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Measurement of polystyrene beads suspended in a turbulent square channel flow: Spatial distributions of velocity and number density

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ABSTRACT

Single view, inline digital holographic cinematography (1 kHz) was used to track near neutrally buoyant, polystyrene beads in a turbulent water channel flow at bulk flow Reynolds number of 10,602. In-house developed algorithms, fine-tuned to tracking single and overlapping beads were developed. In total, 1616 beads were tracked using a nearest neighbor algorithm resulting in an average track length of 53 ms. Overlapping beads were segmented using distance and watershed transforms. In most cases, beads' in-focus positions were determined based on maximum rms of intensity gradients that outperformed other methods. Data processing and tracking was illustrated by a case study of four beads near the bottom channel wall. Bead diameters and in-plane positions/velocities were determined accurately. However, in the illumination direction, bead positions/velocities suffered from inherent in-focus inaccuracy. In agreement with available literature results, ascending beads lagged the mean streamwise water velocity while descending ones had similar velocities. Average streamwise bead velocities and number densities collapsed onto wall-normal-streamwise and spanwise–streamwise planes, indicated preferential segregation of ascending and descending beads up to a height of 100 wall units. Spanwise "lane" separation distances ranged between 150 and 200 wall units, larger but of the same order as the spanwise extent of coherent near-wall turbulence structures.

1. Introduction

Particle-laden flows commonly occur in many industrial and environmental settings such as chemical plants, oil industry, bio-medical applications, wind/water erosion and biological applications (e.g. Crowe et al., 1996; Hunt, 1991). Particle dispersal in turbulent boundary layers has been widely studied both numerically and experimentally (e.g. Kaftori et al., 1995a,b; Niño and Garcia, 1996; Marchioli and Soldati, 2002; Righetti and Romano, 2004; van Hout, 2011). In general, results indicate that coherent turbulence structures such as hairpin packets (e.g. Zhou et al., 1999; van Hout, 2013), are instrumental in particle lift-off and deposition and cause preferential separation into longitudinal low-speed streaks (e.g. Niño and Garcia, 1996; Narayanan et al., 2003). These low speed streaks have streamwise lengths of the order of 1000–2000 wall units (e.g. Niño and Garcia, 1996) and the average transverse spacing is equal to ~100 wall units both with and without particles, and unaffected by particle loading (Yung et al., 1989; Rashidi et al., 1990; Robinson, 1991). Here, wall units indicate normalization by inner wall parameters (in the following denoted by the superscript "+"), i.e. the friction velocity, $u_\tau \equiv (\tau_w/\rho_f)^{0.5}$, and the kinematic fluid viscosity, ν; τ_w is the wall shear stress, ρ is the material density and the subscript "f" denotes "fluid". Experiments by Kaftori et al. (1995a) and Niño and Garcia (1996) indicated that particles submerged in the viscous sublayer had a stabilizing effect on the turbulence structure and caused highly persistent streaks both in time and space. The latter measurements further indicated that heavy particles larger than the viscous sublayer thickness did not tend to accumulate along low speed streaks and Niño and Garcia (1996) concluded that streaks are confined to the viscous sublayer. However, Direct Numerical Simulations (DNS) of a turbulent channel flow indicated that streaks exist at least up to a wall-normal distance of $y^+ = 10$ (e.g. Moin and Kim, 1982) while recent measurements and simulations indicate that coherent near-wall structures such as "hairpins" extend up to $100y^+$ (Zhou et al., 1999; van Hout, 2013).

The ability of particles to respond to changes of the instantaneous turbulent fluid velocity is described by the Stokes number, $\mathrm{St} \equiv \tau_p/\tau_f$, defined as the ratio between the particle response time, $\tau_p = \rho_p d_p^2/18\rho_f \nu$, and a suitable flow time scale, τ_f; d is the particle diameter and the subscript "p" denotes "particle". The choice of τ_f in a wall-bounded flow is non-trivial since it may depend on the

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wall-normal distance. In the literature, different values have been used such as the viscous time scale, $\tau_f = \nu^2/u_\tau$ that is constant, or the characteristic time of energy containing eddies, $t_e = \kappa y^+ \nu/u_\tau^2$ that increases upon moving away from the wall (Tennekes and Lumley, 1972; Righetti and Romano, 2004). DNS by Pedinotti et al. (1992) showed that particle preferential segregation depended on τ_p^+ (or St), with maximum segregation occurring for $\tau_p^+ \approx 3$, independent of particle size. Their DNS results were partially validated by LDA measurements of Niño and Garcia (1996) that showed that large particles ($\tau_p^+ \approx 10$) did not segregate but were rather uniformly distributed.

