and B. J. Boersma, Dynamics of prolate ellipsoidal particles in a turbulent channel flow, Phys. Fluids, **20,** 093302, 2008.
[4] K. Gustavsson, J. Einarsson, and B. Mehlig, Tumbling of small axisymmetric particles in random and turbulent flows, Phys. Rev. Lett., **112,** 014501, 2014.
[5] L. Zhao, C. Marchioli, and H.I. Andersson, Slip velocity of rigid fibers in turbulent channel flow, Phys. Fluids, **26**, 063302, 2014.