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Turbulent properties of a low Reynolds number, axisymmetric, pipe jet

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ABSTRACT

This paper presents the mean and turbulent properties of a low Reynolds number round jet (Re 5500), with a fully turbulent pipe flow initial velocity profile, from nozzle exit to the establishment of self similarity. Experimental data acquired with a 2-D Laser Doppler Anemometry system include jet flow parameters and velocity statistics, such as spreading, entrainment, axial and radial distributions of the axial velocity and higher order moments. A "preserving core" region is identified, in analogy to the potential core region observed in jets with a uniform central initial profile. A transition region is following and thereafter, self similarity is approached in steps with the mean axial velocity attaining first self similar profiles, while the axial fluctuations, the radial fluctuations and the turbulent Reynolds stresses follow. The form of all the measured self similar profiles compares well to previous findings, although the values of the turbulent properties are always lower compared to those of contraction round jets of significantly higher Reynolds number. The triple velocity products and skewness and flatness factors indicate a different eddy structure of the present jet compared to that of earlier reported contraction jets.

1. Introduction

The classical theory of Townsend [1] that defined the unique similarity of all the non-dimensionalized mean and turbulent profiles of flow or scalar properties of jets that grow with the same momentum has been reconsidered and refined during the last decades. According to this theory, it was widely accepted that although initial conditions may affect the development of the shear layer close to the nozzle exit, the resulting differences vanish at a sufficient downstream distance. For many years, a large number of studies presented supporting or conflicting results with respect to the previous statements. However, due to several differences in the experimental configurations and conditions and the variety of the utilized techniques, only recently it became clear that discrepancies were larger than the associated uncertainties and additional similarity concepts were needed to take into account the details of the inflow conditions. George [2] suggested that more sophisticated similarity concepts should be used to accommodate the different findings of previous experiments. By reconsidering earlier results using suitable scales that account for the unique character of each particular flow, he showed that the initial conditions of the jet (or similarly a wake) could substantially affect the flow or scalar field during its development and eventually its self-similar characteristics. During the last decade, the effects of the initial conditions were more systematically investigated trying to distinguish the effects of different initial or/and boundary conditions. These include confinement effects due to test rig or even laboratory walls (which establish recirculation patterns leading to significant "momentum stealing" as the confinement becomes tighter), the existence of a co-flowing stream, the geometry of the nozzle and the Reynolds number. Among the above mentioned parameters, the influence of the latter appears to be one of the most significant ones attracting the interest of many investigators. Besides the significance of jets in basic fluid dynamics research, this interest is furthermore motivated by the utilization of jets at varying Reynolds numbers frequently in complex arrangements, such as multi-jet mixers and reactors, and wall-line jets.

The work of Wygnanski and Fielder [3] represented for many years a reference study for the quantitative description of the mean and turbulent velocity field of axisymmetric jets. Motivated by numerous earlier experiments (for an extensive discussion see the classic review of Chen and Rodi [4]), these authors conducted extended velocity measurements on a jet flow field ($Re \simeq 10^5$). They observed that self-similarity (or self-preserving state) is obtained in steps with the mean velocity becoming self-similar first and the axial, radial and turbulent stresses following. Consequently, they concluded that the self-similarity concept can characterize the flow field only when all the turbulent properties are similar in a dynamic frame of reference. The profiles presented in that study were subsequently reconsidered by Capp [5] and George [2], who identified a "momentum stealing" mechanism due to a recirculation zone developed between the jet and the confining side boundaries of the experimental setup. In order to avoid the "inconsistencies", Hussein et al. [6] conducted experiments in a

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Nomenclature

d	pipe diameter (m)
F_u	flatness of the axial velocity
F_v	flatness of the radial velocity
K	axial velocity decay constant
K_r	spreading rate constant
NF	ormalization factor
$r_{0.5}$	jet half-width (m)
S_u	skewness of the axial velocity
S_v	skewness of the radial velocity
U	axial, mean velocity (m/s)
U_c	axial, mean, centreline velocity (m/s)
U_e	axial, mean, centreline velocity at the exit (m/s)
u'	fluctuation of the axial velocity (m/s)
v'	fluctuation of the radial velocity (m/s)
$\langle uv \rangle$	Reynolds shear stress (m^2/s^2)
$\langle u^3 \rangle$, $\langle v^3 \rangle$, $\langle u^2 v \rangle$, $\langle uv^2 \rangle$	third order moments of the velocity (m^3/s^3)
x_0	virtual origin
x_{0r}	geometrical virtual origin

Greek symbols

δ_d	displacement thickness (m)
δ_m	momentum thickness (m)

much larger enclosure and introduced a simple "a posteriori" model to calculate the effect of confinement based on the axial velocity features and the cross-sectional area.

