International Journal of Heat and Fluid Flow 29 (2008) 1699–1715

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Effect of axisymmetric forcing on the structure of a swirling turbulent jet ☆

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ARTICLE INFO

Article history:
Received 5 November 2007
Received in revised form 30 June 2008
Accepted 27 July 2008
Available online 26 September 2008

Keywords:
Swirling jets
Turbulent jets
Control
External forcing
Stereo PIV
Conditional sampling

ABSTRACT

With the aid of the Stereo PIV technique, the local structure of swirling free turbulent jets is investigated under the following flow conditions: the Reynolds number was equal to 8900, and the swirl number varied from 0 to 1.0. The effect on the jet flow structure of external periodical forcing, applied with an axisymmetric mode to the inlet velocity, was studied. Also investigated were the flow response to the forcing at two Strouhal numbers, $St = 0.52$ and 1.2, and with various forcing amplitudes. Additional measurements with application of the conditional sampling approach were performed in order to analyze spatio-temporal dynamics of the large-scale ring-like vortices, generated in the forced jet at a low swirl rate. The greatest effect of the forcing on the swirling jet structure was observed in the case of the high swirl rate ($S = 1.0$), which was previously considered to be largely insensitive to external forcing. The forcing at $St = 1.2$ with relatively high amplitude resulted in an abrupt change in the turbulent structure of the flow: an increase of total turbulent kinetic energy and strong anisotropy of its components took place.

1. Introduction

The imposition of swirl on jet flows is often used in a number of industrial devices, burners, propulsion systems such as jet engines. In combustion facilities, one peculiarity of strongly swirling jets is the presence of reverse flow near the nozzle, which provides reliable stabilization of the flame. In chemical reactors and mixing chambers, faster spreading of the swirling jets relative to the non-swirling ones plays an important role and leads to greater entrainment of the surrounding media. A number of swirling flows is also observed in nature (tornados, water spouts, etc.) which have to be carefully studied in order to forecast and prevent catastrophes.

At the same time, the turbulent structure of jet flow depends strongly on the conditions of the swirl superimposition. Depending on the swirl rate and the manner in which the swirl is applied, substantially different flow regimes can be observed: vortex rings for non-swirling and weakly swirling jets; helical waves with different wavenumbers for strongly swirling jets (e.g., Alekseenko et al., 1999). Finally, a vortex breakdown (VB) appears for sufficiently high swirl rates. The VB is known to have different states (Alekseenko et al., 2007a): spiral, bubble, or conical, where the last two can be either symmetric or asymmetric (e.g., Billant et al., 1998). The bases of swirling flows are described in detail in the work of Gupta et al. (1984), and an introduction to the theory of helical vortices appearing in swirl flows can be found in Alekseenko et al. (2007c). Detailed studies of different types of swirling jet flows were done in a number of experimental, numerical and theoretical works, considering different inflow geometries (Ribeiro and Whitelaw, 1980; Mehta et al., 1991; Panda and McLaughlin, 1994; Shtern and Hussain, 1996; Billant et al., 1998; Sun et al., 2002; Gallaire and Chomaz, 2003, 2004; Loiseleux and Chomaz, 2003; Ruith et al., 2003; Gallaire et al., 2004; Cala et al., 2005; Liang and Maxworthy, 2005; Duwig and Fuchs, 2007; Mourtazin and Cohen, 2007; etc.). Most of these works are devoted to the analysis of azimuthal instabilities and to the study of VB dynamics in swirling jets at comparatively small Reynolds numbers (up to 1000). Concerning swirling jets at high Reynolds numbers, significantly fewer works reporting comprehensive data on turbulence characteristics can be found in the literature (e.g., Cala et al., 2005; Alekseenko et al., 2007a). It has been reported by many authors that Kelvin–Helmholtz instability in the jet shear layer leading to vortex ring formation dominates non-swirling and weakly swirling jets. For a high enough swirl rate (before VB), the strong helical waves are most pronounced in the jet mixing layer. Further increase of the swirl rate results in VB. Strong helical waves were usually observed in the outer mixing layer of the jet, and single and/or double helixes were determined in the VB region (e.g., Billant et al., 1998; Loiseleux et al., 1998; Ruith et al., 2003; Liang and Maxworthy, 2005). However, among these results there are substantially different flow regimes and VB states, which depend strongly on the inflow velocity profiles. The strong influence of buoyancy effects on the VB shape was also shown in the recent paper by Mourtazin and Cohen (2007).

☆ This paper was originally presented at the International Symposium on Turbulence and Shear Flow Phenomena held in Munich on August 26-29, 2007, and later expanded, revised, and submitted; See Volume 29 No 3, June 2008

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0142-727X/$ - see front matter © 2008 Elsevier Inc. All rights reserved.
doi:10.1016/j.ijheatfluidflow.2008.07.005

Nomenclature

Re	Reynolds number
St	Strouhal number
TKE	turbulent kinetic energy
G_θ	axial flux of angular momentum (kg m^2/s^2)
G_z	axial flux of axial momentum (kg m/s^2)
S	swirl rate based on geometry of swirler
Sw	swirl rate based on inflow velocity
U_0	mean flow rate velocity (m/s)
V, W, U	radial, azimuthal, and axial components of mean velocity (m/s)
a	amplitude of forcing (%)
d	nozzle exit diameter (m)
d_0	diameter of nozzle plenum chamber (m)
d_1	centerbody diameter (m)
d_2	external diameter of swirler (m)
r, θ, z	radial, azimuthal, and axial directions in a cylindrical coordinate system
φ	blade angle (rad)
ϕ	phase shift between signals of forcing and data acquisition (rad)
u'_0	average intensity of axial velocity fluctuations at nozzle exit (m/s)
v, w, u	radial, azimuthal, and axial components of fluctuating velocity (m/s)
v', w', u'	intensities of radial, azimuthal, and axial velocity fluctuations (m/s)
ω_θ	azimuthal component of vorticity fluctuations (1/s)
$\langle\,\rangle$	ensemble averaging operator
$\langle\,\rangle_\phi$	phase-averaging operator
*	indicates instantaneous quantity

