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On the Lagrangian features of circular and semicircular jets via 3D Particle Tracking Velocimetry

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ABSTRACT

Three-dimensional Particle Tracking Velocimetry was employed to characterize jets from circular and semi-circular pipes in the intermediate and far fields. Grid-interpolated velocity were used to validate the measurements, and confirmed the negligible effect of the pipe shape on the mean flow in the intermediate field. Several volumetric regions were defined to get Lagrangian statistical description of the flow from categorized particle trajectories. Probability density functions of the velocity fluctuations, particle acceleration, and curvature of the trajectories revealed common and distinctive features of the jets. The first one showed departure from the Gaussian distribution away from the core, and the acceleration exhibited heavy tails in the two jets; however the curvature pdf revealed distinctive footprint of the pipe shape.

1. Introduction

Turbulent jets from non-circular pipes are ubiquitous in engineering applications. Detailed characterization of the turbulence induced by such flows is needed in a broad spectrum of practical problems related to scalar transport, mixing, and momentum exchange, among others. Most research efforts have placed their attention on jets from circular nozzles and, only to a limited extent, complex geometries. Various investigations show that jets share a number of similarities regardless of the geometry of the nozzle or pipe generating the jet. For instance, a recent work of Bejan et al. [1] suggests that the mean velocity distribution of turbulent jets from rectangular nozzles of width b becomes axisymmetric as close as $x/b \sim 10$, where x is the distance from the jet origin. Hashiehbaf et al. [2] investigated circular and non-circular synthetic jets from sharp-edge orifices, and found that self-similarity of the axial velocity distribution is achieved at $x/d_h > 5$, where d_h is hydraulic diameter. Mi and Nathan [3] investigated the centerline flow statistics of jets from nine differently-shaped nozzles, and pointed out that in the intermediate field, $x/d_h \geqslant 10$, the fluctuating velocity probability density function (pdf) exhibits Gaussian distribution irrespective of the nozzle shape. Although self-similar behavior in circular jets is suggested to hold at $x/d_h > 30$ [4,5], numerous experimental evidence indicates that this feature depends on the flow statistics. For example, Di Cicca and Iuso [6] observed self-similar velocity distribution in axisymmetric synthetic jet as close as $x/d_h = 6$, whereas the Reynolds shear stresses self-similarity started at $x/d_h = 25$. Cater and Soria [7] found that synthetic jets reached a self-similar velocity at $x/d_h = 15$.

Several experimental techniques have been used to characterize and uncover the dynamics of complex jet flows. Point measurements with hotwire anemometry have been extensively used to study, for example, the effect of nozzle shape on the mixing along the jet axis [8], characteristics of jet impingement cooling [9], the influence long slot nozzle geometry on a plane jet [10], and turbulence characteristics of jets from a triangular orifice [11]. Particle image velocimetry (PIV) has been used to investigate synthetic jets issuing from different non-circular nozzle shape at high Reynolds numbers [2], subcooled boiling in bubble-top jet flows [12,13], and lobed jets [14], among others. Tomographic PIV has also been used in planar jet flows to characterize 3D vortex structures [15].

Another technique particularly suitable to describe a turbulent flow field in a Lagrangian frame of reference is the so-called 3D Particle Tracking Velocimetry (3D-PTV), or Lagrangian particle

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tracking (LPT), which allows the reconstruction of particle trajectories within an interrogation volume using multi-view stereoscopy. It was first introduced by Chang et al. [16] and further developed by Racca and Dewey [17]. 3D-PTV has helped to understand a number of turbulence-driven phenomena [e.g. 18], clustering of large particles [19], open-channel flows [20], and the stagnation region of an axisymmetric impinging jet flow [21]. In addition, 3D-PTV has been compared with direct numerical simulation (DNS) of plane channel with abrupt expansions [22] and plane Couette flows [23]. Recently, Rosi [24] has used 3D-PTV to resolve flow structures in the lower atmosphere with a domain size of $4\ \text{m} \times 2\ \text{m} \times 2\ \text{m}$. Since 3D-PTV is not limited to stationary flows, there have been extensive studies on pulsatile flows such as those in micro silicon Y-channels flows [25] and arterial stiffness [26] as well as temporal dispersion in aortic flows [27].

Many studies, focused on the Lagrangian dynamics of turbulence using 3D-PTV, have reported strong acceleration events [18]. La Porta et al. [28] observed that acceleration events in excess of 1500 times the gravity can be attained in turbulent flows. They and Voth et al. [29] found that the probability distribution of acceleration is heavily non-Gaussian with strong pronounced tails. Mordant et al. [30] performed detailed measurements of the acceleration probability to get high-order moments. Liberzon et al. [31] studied the alignment features of total and convective acceleration statistics in an isotropic turbulent flow. Xu et al. [32] used the Frenet–Serret frame to study isotropic turbulence, and showed that instantaneous curvature pdf exhibits robust power-law tails [32,33].

In this work, we experimentally investigate some Lagrangian statistical properties of jets from circular and semi-circular pipes sharing the same hydraulic diameter and Reynolds number. Two independent setups and PTV systems are used to describe the jets at different spatial resolution. The details of the experimental setups are described in Section 2, main results are discussed in Section 3, and main remarks are summarized in Section 4.

