CHARACTERIZATION OF THE PHENOMENON OF VORTEX PRECESSION (PVC) IN A LEAN PREMIXED COMBUSTION CHAMBER.

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Abstract. *Gas turbines have many applications and are available in a wide range of sizes. They are used for power generation, exploration, production and transportation of oil and gas as well as marine propulsion systems and aircraft. Therefore, they have become a dominant technology in the production of energy worldwide. Environmental awareness and the need for power generation systems more efficient accelerated their development in recent decades. Efforts were focused on reducing levels of pollutants by improving efficiency and increasing reliability of equipment. Particularly, NOx continues to be a major pollutant to be controlled. In any attempt to reduce NOx, the main objective should be reduce the temperature of reaction because the mechanism of formation of thermal NO is the largest emitter. On this regard, the technological approach of Lean Premixed Combustion (LPM) is based on the supply of a homogeneous mixture of fuel and air to the combustion zone,which then operates at an equivalence ratio close to flame blowoff. These conditions allow low temperature flame front, avoiding the formation of NO through the regions due to increased temperature. At the same time, the vast majority of gas turbine systems employ swirl injectors that produce central toroidal recirculation zones (ZRCs) to provide the dominant flame stabilization mechanism. The flow structures of a typical gas turbine swirl injector are vortex breakdown-induced center recirculation zone downstream of the injector, precessing vortex (PVC) layer surrounding the center recirculation zone, and shear layers originating from the outer edge of the inlet annulus. Previous work identified the PVC in the laboratory model studied in this article through a variety of measurement techniques, including laser Doppler velocimetry (LDV). This article aims at characterizing the turbulent three-dimensional structures that lead to instabilities, in a laboratory model of a LPM combustion chamber through the planar velocimetry imaging technique (PIV) and dynamic pressure measurement. PIV technique has the characteristics that, in addition to obtain the values of velocities in the flow field at the same time, it depicts the flow structure, identifying the phenomena that lead to instabilities. The results showed a well-defined ZRC, induced by vortex breakdown and shear layer, mainly located around it. Vortical coherent structures were found in their mean fields and coinciding with the limits of ZRC, indicating the presence of PVC. Compared to the mean flow, which showed only a pair of vortices in its structure with the snapshot, we noted that the average velocity field is only part of the global trends of the flow, whereas fluctuations in the instantaneous field lead the flow fields in real time and has a great impact on combustion performance. Through dynamic pressure measurements, this study aims to identify frequencies related to the combustor instabilities. Acoustic pressure measurements were made using a ½-inch condenser microphone inside of a pressure probe. Spectral results were obtained at different positions and configurations of the combustor, which shows the dominant frequency of the system. Based on previous studies we identified dominant instability's frequency that represents PVC phenomenon.*

Keywords*: precessing vortex core, lean premixed combustion, PIV, acoustic probe*

1. INTRODUCTION

Swirling flows are found in atmosphere and in many manmade devices. Some of the devices in which the swirling phenomenon has a strong influence include centrifugal pumps, combustion chambers, gas turbines and cyclones. Most gas turbine injectors employ swirl configuration to improve and control the mixing process between fuel and oxidant and stabilize the combustion through a central recirculation zone.

The gas turbine manufacturers are currently facing two major challenges: to reduce emissions and improve efficiency. Lean premixed combustion has become an important technology option for reducing emissions for gas turbine power systems. With lean premixed combustion, the flame temperature is reduced by use of excess air. In turn, the low temperature reduces the NOx formation rate. However, these flames are inherently unstable; they exhibit not only turbulent motions but also large-scale coherent structure dynamics. This unstable motion could trigger not only noise, but also combustion oscillations and structural damage. For swirl numbers greater than 0,5 a central recirculation zone is generated due to vortex breakdown. In some cases appears a three-dimensional unsteady asymmetric flow structure called Precessing Vortex Core (PVC). The PVC develops when a central vortex core starts to precess around the axis of symmetry at a well-defined frequency. This phenomenon is usually linked to vortex breakdown and the associated recirculation zone in a high Reynolds number flow. (Huang and Yang, 2009). The PVC strongly affects the flow and flame evolution in combustion systems. The displacement of the vortex core squeezes the flowfield at one side against the chamber wall, and causes a considerable increase in the tangential velocity in the squeezed flow region due to the conservation of angular momentum. The presence of a PVC also helps explain the occurrence of instantaneous negative azimuthal velocity in the region near the centerline of the chamber. The PVC may improve combustion efficiency through its enhancement of turbulence intensity and mixing, but it also represents a largely undesired characteristic because of the possible resonant coupling with low-frequency acoustic oscillation in gas turbine combustors

