AN EXPERIMENTAL INVESTIGATION ON ISOTHERMAL FREE SWIRLING JET

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Abstract

This paper reports an experimental investigation on the dynamics of turbulent unconfined swirling flows. Isothermal free swirling jets with five different swirl numbers (S) and fixed Reynolds number (Re = 21800) are investigated to analyze the effect of swirl intensity on the recirculation, vortex breakdown and the occurrence of the precession vortex core (PVC) by means of 3C-2D Stereoscopic Particle image velocimetry (PIV). The contours and radial profiles of mean axial velocity confirmed the central recirculation zone (CRZ) for high swirl number. The importance of central recirculation zone is to ensure a good mixing of air/ fuel and combustion products and to generate a low velocity region for flame stabilization. Results shows that swirl intensity increases the backflow rate in the recirculation zone and jet spreads almost linearly with a higher spread rate as compared to non swirling flow. The frequency characteristics have been measured with a capacitive microphone. The frequency spectrum indicates the presence of periodic oscillation related to the existence of PVC. The Strouhal number associated with the frequency of the PVC vary almost linearly with swirl intensity.

Introduction

Swirling flows are commonly find in most practical applications, such as gas turbines combustors, swirl burner, furnaces, spraying machines, whirlpools, cyclone seprators, and vortex shedding from aircraft wings [1]. The swirl intensity for rotating flows is usally characterized by the non-dimensional swirl number, $S = G_\theta / G_z R$, which represents the ratio of the axial flux of angular momentum, G_θ to the axial flux of axial momentum, G_z times a nozzle radius R [1,6]. $G_\theta = \int_0^{R_j} \rho(uw)\, r^2 2\pi dr$ and $G_z = \int_0^{R_j} \rho(u^2 - 0.5w^2)\, r 2\pi dr$ are computed by an integral of the measured mean velocity profiles, where u, w and ρ are the mean axial velocity, mean tangential velocity, and air density respectively and R_j = radius of the jet. Swirl jets can be classified as high or low swirling flow if the swirl number S is respectively higher or lower than the critical value, S_{cr}, for the onset of vortex breakdown, VB (S_{cr}~0,6 according to [1]). Apart from VB it is well known that another instability, called PVC (precessing vortex core) which is periodic in nature occurs in swirl flows [2]. Flow recirculation associated to vortex breakdown and the precessing vortex core, observed in highly swirling flows can significantly affect the combustion processes [1,3]. Several groups have established various forms of precession motion and instability mode in swirling flow field [3,4] and jet precession is also know to occur even in low swirling jets [3, 4, 5]. Despite many experimental and numerical works, Vortex Breakdown and PVC phenomena are still not fully understood and further investigation are required [3,5]. The present study focusses on the experimental investigation of the flow structure of a swirling flows by means of a Stereo-PIV system and on the onset and frequency of the PVC.

Experimental setup

A vertically mounted swirl burner was used to generate isothermal free swirling air jets. The swirl burner consists of central pipe surrounded by an annulus supplying swirling air and characterized by a converging nozzle whose exit section has a diameter D=36 mm. The Reynolds number, $Re = \rho U_{mean} D/\mu$, is based on nozzle diameter, D, the bulk mean velocity, U_{mean}, and the dynamic air viscosity, μ. The swirl generator is of axial-plus-tangential entry type, it allows changing swirl intensity by varying the axial and tangential flow rates of air by means of thermal mass flow meters with 1% accuracy. The axial air enters through four radial inlets in the cylindrical chamber and passes through a plate with 24 numbers of holes of 2 mm in diameter to produce a uniform axial stream. The tangential air is introduced through eight tangential inlets to impart angular momentum, upstream from the burner throat. More information of the experimental set up can be found in [7].

