Particle Image Velocimetry measurements in a turbulent channel flow laden with elongated particles

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Abstract. Particle Image Velocimetry is employed to investigate the turbulence modulation induced by dispersed elongated, rod-like particles in a turbulent channel flow. Particles with two different aspect ratios AR=40,80 are tested, at a volume fraction of $10^{-5}$. Carrier flow velocimetry data and distribution and orientation data of dispersed particles are obtained by an ad-hoc single-camera phase-discrimination technique. Carrier flow data shows that in the near-wall region turbulence modulation by particle occurs as well as a decrease of average streamwise velocity. Analysis of conditional probability density function of particles location reveals that particles locations statistically match flow regions with instantaneous low vorticity and high streamwise velocity, in particular in the near-wall region.

1. Introduction

Turbulent multi-phase flows where a solid dispersed phase is transported by a carrier liquid or gas flow are ubiquitous in applications and natural processes. A specific class of such flows is represented by suspensions where the dispersed particles are non-spherical bodies. Anisotropic particles may take the form of rods, disks or platelets. In particular, elongated axisymmetric particles, also called fibers, are encountered in a range of applications (paper-making processes, pneumatic transport) and environmental phenomena (ice-crystal formation within clouds, micro-plastic waterways pollution).

Analysis of turbulent multi-phase flows is inherently challenging due to the dynamic coupling which takes place between the dispersed particle phase and the carrier flow phase. The degree of interaction depends on many factors, the particles volume fraction being the most important. One-way, two-way and four-way coupling regimes are identified based on the dynamic coupling between phases. One-way coupling is characterized by a one-sided action exerted by the carrier flow upon the dispersed particles. This regime is characterized by selective concentration, accumulation and, in case of anisotropic particles orientation, of particles within the flow. Transported particles on the other hand do not affect the carrier flow features. For higher particles volume fractions, momentum transfer from particles towards carrier flow takes place and the suspension is considered to be in the two-way coupling regime.

Under these circumstances, carrier flow turbulence attenuation or enhancement may occur under the action of dispersed particles. As particles volume fraction is so high as to bring about inter-particle...
interactions, four-way coupling is reached. Due to its interest for applications and fundamental research, we will hereafter focus on the two-way coupling regime.

A thorough understanding of turbulent multiphase flows in which two-way coupling between phases occurs entails the distinct analysis of the particles and flow dynamics. This scenario is made even more complex when non-spherical particles are under investigation because interactions between flow and suspended phase are in this case dependent on particles orientation within the flow. The role of single particle orientation in three-dimensional space plays a pivotal role as it affects torques and forces exerted by the flow on the particle itself and for some applications, i.e. paper-making, is also important for end-product quality.

As a matter of fact, a complete picture of the phase interactions is provided by the simultaneous analysis of fiber distribution and orientation data combined to the flow velocity fields. Several works in literature have focused on either end of the two-way coupling interactions. With this latter respect, several Authors studied the effect of particle dispersion on the turbulent flow in terms of turbulence modulation. A review of this aspect is provided in [1]. On the other hand, analysis on particles behavior subject to the turbulent flows is found in several literature works, both numerical ([2] and [3] among the others), and experimental ([4]).

In the specific field of non-spherical particles transport by turbulent flows, recently several studies were carried out in different configurations ([5],[6],[7],[8]). A review of current open problems in experimental analysis and modeling of such flows is provided in [8].