In square duct flows, turbulence driven secondary flows transfer fluid momentum from the duct core to the corners (e.g. Melling and Whitelaw, 1976; Gavrilakis, 1992; Huser et al., 1994; Petterson Reif and Andersson, 2002). Maximum secondary velocity magnitudes are about 2% of the bulk flow velocity (e.g. Gavrilakis, 1992) and result in wall shear stress maxima at one third and half the duct wall width. While there are quite some experimental and numerical studies that investigated the effect of secondary flows, only a few numerical studies on particle-laden flows in square ducts have been performed (Winkler et al., 2004; Sharma and Phares, 2006; Phares and Sharma, 2006; Winkler and Rani, 2009; Yao and Fairweather, 2010, 2012) and there is a complete lack of experiments. Numerical results showed that inertial particles segregated in streamwise, high number density streaks similar as observed in plane channel flows (e.g. Niño and Garcia, 1996; Narayanan et al., 2003). However, Phares and Sharma (2006) and Yao and Fairweather (2012) showed that as a result of secondary flows, high inertia particles ($\tau_p^+ > 10$) deposit near to the duct corners while low inertia particles ($\tau_p^+ < 10$) deposit near to the center of the bottom duct wall. In addition, off-axis secondary flows tend to enhance lateral mixing (Sharma and Phares, 2006).

DNS and Large Eddy Simulations (LES) combined with Lagrangian particle tracking have been instrumental in providing a better understanding of particle-flow interactions, while experiments have lagged behind mainly due to technological difficulties. However, in the last decade, Lagrangian particle tracking techniques (e.g. Voth et al., 1998) such as high speed tomography using three or more cameras (Lüthi et al., 2005; Scarano, 2013) or holography using one or two cameras have become widely used (e.g. Buraga-Lefebvre et al., 2000; Xu et al., 2003; Meng et al., 2004; Pu et al., 2005; Palero et al., 2007; Lu et al., 2008; Sheng et al., 2006; Katz and Sheng, 2010; De Jong et al., 2010; Sabban and van Hout, 2011; Sabban et al., 2012). An advantage of single view, digital in-line holography compared to multiple camera tomographic velocimetry, is the relative simple optical setup. Furthermore, Lu et al. (2008) compared two orthogonal view, in-line holography to a single view setup and concluded that except for acceleration statistics in the illumination direction, velocity and acceleration statistics of small droplets were well captured by the latter setup.

In the present experiments, high-speed, single view, digital in-line holography was used to track a dilute suspension of polystyrene beads in a fully developed turbulent square duct flow. The aim of the present work is to measure the spatial bead velocity and number density distributions in the lower part of the channel, specifically focused on bead preferential segregation. An overview of the experimental setup and in-house developed data processing algorithms is presented in Sections 2 and 3. A case study of four beads presented in Section 4, illustrates the data processing. Spatial number density and velocity distributions indicating bead segregation are presented in Section 5.

2. Experimental setup and methodology

The present measurements were performed in a closed loop, horizontal water channel facility schematically shown in Fig. 1. The facility comprised a tapered water tank, a frequency controlled pump, a magnetic flow meter, an inlet diffuser, a honeycomb and

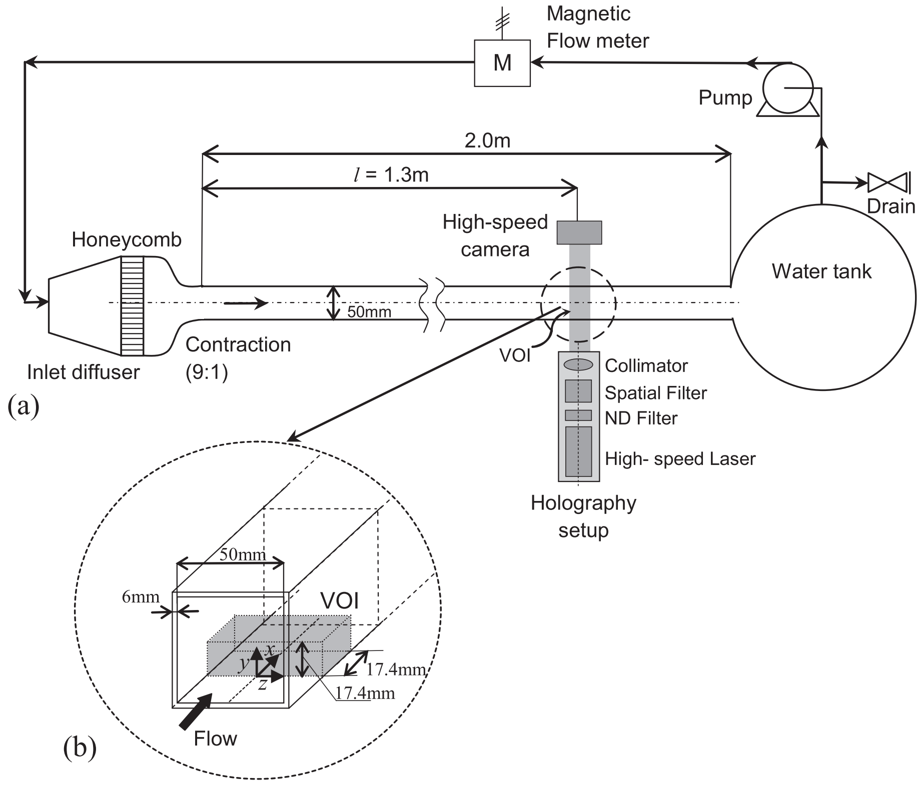

Fig. 1. Schematic layout of the experimental facility. (a) Closed loop water channel and holography setup (not to scale); (b) close-up of VOI and coordinate system. The right-handed Cartesian coordinate system is positioned at the center of the bottom channel.