Flow visualization method

3C-2D Stereoscopic PIV was employed to characterize the flow field patterns under isothermal conditions. The velocity field of the swirling jet was measured at the nozzle exit in a vertical plane. A double pulse Nd:YAG laser (energy ≈ 200 mJ/pulse; λ = 532 nm) unit enabled to measure velocity vectors in the axial-radial direction. Here, a laser sheet (approximate thickness of about 1mm) fired vertically close to the exhaust of the burner illuminated fine particles of oil droplets. Two CCD cameras of 1344 * 1024 pixels equipped with a Nikon 60 mm focal length were mounted according to the Scheimpflug rules, they view the laser sheet from opposite side at about the same angle of 45°, both the cameras were oriented in the particle's forward scattering direction. Measurements were conducted in double frame mode with time between pulses of the order of 10-30 μs, depending on the swirl intensity and Double images were acquired at a rate of 5 Hz. The jet flow was seeded with oil droplets with average diameter of 1-2 μm produced by a jet atomizer. The external seeding particles are homogeneously distributed throughout the measurement plane and generated by a six-jet Atomizer. Dantec's DynamicStudio 4.15 software is used to acquire and to process the images. The raw images were subjected to an image balancing filter with a smooth cell size of 5 x 5 to correct the non-uniformities of laser light sheet prior to cross-correlation. An adaptive cross correlation algorithm, including peak validation and 50% overlap area is implemented. The final size of the interrogation area is 32x32 pixels. Finally the third velocity component is reconstructed from the two 2D vectors fields by using the method proposed by Soloff

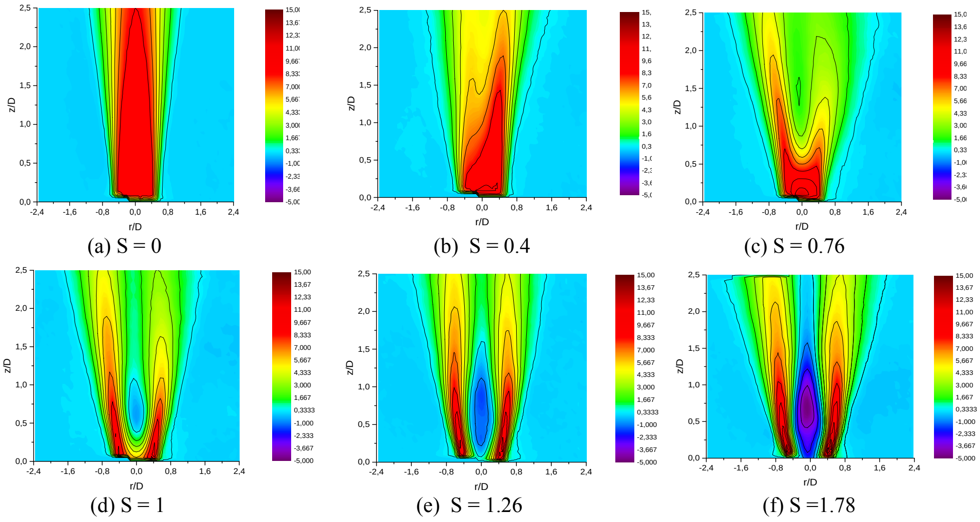
[8] and implemented in the Dantec software. Average flow map were obtained by averaging 700 instantaneous vector fields.

Results and discussion

This section discusses the experimental results focussing on characteristics of the swirling flow fields such as recirculation, vortex breakdown, and occurrence of the PVC structure for various flow conditions. First the occurrence of recirculation, vortex breakdown and its relationship with swirl intensity will be discussed. Second the frequency of pressure oscillation associated to the PVC and its onset at a swirl numbers above a critical value (S =1) will be presented.