In this work we build on the literature results currently available and investigate on the behavior of elongated particles suspensions in a turbulent channel flow, at a dilute concentration of $10^{-5}$ volume fraction for which two-way coupling takes place. We present the results of two kind of fiber particles which differ from their size and aspect ratio. Acquisitions are carried out via standard planar Particle Image Velocimetry and simultaneous information on particle location and orientation and carrier flow velocity is obtained and separately discussed. This approach allows analysis of the mutual effect of each phase on the other. The experimental methodology makes it possible to shed light onto the role played by elongated particles aspect ratio on phases interactions.
2. Experimental set-up

The turbulent channel flow facility consists of a rectangular section channel 140H long, 2H high and 20H wide, where H=1cm is the half channel height. The rectangular section is preceded by a 10:1 contraction and by a 5H long flow straightener module. The latter is designed to increase flow uniformity within the channel. The contraction section, 20H long, is designed in order to prevent flow separation. The channel width ensures that the flow can be reasonably considered on average as two dimensional in the plane parallel to the flow main direction. The flow is gravity-driven by a reservoir tank which is 55H high and supplied by a submerged pump sitting inside a stagnation chamber. Schematics of the apparatus is shown in Figure 1. Images are acquired by a cross-correlation CCD camera (PCO Pixelfly QE, 14-bit dynamic range, 1392 × 1024 pixels image resolution) equipped with a Nikon F 50 mm. Laser lighting is provided by a Nd:YAG double cavity unit (200 mJ per pulse at 12.5 Hz). Estimated laser sheet thickness is 2 mm. The dispersed phase is represented by nylon fibers (Polyamide 6.6, density 1.13 g/cm³). Two different mean lengths were tested: L₁=2mm and L₂=4mm. Mean diameter is for both sizes d=50µm so that fibers aspect ratio are respectively k₁=L₁/d=40 and k₂=L₂/d=80. Fluid tracers are neutrally buoyant silver coated 10µm diameter hollow glass spheres (Dantec HGS-10). Images are acquired at 100H downstream of the channel inlet, where the turbulent flow is fully developed. The acquisition plane is located at the centerline, perpendicular to the bottom and upper wall of the channel. The tested conditions are three: a reference case with no dispersed particles and two test cases with the selected fibers. The volume fraction for both fiber-laden cases is 10⁻⁵ which is associated to two-way phase coupling.

Flow velocity fields are obtained via planar Particle Image Velocimetry with the commercial software Insight 4G by TSI, Inc. The algorithm implements an iterative multi-pass, multigrid, image deformation scheme with window-offset. PIV interrogation window size is set to 64 × 64 pixels for the first pass and 32 x 32 pixels and 16 x 16 pixels for the second and final passes. For each test case, 5000 image pairs were acquired with a system acquisition frequency of 13Hz. Fiber location and orientation data were obtained via image processing of acquired images according to the scheme described in [7].

3. Effects of elongated particles on carrier flow

In Figure 2 and Figure 3 the flow field data obtained via PIV are shown for the reference and the particle-laden cases. In particular the average and turbulent fluctuations of the horizontal and vertical components, respectively U, u’, V and v’, are plotted versus the distance from the wall normalized by the channel half height H. Velocity are all normalized versus channel centreline U₀.

The presence of elongated particles within the flow affects the average velocity profile in particular in the near-wall region. Within this region the flow is slowed down by the presence of dispersed fibers, to an extent which depends on the fibers length, with longer fibers appearing to have a stronger impact on the flow. This phenomenon is reported mostly for the horizontal component of the velocity field, whereas it is less relevant for the vertical one. This circumstance hints at a role played by the preferential orientation of the particles which tend to orientate parallel to the flow close to the wall.

Analysis of horizontal and vertical turbulent fluctuations again suggests that in the near-wall region particles exert a turbulence modulation effect on the carrier flow. As reported in Figure 2 and Figure 3, turbulence is enhanced by the presence of fibers supposedly due to vortex shedding stemming from the particles themselves. With this respect we point out that longer fibers tend to be associated to larger increases of turbulent fluctuations. Furthermore, comparison between velocity components show that the relative turbulence enhancement is higher for the vertical fluctuations. This is supposedly due to the
tendency by fibers to change orientation when close to the wall in a pole-vaulting motion described in literature by other Authors [5].

Figure 2: Mean (left) and RMS (right) of the horizontal velocity for the reference and fiber-laden cases.

