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Lagrangian velocity and acceleration statistics of fluid and inertial particles measured in pipe flow with 3D particle tracking velocimetry

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ABSTRACT

Three-dimensional particle tracking velocimetry (3D-PTV) has been applied to *particle-laden* pipe flow at Reynolds number 10,300, based on the bulk velocity and the pipe diameter. The volume fraction of the inertial particles was equal to 1.4×10^{-5}. Lagrangian velocity and *acceleration* statistics were determined both for tracers and for *inertial* particles with Stokes number equal to 2.3, based on the particle relaxation time and the viscous time scale. The decay of Lagrangian velocity and acceleration correlation functions was measured both for the fluid and for the dispersed phase at various radial positions. The decay of Lagrangian velocity correlations is faster for inertial particles than for flow tracers, whereas the decay of Lagrangian acceleration correlations is about 25% slower for inertial particles than for flow tracers. Further differences between inertial and tracer particles are found in velocity fluctuations evaluated for both positive and negative time lags. The asymmetry in time of velocity cross-correlations is more pronounced for inertial particles. Quadrant analysis revealed another difference still near the wall: ejection and sweep events are less frequent for inertial particles than for tracers.

Introduction

Turbulent dispersed two-phase flows are ubiquitous in industry and nature. For this reason, the dispersion of pollutants in an urban environment, combustion, industrial mixing, sediment transport or the fluidized catalytic cracking of carbohydrates is often studied, Poelma et al. (2006). Flows of this kind are characterized by particles, droplets or bubbles dispersed within a carrier phase. Many of such flows occur in pipes, *e.g.* pneumatic conveying systems and chemical reactors, Kartusinsky et al. (2009). The ability to predict the behavior of this kind of flow is therefore of considerable interest. However, due to the complexity of these flows, available models are usually simplifications and cannot predict fluid and particle behavior for the whole range of process conditions of interest.

Therefore, stochastic models of turbulent transport are promising, Pope (1994) and Yeung (2002). Experimental determination of statistical properties of particles in a Lagrangian frame of reference is essential for the development of stochastic models. For a complete description of particle statistics it is necessary to follow particle paths with high spatial and temporal resolution, on the order of the Kolmogorov length and time scales, η and τ_k, respectively. To capture the large-scale behavior in a turbulent pipe flow, trajectories should be tracked for long times, *i.e.* multitudes of τ_k. This obviously necessitates access to an experimental measurement volume with a typical length scale on the order of the bulk velocity times the typical Lagrangian correlation time, Biferale et al. (2008) and Brouwers (2002).

Despite the higher practical importance of inhomogeneous turbulent flows, experimental Lagrangian results in literature are mostly restricted to homogeneous turbulence. Lagrangian measurements in flow geometries with non-zero mean velocity component are scarce. The work of Suzuki and Kasagi (2000) represents one of the few exceptions. For the industrially relevant pipe flow, only the 3D-PTV results of Walpot et al. (2006) and Oliveira et al. (2013) are available, to the best of our knowledge. These were single-phase pipe flows. Veenman (2004) provided Eulerian and Lagrangian DNS computations of single-phase pipe flow at bulk Reynolds number, Re_b equal to 5300 and 10,300. Walpot et al. (2006) presented experimental data for $Re_b = 5300$ and some preliminary results at $Re_b = 10{,}300$. Recently, Oliveira et al. (2013) presented new experimental Lagrangian results for

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single-phase pipe flow at Re_b = 10,300 and compared these with DNS-data of Veenman (2004). *All these results were for flow tracers only*.

The present work aims at providing Lagrangian velocity and acceleration statistics of flow tracers and one class of inertial particles (with Stokes number 2.3 based on the particle relaxation time and the viscous time scale and diameter 0.8 mm), measured simultaneously and in *particle-laden* flow. To the best of our knowledge, experimental data of this kind have not been provided up to now. 3D-PTV is applied to particle-laden pipe flow in upward vertical direction at Re_b = 10,300. Here, Re_b is based on the bulk velocity and the pipe diameter. The mean volumetric concentration of inertial particles is equal to 1.4×10^{-5}. The mass density of the inertial particles ($\rho_p \approx 1050$ kg/m^3) exceeds the mass density of the carrier fluid ($\rho_f \approx 1000$ kg/m^3).

The structure of the paper is as follows. In section 'Experimental setup', the experimental set-up is presented, including specifications of flow tracers and inertial particles. Section 'Results' gives the 3D-PTV results for the particle-laden flow, in particular velocity and acceleration fluctuations of fluid and dispersed phase, velocity fluctuations for "negative" time lags and quadrant analysis. A discussion of the experimental findings is given in section 'Discussion'. Finally, conclusions are presented in section 'Conclusions'.