Recirculation and vortex breakdown

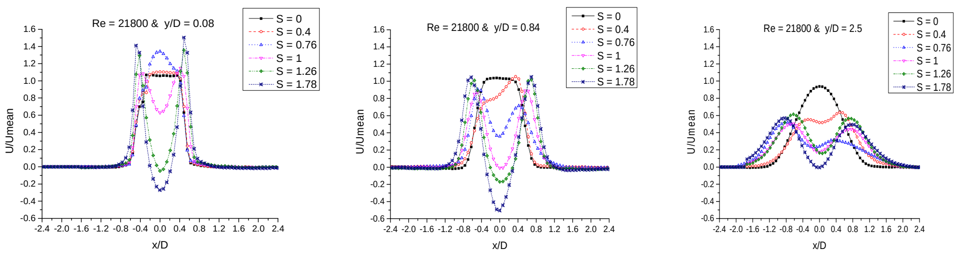
Fig. 1 shows the contour plots of mean axial velocity in a longitudinal plane for S = 0, 0.4, 0.76, 1, 1.26, 1.78 and Reynold's number = 21800. The axial velocities in figure are normalized with respect to the mean axial velocity (U_{mean}), while the radial, r, and axial, y, coordinate are normalized by the nozzle diameter D. The effect of swirl intensity on the spreading rate of the jet is quite significant. The non swirling flow, S= 0, has narrow jet with no reverse velocity throughout the flow, Fig. 1(a), and close to nozzle, y/D=0.08, the radial profile of the axial velocity shows a top-hat shape, Fig. 1(a). Moving downstream and after about y/D = 0.84 the profile evolves to a gaussian shape, Fig. 2(c), nevertheless the potential core of the jet is visible upto the highest axial coordinate. Jet spreading is described by the jet half radius (R_{jet}) which is the point in the radial direction where the mean axial velocity is half of the maximum axial velocity and the slope of the curve $R_{jet}(y)$ is the spreading rate. At S=0 the jet half radius stay almost constant showing a very sligthly increase by moving downstream as shown in Fig. 3(a), while the swirling jets expand with a spreading rate of about 0.28 and 0.31 for S=1 and S=1.78 respectively. By increasing S to 0.4, Fig. 2(b), the jet looses its axysimmetric structure and the potential core of the jet shortnes. The analysis of the instantaneous velocity maps, not shown here, revealed that jet asymmetry arise due the random occurrence of localised asymmetric reverse axial flow. By increasing S to 0.76 the potential core is almost disappeard and the jet shows a more axysimmetric shape. Compared to the lower swirl cases, the axial velocity profile at y/D=0.08 clearly shows a higher velocity on the axis, Fig. 2(a), this is likely due to the low pressure axial region generated by the higher swirl intensity. Downstream the mean axial velocity distribution shows a wake-like profile, Fig. 2(b&c), (transition between jet-like profile to wake-like profile) but no reverse flow can be observed, Fig. 1(c). For swirl number, S = 1, 1.26 and 1.78, the mean centerline axial velocity become negative, Fig. 1(d,e,f) and Fig. 3(b), evidencing the occurrence of the vortex breakdown. The mean reverse axial velocity increases with S, for the cases with swirl numbers 1, 1.26 and 1.78, the minimum axial velocities of about -0.56 m/s, -1.47 m/s and -4.87 m/s occur at approximately y/D = 0.608, y/D = 0.88 and y/D =0.715 respectively. The reverse velocity keep decreasing after y/D = 0.608 & 0.88 for S = 1 and S = 1.26 and reach to positive values towards downstream but for S = 1.78, the axial velocity stay negative within the range of 0.07-2.53. Increasing the swirl intensity from 1 to 1.78 increases the axial extent of the vortex bubble and the jet became wider and more symmetrical. The spatial structure of the mean axial velocity fields reported in Fig. 2 showed the expected symmetries, and it is in qualitative agreement with previous finding [9,10].



(a) S = 0 (b) S = 0.4 (c) S = 0.76

(d) S = 1 (e) S = 1.26 (f) S =1.78

Figure 1. Contour plots of mean axial velocity in a longitudinal plane for (a) S= 0, (b) S=0.4, (c) S=0.76, (d) S=1, (e) S=1.26, (f) S=1.78 for Re = 21800



(a) y/D = 0.08 (b) y/D = 0.84 (c) y/D = 2.5

Figure 2. Radial profiles of mean axial velocity in vertical plane, (a)y/D=0.08, (b)y/D=0.84, (c)y/D=2.5 for S=0,0.4,0.76,1,1.26,1.78 and Re = 21800

Precessing vortex core (PVC)