In their work Hussein et al. [6] evaluated three different measuring techniques and they suggested that Flying Hot Wires and Laser Doppler Anemometry were the most appropriate methods to assess with sufficient accuracy the turbulent velocity components. Panchapakesan and Lumley [7] recorded the self-similar profiles of a turbulent jet using *X*-wire probes and noticed that the turbulent terms were always lower compared to those of Hussein et al. [6]. They admitted that the flow reversal that is established in the outer part of the jet could influence the measurements in a different manner for each measuring technique but in the central part all the data should not differ substantially. The influence of the Reynolds number seemed to be a plausible source for the differences in the turbulent properties since the Reynolds number of their jet was one order of magnitude lower compared to that of Hussein et al. [6] (i.e. 10^4 instead of 10^5). They suggested that a more systematic work was required to distinguish the influence related to the experimental technique from those due to physical effects. Malmstrom et al. [8] presented axial velocity measurements in the development region of an axisymmetric jet for a wide range of Reynolds numbers that lie between those used by Hussein et al. [6] and Panchapakesan and Lumley [7]. They tried to distinguish the effects of the jet exit diameter and the initial velocity, concluding that some of the trends of the axial decay and the virtual origin could be correlated with the velocity itself rather than the Reynolds number. Weigrabber and Liepmann [9] focused on the structure of turbulent water jets at two Reynolds numbers (16,000 and 5000) and mainly in the transition to self-similarity zone using Particle Image Velocimetry. By comparing the radial distributions of second and third order velocity terms to those in the literature, they concluded that the turbulent properties are indeed lower for lower Reynolds numbers.

Recently, the development of novel and more robust techniques, such as Particle Image Tracking or Velocimetry and Laser Induced Fluorescence, provided the opportunity to study more precisely the flow field of axisymmetric jets using a wide variety of flow and geometry conditions. Velocity and passive scalars topology have been recorded in detail and profiles at several distances compared to previous findings illustrated the influence of different Reynolds numbers. Borg et al. [10] reported the flow and concentration fields in the near field of a liquid jet with Reynolds number 6000, while Cowen et al. [11] assessed the self preservation state for a slightly lower Reynolds number (4000). Webster et al. [12] showed that the radial distributions of the velocity moments reached similarity after 50 diameters. The magnitudes were always higher compared to earlier experiments including those of Wygnanski and Fielder [2] and Papanicolaou and List [13]) although the jet emanated with a lower Reynolds number (about 3000). Kwon and Seo [14], Xia and Lam [15] and Todde et al. [16] presented almost similar studies focused on the influence of reduced Reynolds number, in a range, where transitional or even laminar states were present in the flow. The results were compared to earlier investigations regarding the axial velocity decay, the half-width variation and also the magnitude of turbulent intensities close to the self-similarity state. They showed that the increase in Reynolds number has a clear tendency to foster the turbulent character, pushing the values the turbulent terms closer to those of typical jets, i.e. jets at high Reynolds numbers. Recently, Fellouah et al. [17] conducted Hot-Wire measurements in the near field development region of a circular jet at three Reynolds numbers (6,000, 10,000 and 30,000) and reported similar findings regarding the mean velocity, turbulent fluctuations and Reynolds stresses.

The present research has two main objectives. The first is to record the development of a relatively low Reynolds number, round pipe jet to supplement available literature, in which the comprehensive study of this particular flow, is until now missing. The second is to evaluate the self preservation features of the flow field and compare it to those reported on jets of higher Reynolds numbers based on a systematic and detailed approach. In the present work, the distributions of the mean axial velocity on the centreline and jet spreading are used to characterize the jet development regions. The radial distributions of the mean and turbulent components are presented for the near and the far field in comparison to earlier experimental data, in order to assess the influence of the initial profile and the Reynolds number. Triple velocity correlations and skewness and flatness factors are also presented while the development of the flow field based on the summary of the experimental findings is discussed.

2. Experimental apparatus

2.1. Experimental device and inflow conditions

The jet emanates vertically from a 4 mm diameter and 50 cm long pipe inside an open top cubical test section with 1 meter length, width and height, while its exit is positioned 10 cm above the lower surface of the rig (Fig. 1). A frequency inverter is used to adjust the speed of the variable speed blower and control airflow rate. Flow discharge was systematically checked before and after each measurement set at the different axial distances to ensure constant air supply. The Reynolds number at exit ($Re = U_b d/\nu$) is 5500, based on the bulk exit velocity calculated using the momentum integral ($U_b^2 \pi d^2/4 = \int_0^r U^2(r)dr$). Initial velocity distributions