Figure 3: Mean (left) and RMS (right) of the vertical velocity for the reference and fiber-laden cases.
4. Effects of carrier flow on elongated particles: selective concentration and orientation

The effect of the carrier flow on the distribution of particle is explored by analysing the fibers concentration and orientation within the flow. These data are obtained by post-processing of tracers-particle images as explained in [7]. In Figure 4 it is reported the statistical distribution of particles center of gravity versus their distance from the wall. Fibers tend to reach a levelled concentration from approximately $Y/H>0.2$, independently from their length. On the other hand the near-wall region shows a different trend: fibers concentration undergoes a steep increase up to approximately $Y/H=0.75$, where a peak is reached. This concentration peak is more pronounced for the longest fibers. Further insight into the interactions between carrier and transported phases is provided by the conditional probabilities obtained by simultaneous fiber and flow velocity data. To this aim for each identified particles interpolation is carried out to calculate the flow velocity in the location of the particle center of gravity. This information is employed to extract fiber features distribution conditioned to fiber location within the flow. In Figure 5 and Figure 6 it is shown the probability density function of horizontal and vertical velocity on fibers location independent from fibers location (left) and conditioned to fibers located not farther than 0.1H from the wall (right). Interestingly, the horizontal component distribution exhibits values concentrated around higher values for fibers closer to the wall. This occurrence contrasts with the observation that close to the wall, in the unladen case, flow velocity is on average lower than far from the wall. Furthermore, this result shows that even when statistically instantaneous flow velocity is lower, particles tend to concentrate in positions where local horizontal velocity is higher. This phenomenon is reported only for the horizontal velocity, whereas the vertical one does not exhibit such trend. Also, fiber size does not seem to play a role with this respect. Distribution of conditional vorticity is shown in Figure 7, which conveys a scenario where closer to the wall, particles of both sizes tend more to concentrate in flow regions with zero vorticity than in regions far from the wall. This may be explained with the observation that high levels of vorticity are associated to fibers rotating motion which in turn pushes the particle away from the wall.

Fiber orientation distribution are provided in Figure 8, which shows that regardless of distance from the wall, particles tend to orient themselves at a slightly negative angle with respect to the wall. A fiber parallel to the wall is considered here as having a 0° orientation, whereas ±90° indicates a particle perpendicular to the channel wall. The occurrence that fibers tend to orientate at moderate angle with respect to the wall (the peak of the distribution lies within the 10°-20° interval) has been reported in other works ([6],[7]); here it is observed that longer fibers exhibit a narrower distribution peak, while shorter particles feature a flatter profile. This difference is less evident when looking at the particles in the near-wall region, at the right end side of Figure 8. Fibers close to the wall are more restricted in their orientation status by the wall constraint. The latter acts to level the differences between the different size fibers.
Figure 4: Particles relative concentration versus wall distance.

Figure 5: Distribution of horizontal flow velocity at particle location, independent from particle position (left) and conditioned to particles located at Y<0.1H
Figure 6: Distribution of vertical flow velocity at particle location, independent from particle position (left) and conditioned to particles located at $Y<0.1H$.

Figure 7: Distribution of vorticity at particle location, independent from particle position (left) and conditioned to particles located at $Y<0.1H$. 
5. Conclusions

Investigation of dispersion of elongated particles of two different sizes in a turbulent channel flow is carried out by PIV. Image post-processing is used to obtain separately flow velocity data and fiber orientation and distribution data. For the fiber-laden case the average flow velocity is lower in the near-wall region with respect to the reference, unladen case. Turbulent fluctuations are reported to be enhanced by the presence of particles, in particular in the near-wall region and to a larger extent by longer particles. Under the action of the turbulent flow, particles tend to reach a concentration peak close to the wall, in particular the longest fibers, while they tend to reach a constant concentration value away from the wall. Probability density function of flow velocity and vorticity interpolated at fibers location show a tendency of fibers to be located in low vorticity, high speed regions, in particular close to the wall.

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