A microphone probe, installed at the jet boundary is used to detect the pressure oscillations associated to the PVC. A spectral analysis according to the Bartlett method [11] and with a frequency resolution of 1 Hz was applied to the pressure signal to identify the PVC frequency. The discrete peaks in the pressure spectra become clearly identifiable at S=1.13 and this value is assumed as the critical one for the onset of the periodic oscillation. The pulsation amplitude is observed to change rapidly by two orders of magnitude through this critical point. It is known that, at constant *Re*, the swirl intensity leads to a gradual increase in the PVC frequency [12] and the same behaviour was observed in our work. The frequency of the PVC can be characterised by a Strouhal number, *Sr*, defined as $Sr = fD/U_{mean}$ where *f* is the frequency of the PVC, *D* is nozzle diameter and U_{mean} is the average bulk axial velocity. Our results exhibits an almost linear evolution of *Sr* vs. S as shown in Fig. 4(a) and *Sr* resulted to be independent of the viscosity for Reynolds number above 20000, Fig. 4(b). Similar results are reported in the works of Syred [3] and Cassidy and Falvey [12].

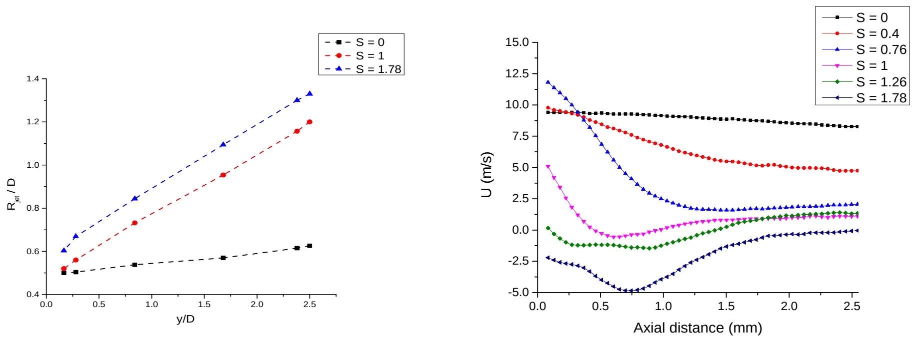
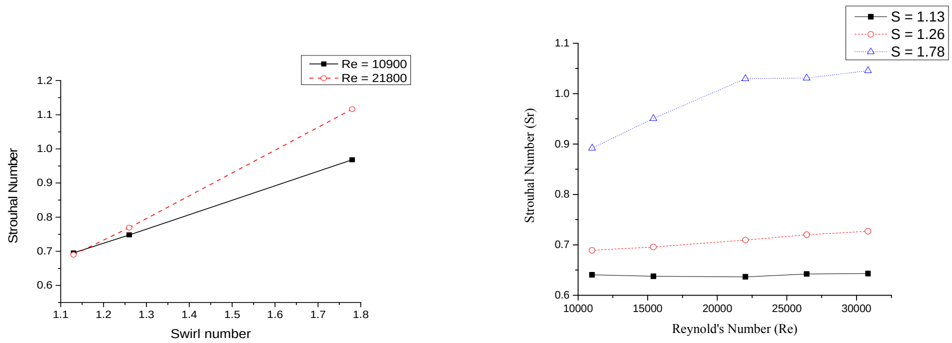


Figure 3. (a) Jet radius, $R_{jet,}$ for S=0, 1, 1.78 (b) Mean centerline axial velocity



(a) (b)

Figure 4. (a) Sr vs. S. **(b)** Sr vs. Re. For both figures, S = 1.13, 1.26, 1.78

Conclusions

A vertically mounted swirl burner, has been experimentally investigated for non-reacting cases with different swirling intensity to characterize the flow structure using stereo PIV. This study was investigated to determine the influence of swirl intensity on central recirculation zone, vortex breakdown, precessing vortex core, precession frequencies and Strouhal number. Increasing the swirl number under fixed Reynolds number conditions leads to a greater spread rate of the flowfield in the downstream regions and also increases the axial extent of the vortex bubble. It was also found that the Strouhal number varies almost linearly with swirl number and become constant for large Reynolds number.

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