For a non-swirling round jet, as for a plane shear layer, it is well known that the formation and downstream evolution of vortices can be controlled by the flow excitation (Crow and Champagne, 1971; Zaman and Hussain, 1981; Broze and Hussain, 1996). It was found that forcing at the prevailing ("natural") frequency gives the strongest increase of the ring-like formation, and thus the greatest turbulent mixing rate in the initial region of the jet. Generally, for the jet "column" the prevailing frequency ranges from $St = 0.3$ to 0.6 (Crow and Champagne, 1971; Hussain and Zaman, 1981; Alekseenko et al., 1997; Drobniak et al., 1998; Vejrazka et al., 2005). The influence of the excitation frequency and amplitude on the behavior of vortex structures was well documented in Broze and Hussain (1996). This excitation promotes the growth of various instability modes (not only fundamental) and provides flow regimes, which are not observed in an unexcited jet. The variety of flow regimes appearing for an excited jet can be explained by the pressured feedback mechanism from the downstream flow events (see Broze and Hussain, 1996). The effect of forcing the free swirling jets at various azimuthal modes was investigated in works by Panda and McLaughlin (1994) and Gallaire et al. (2004). For flow conditions preceding VB, these studies showed that axisymmetric or azimuthal forcing intensifies the development of corresponding instabilities and leads to domination of axisymmetric or helical vortices in the outer mixing layer. For swirling jets with high swirl rates, Gallaire et al. (2004) have shown that VB appears to be insensitive to forcing attempts, at least for the studied parameters. In the work of Khalil et al. (2006), describing the study of the swirling jet at $Re = 600$ with conical VB, the application of high-level forcing at the natural frequency was found to intensify ring-like vortices in the outer mixing layer that resulted in a downstream shift of the VB position. However, the structure of VB almost was not affected. Generally, on the basis of previous works, it can be concluded that combined application of swirl and external forcing can be used as an efficient tool for mixing enhancement in a number of devices utilizing confined jet configurations (chemical reactors, burners, mixing chambers, etc.).

Particle Image Velocimetry (PIV) provides the spatial distributions of instantaneous flow velocity and, consequently, a direct measurement of the spatial velocity derivatives, including vorticity. Besides, PIV can support the storage and processing of extremely large amounts of data that are necessary for reliable calculation of statistical characteristics. This provides a convenient tool for measurement in a turbulent swirling jet with a complex structure. At the same time, for accurate estimation of the abovementioned quantities, it is necessary to carry out a number of complex pre- and post-processing PIV algorithms. Presently, an iterative cross-correlation approach with image deformation is acknowledged as the most suitable in terms of accuracy and processing time. In Stereo PIV measurements the calibration-based methods with an angular stereoscopic experiment configuration are the most frequently used. Also, an iterative correction procedure can be applied to minimize the error from inaccurate alignment of the laser sheet and calibration target planes. Additional attention should be paid to the PIV data post-processing algorithms before calculation of flow characteristics. As an example, Heinz et al. (2004) have demonstrated that the presence of false vectors in raw data significantly affects the accuracy of calculations of high-order statistical moments. Thus, the stages of raw velocity field validation, false vectors removal (e.g., Westerweel, 1994) and "empty holes" interpolation are needed before stereo reconstruction or further steps of post-processing. As was shown by several authors (Raffel et al., 2007; Foucaut and Stanislas, 2002), the correct calculation of instantaneous velocity gradients requires application of a proper derivative filter in order to minimize both the truncation error linked with the finite form of the filter and the noise error.

The objective of the present work is an experimental study of swirling free turbulent jet flow under the imposition of external axisymmetric velocity fluctuations. The measurements focus on the spatial distributions of the mean flow velocity and turbulent kinetic energy components in the central cross-section of the jet. The Reynolds number of the flow was equal to 8900. Three typical jet configurations were considered: non-swirling jet flow and swirling jet flow with and without pronounced VB. The central point of the present paper is to obtain comprehensive experimental data on the forced turbulent swirling jet by applying an advanced non-intrusive whole-field measurement technique (stereo PIV).

2. Experimental setup, apparatus and data processing

The experimental setup represented a hydrodynamic loop equipped with a rectangular working section (Fig. 1a) made of Plexiglas in order to provide PIV measurements, a pump, a flowmeter and a temperature stabilizing device. Water flow was driven by the pump, the rotation speed of which was precisely controlled by an inverter. A thermostat was used to maintain a constant water temperature of 26 °C with an accuracy of ±0.2 °C. The Reynolds number, defined on the basis of the mean flow rate velocity $U_0 = 0.52$ m/s and nozzle diameter $d = 15$ mm, was equal to 8900. For organization of non-swirling jet flow with a top-hat exit velocity profile, a Vitoshinsky contraction nozzle (see equation below), shown in Fig. 1b, was used (Dyban and Mazur, 1982).