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Finite-length effects on dynamical behavior of rod-like particles in wall-bounded turbulent flow

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ABSTRACT

Combined Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) measurements have been performed in dilute suspensions of rod-like particles in wall turbulence. PIV results for the turbulence field in the water table flow apparatus compared favorably with data from Direct Numerical Simulations (DNS) of channel flow turbulence and the universality of near-wall turbulence justified comparisons with DNS of fiber-laden channel flow. In order to examine any shape effects on the dynamical behavior of elongated particles in wall-bounded turbulent flow, fibers with three different lengths but the same diameter were used. In the logarithmic part of the wall-layer, the translational fiber velocity was practically unaffected by the fiber length l. In the buffer layer, however, the fiber dynamics turned out to be severely constrained by the distance z to the wall. The short fibers accumulated preferentially in low-speed areas and adhered to the local fluid speed. The longer fibers ($l/z > 1$) exhibited a bi-modal probability distribution for the fiber velocity, which reflected an almost equal likelihood for a long fiber to reside in an ejection or in a sweep. It was also observed that in the buffer region, high-speed long fibers were almost randomly oriented whereas for all size cases the slowly moving fibers preferentially oriented in the streamwise direction. These phenomena have not been observed in DNS studies of fiber suspension flows and suggested l/z to be an essential parameter in a new generation of wall-collision models to be used in numerical studies.

Introduction

Knowledge of the dynamical behavior of rod-like particles suspended in a turbulent flow field plays a key role in a wide range of applications in science and engineering. Separation of solid particles from industrial suspensions, long-distance material transport, papermaking, aerosols in the atmosphere, and transport and sedimentation of various substances in rivers and canals are typical examples. Because of the practical importance of dispersed turbulent multiphase flows, numerous computational and experimental studies of such suspensions have been performed.

Some computational investigations have focused on the dispersion of prolate ellipsoidal particles as a representative model of fibers (i.e. rod-like particles) in turbulence with point-mass treatment of the solid particles (Andersson et al., 2012; Fan and Ahmadi, 1995; Marchioli et al., 2010; Mortensen et al., 2008; Olson, 2001; Paschkewitz et al., 2004; Zhang et al., 2001). These numerical approaches have given a valuable insight in turbulent suspension flows, although the validity of the point-particle assumption is limited to particle sizes smaller than the tiniest scales of the fluid turbulence, namely the so-called Kolmogorov length scale. The mathematical expressions for the forces and torques exerted by the fluid on the rod-like particles are accordingly based on the assumption of creeping flow conditions in the immediate vicinity of the particle. Fully-resolved simulations of finite-size rod-like particles dispersed in a turbulent channel flow have only recently become feasible, and he distortion of the flow field around the individual particles is thus resolved (Do-Quang et al., 2014).

The presence of rod-like fibers as the dispersed phase makes experimental measurements much more complicated than those in single-phase flow because of the fibers interference, either optically or mechanically, with the probes. A particular challenge in this type of experiments is the measurement of the fluid-phase velocity in the immediate vicinity of the particle surface. Experimental studies have therefore concentrated on measuring

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the mean velocity and Reynolds stresses of the carrier-phase, and the mean velocity, fluctuations, orientation and accumulation of the rod-like particles. Higher-order statistics, including the carrier-phase turbulence modulation, two-fiber and fiber-fluid velocity correlations, are also of interest (Bellani et al., 2012; Carlsson et al., 2010; Melander and Rasmuson, 2004; Metzger et al., 2007; Newsom and Bruce, 1998; Parsheh et al., 2005; Shapiro and Goldenberg, 1993; van Hout et al., 2013; Xu and Aidun, 2005). It has been found that translational and rotational motion rod-like particles depend on the nature of the carrier-phase flow and fiber characteristics such as particle aspect ratio, particle Reynolds number, Stokes number, and ratio between a relevant flow length scale to the fiber length.

After the development of high-spatial-resolution PIV (Particle Image Velocimetry) and PTV (Particle Tracking Velocimetry) techniques, a combined PIV/PTV approach is probably the best available choice for experimental studies of dispersed two-phase flows (Balachandar and Eaton, 2010; Khalitov and Longmire, 2002; Kiger and Pan, 2000; Lindken and Merzkirch, 2002). The purpose of combined PIV/PTV measurements of two-phase systems are simultaneous measurements of the velocities of both the fluid and the dispersed particles, i.e. the PIV measurement of the fluid phase is combined with PTV measurement of the dispersed phase.