Experimental setup

Test rig

Turbulent particle-laden pipe flow has been created in a water loop driven by a centrifugal pump (see Fig. 1). The in-line 3 kW centrifugal pump of type DPV18-30, manufactured by Duijvelaar pompen, allows Reynolds numbers based on the bulk velocity, U_b, and pipe diameter, D, in the range 10^3–10^5. A frequency controller permits fine-tuning of the Reynolds number by adjusting the mass flow rate of the upward vertical flow in the measurement section.

Fig. 1. Schematic of the 3D-PTV experimental setup for particle-laden pipe flow.

The mass flow rate is measured by means of a Micro Motion Elite CMF300 mass flow and mass density meter, whose inaccuracy is less than 0.5% of the registered flow rate. A water reservoir contains about 2 m^3 of water. This large amount facilitates water temperature stabilization and Reynolds number control. The temperature during a test-run was essentially constant, varying by typically 0.1 °C only. Submerged pumps are placed in the reservoir tank in order to promote homogeneous dispersion of the added tracers and inertial particles. The measurement section consists of a glass pipe to ensure optical accessibility. A water-filled rectangular glass box around the pipe minimizes optical distortions. The pipe diameter is chosen relatively large, 100 mm inner diameter, because measurements at high Reynolds numbers are required. For a certain Reynolds number, bulk velocities are lower for higher pipe diameters, which is advantageous for the acquisition of Lagrangian statistics.

A flow straightener, tube bundle conditioner of ISO 5167-1:1991 (see Miller (1996)), has been placed downstream of the 90° bend, about 45 pipe diameters upstream of the measuring section. The flow straightener removes secondary flows and shortens the length required to obtain a fully developed flow. At the location of the test section a fully developed flow has been achieved; see Oliveira et al. (2013).

Properties of applied particles

Properties of polystyrene particles applied in the present particle-laden flow are given in Table 1. The fluid time-scale τ_f used in the Stokes number, St, is based on the kinematic viscosity, ν, and the wall shear velocity: $\tau_f = \nu/u_\tau^2$. For $Re_b < 10^5$, the wall shear velocity is estimated as

$$u_\tau = \left(\frac{U_b^2 f}{8}\right)^{0.5} \quad (1)$$

with $f = a\ Re_b^{-m}$, m = 0.25 and a = 0.316; see Hinze (1975), τ_f is roughly 28 ms. See also the caption of Table 1. The fluid length-scale is the Kolmogorov scale for fully developed single-phase pipe flow at Re_b = 10,300 as computed by Veenman (2004). The Kolmogorov length is about 0.60 mm in the pipe core and 0.23 mm close to the wall. For evaluation of the particle timescale, τ_p, the relaxation time for particles in stationary flow is used, see Albrecht et al. (2003):

$$\tau_p = \left(\frac{d_p^2 \rho_p}{18\mu}\right)\left(1 + \frac{0.5\rho_f}{\rho_p}\right) \quad (2)$$

where μ is the dynamic viscosity, d_p is the particle diameter and ρ_p and ρ_f are the mass densities of particles and fluid, respectively. A relaxation time of $\tau_p \approx 4$ ms is obtained for the tracers. Note that

Table 1
Properties of particles applied in the present particle-laden flow.

Particles	Mass density (kg/m^3)	Diameter d_p (mm)	Terminal velocity[a], U_{TV} (mm/s)	Re_p	[b]$St = \tau_p/\tau_f$	[c]Length-scale ratio: d_p/η
Flow tracers	1050	0.2	1.0	0.18	0.14	0.33–1
Inertial particles	1050	0.8	10.2	7.76	2.31	1.33–3.5

[a] Settling velocity of a particle in an infinite, stagnant pool of water.
[b] Fluid time-scale is based on viscous scales as given by: $\tau_f = \nu/u_\tau^2$. For $Re_b < 10^5$, the wall shear velocity can be estimated as $u_\tau = (U_b^2 f/8)^{1/2}$ with $f = a\ Re_b^{-m}$, m = 0.25 and a = 0.316; τ_f is roughly 28 ms.
[c] Kolmogorov length-scales for a fully developed single-phase pipe flow at Re_b = 10,300 as computed from the DNS code developed by Veenman (2004): ≈0.60 mm at pipe centerline and ≈0.23 mm close to the wall.