2. Experimental setup

Jets from circular and semi-circular pipes were characterized from two independent setups at a Reynolds number $Re = U_J d_h/\nu = 6000$, where U_J is the mean velocity at the pipe exit, and ν is the kinematic viscosity of the fluid. The pipes were manufactured using a Stereolithography 3D printer with a resolution of 25.4 μm. They share the same hydraulic diameter $d_h = 4S/P = 0.01$ m, where S and P are the cross-sectional area and perimeter, and length $L = 16d_h$. A $5.1d_h$ long, 6.3:1 contraction area ratio preceded the each pipe to minimize flow singularities at the pipe's inlet. Air was used as the working fluid in one setup, where a scalable real-time LS-PTV [34] was implemented to describe the flow in the intermediate and far fields, $x/d_h \in [15, 40]$, within a large interrogation volume covering $\sim 25d_h \times \sim 10d_h \times \sim 10d_h$ in the streamwise, spanwise and vertical directions. The other setup used water as working fluid. There, high-resolution flow measurements were performed with a SS-PTV [35] in a small region of $\sim 4d_h \times \sim 4d_h \times \sim 4d_h$ within the intermediate field $x/d_h \in [14.5, 18.5]$ for detailed characterization. Basic schematics of the two setups are illustrated in Fig. 1, and details are described as follows.

2.1. LS-PTV and air-jet setup

In this setup, air flow was released from the pipes in an unbounded, quiescent room at a fix rate. The jets were seeded with neutrally buoyant Helium filled soap bubbles (HFSB) from a SAGE Action Model 5 bubble generator. The bubbles were illuminated by

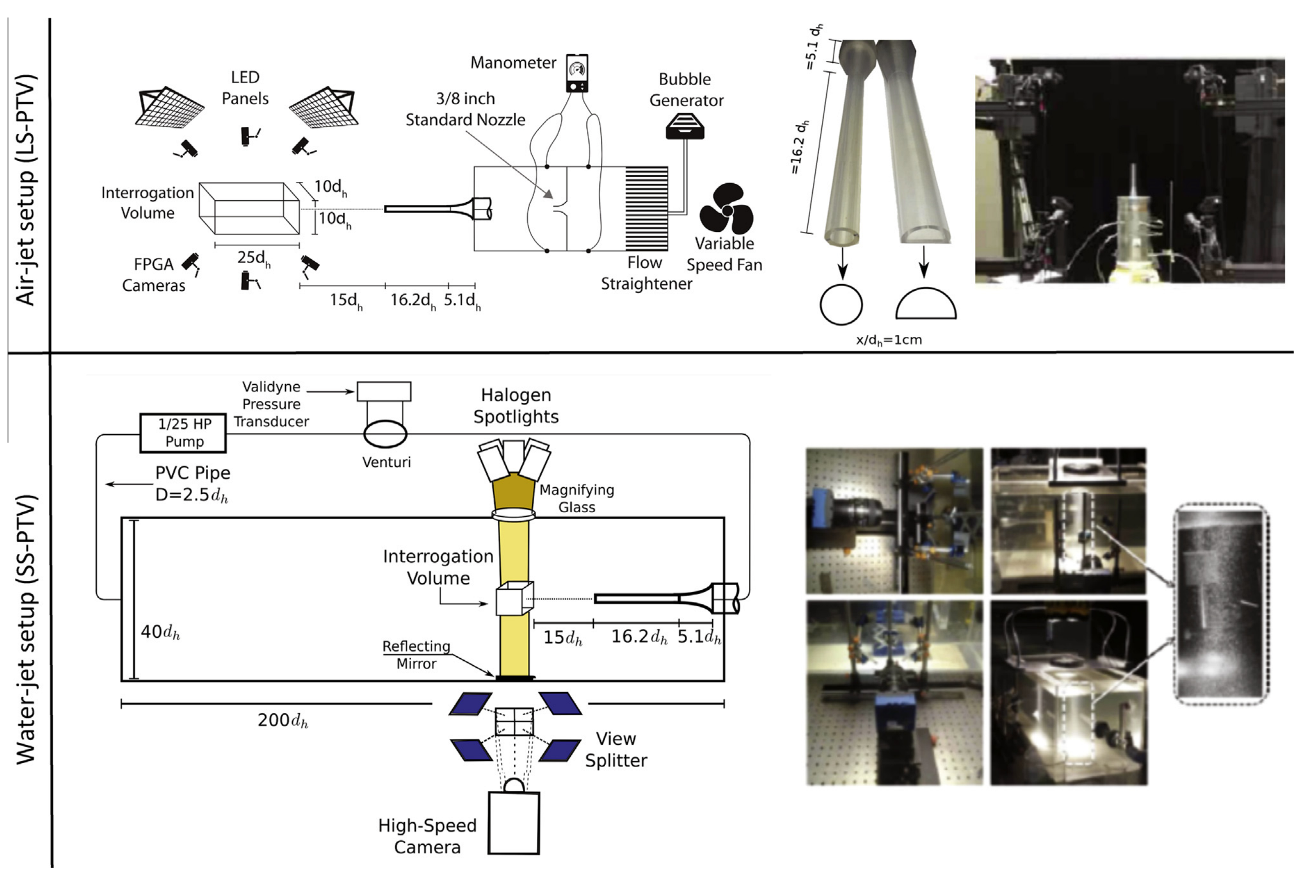

Fig. 1. Basic schematic an photograph of the experimental setups for the LS-PTV and SS-PTV.