Using PIV measurements of the structures of sedimentation flow, Metzger et al. (2007) investigated the instability of a sediment suspension of rigid and high aspect ratio fibers within a viscous fluid. Their observations confirmed the existence of instability. They reported the mean velocities and velocity fluctuations; the strength of the velocity fluctuations strongly correlates with the size of the vertical component of the sedimentation structure. Parsa et al. (2011) were able to provide direct measurements of rod-shaped particle dynamics simultaneously with the two-dimensional fluid velocity field in chaotic non-periodic flow by means of video particle tracking. They reported that the small rod-like particles shown preferential alignment with the velocity gradient of the flow. Bellani et al. (2012) investigated experimentally shape effects on turbulence modulation. They found that ellipsoidal particles cause less reduction of the mean turbulent kinetic energy (TKE) in comparison with spherical particles. The reason for this is changes in production and dissipation of TKE, as well as redistribution of TKE across scales by ellipsoids and spheres. van Hout et al. (2013) proposed a combined PIV and digital holographic cinematography to study the fiber-flow interaction mechanisms in turbulent flow. They focused on the extraction of the velocity field in the vicinity of the fibers and their rotational and translation motion. When they applied in-line digital holography to image the fiber orientation and positions, the fiber diameters were not resolved in a high resolution, but their lengths were different. However, their PIV results showed a relation between the instantaneous vorticity field and the orientation of the fiber, but they explained that a larger ensemble size is needed to confirm this in a statistical sense. Parsa and Voth (2014) deduced the rotational dynamics of long rods from stereoscopic images and found that the rotation rates of the particles were significantly smaller than for randomly oriented rods. Ni et al. (2015) simultaneously tracked rod-shaped particles and spherical tracers in homogenous turbulence with a sufficiently high seeding density to enable measurements of the full fluid velocity gradient tensor in the vicinity for the rod.

The objective of the current work is to study the behavior of finite-size fibers in wall turbulence by simultaneous PIV/PTV measurements of fluid velocity and fiber motion. We study dilute suspensions with negligible fiber-fiber interactions and no flocculation. The measurements are carried out in parallel planes illuminated by a laser in the streamwise direction within a film suspension flowing on a water table set-up. The flow in this particular experimental set-up closely resembles a turbulent channel flow frequently studied by means of Direct Numerical Simulations (DNS). In the present paper, we present statistics of fiber rotational and translational motions and the surrounding fluid velocity. To the authors' knowledge, remarkably little experimental work has been published to date on simultaneous measurements of fiber motion and turbulence in a turbulent fiber suspension flow. Therefore, the present results are essential in order to achieve a better understanding of such multiphase flows. In Section 'Experimental set-up and methodology', the experimental set-up is introduced, the flow quality is assessed, and the measurement and analysis techniques are described. The results are presented and discussed in Section 'Results and discussion', and the major findings are summarized in Section 'Conclusion'. The results presented are in terms of viscous wall units wherever are denoted by superscript "+".

Experimental set-up and methodology

The experiments were conducted in the water table facility at Linné FLOW Centre at KTH in Stockholm through combined PIV/PTV measurements. We used a single-camera PIV technique to measure the flowing suspension. Pre-processing of the images was thus required to separate images of the two phases, namely the tracer particle images representing the fluid phase flow and fibers representing the suspended rod-like particles. Well-known PIV techniques were used for the measurement of the fluid flow, and a novel PTV approach was applied to track fibers in the flow in order to measure the fiber velocity.

Experiment apparatus and fluid flow measurements

The test section of the water table is made of a glass plate with length 230 cm and width 56 cm. The measurement area is situated 130 cm downstream of the beginning point of the flow and at the center of the table. These dimensions assure a fully developed turbulent flow and absence of any sidewall boundary effects and disturbances due to the reservoirs on the flow over the measurement area. Reservoirs are located upstream and downstream of the test section for mixing and storing the suspension, see Fig. 1.

The suspension film flows down along the slightly inclined table driven by gravity alone. The suspension is pumped back from the downstream tank to the upstream tanks to make a closed-loop flow. For a given inclination angle θ, the thickness h of the free-surface flow is set by controlling the flow rate of the pump. An especially attractive feature of this flow apparatus is that the friction Reynolds number (Re_τ) is controlled by the inclination angle θ and the film thickness h as (Abbasi Hoseini, 2014):

$$Re_\tau = \frac{hu_\tau}{\nu} = \frac{h\sqrt{gh\sin\theta}}{\nu},$$

where ν is the kinematic viscosity of the suspension and g is the acceleration of gravity. A desired Re_τ can therefore be obtained by appropriate settings of the pump and the table angle. The resulting fully developed film flow is characterized by a planar free surface. The flow in the vicinity of the wall is then representative of the flow in a plane channel where the two parallel channel walls are $2h$ apart.

A single camera (Imager Pro HS 4M; double-frame 12 bit CMOS with resolution of 2016×2016 pixels and pixel size of $11\ \mu m \times 11\ \mu m$) was placed beneath the water table facing upwards at the location of the measurement area in order to record images of the flow over the table; see the upper panel in Fig. 1. The measurements were carried out in planes parallel to the table wall (i.e. x–y planes) illuminated using an Nd: YLF laser (Litron Lasers;