Detailed measurements in natural scale combustors are hardly possible and very expensive and numerical tools have not achieved a sufficient level of results accuracy to fully understand of mechanisms that generate the precessing vortex core (PVC). One promising strategy is, therefore, establish of model laboratory combustor with practical relevance and detailed measurements, using non-intrusive techniques with high accuracy. The data obtained will be used for validation and optimization of numerical simulation codes, which can then be applied to simulate the behavior of real combustors. Measurements using intrusive techniques are less suitable for these applications because they disturb the local flow field and change the conditions for stabilization and for the reaction in the flame, both local and general, as mentioned in the review work of Lucca-Negro and O'Doherty (2001). Several researchers studied they observed a fast-moving, upstream of vortex breakdown, if one probe is inserted into the stream. In turbulent flows with combustion, the use of optical techniques of measurement is essential for reliable information. Laser-based tools (LDA measurements, PIV and Rayleigh scattering) are the preferred methods which offer the potential to measure most of the relevant parameters in the flow with high temporal and spatial resolution.

The present work aims to identify and characterize the turbulent three-dimensional structures (PVC) that lead to instabilities in swirling flows in LPM combustion model and its influence on flow stability, using planar velocimetry measurements (PIV) and acoustic probe. PIV technique has the advantage that, in addition to obtain the values of velocities in entire flow field, is possible to see the structure within this field, identifying the phenomena that lead to instabilities.

2. EXPERIMENTAL SETUP

The experimental facility was built by Anacleto et al (2003), Fernandes et al (2005a and b) and Shtork et al (2007) at IST, Technical University of Lisbon. A schematic of the gas turbine model combustor is shown in Fig. 1. Flow passes through vaned type swirl, with an outer diameter of 120 mm, and then is converged to a long premixing section (160mm length, 50 mm diameter) before passing through a sudden expansion with a 40 mm contraction to the final combustion chamber of 110 mm diameter. Both the pre-mixing chamber as the combustion chamber, have optical access to allow the use of PIV. The PVC was characterized under isothermal conditions just past the 40 mm contraction without the final combustion chamber.

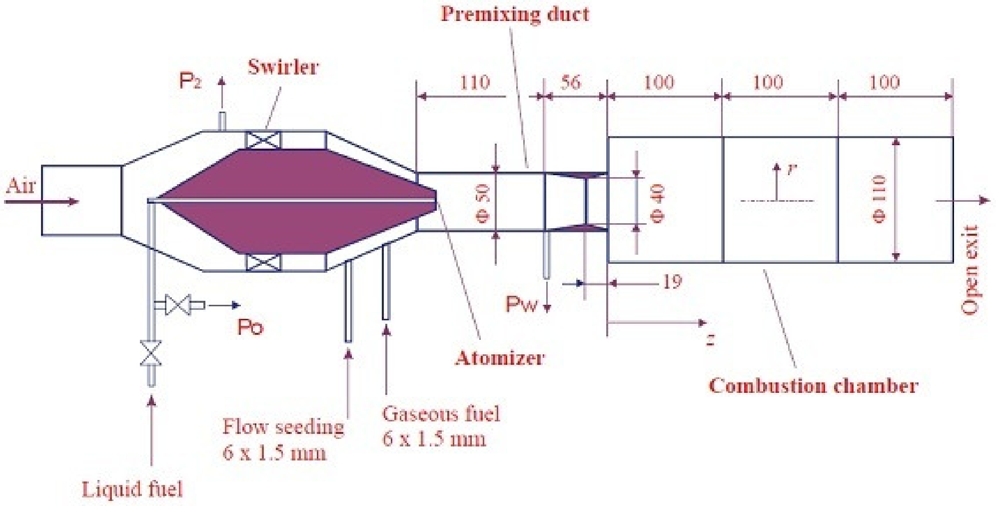


Figure 1. Details of experimental set-up (Anacleto et al, 2003)

The swirl generator has a variable geometry, which allows shifting the angle of the vanes between 0º and 60º, in order to control the swirl level of the flow. The swirl number was defined through the swirler geometry according to Eq. 1.

$$S = \frac{2}{3}\left[\frac{1-\left(\frac{D_1}{D_2}\right)^3}{1-\left(\frac{D_1}{D_2}\right)^2}\right]\tan\varphi \tag{1}$$

where D_1=90mm and D_2=120mm are the diameters of the central hub supporting blades and the outer chamber of the swirling device, respectively, and φ is the blade angle.

The velocity field in the combustor was measured using Particle Image Velocimetry (2D-PIV) as explained by Raffel et. al. (1998). The system consists of a dual head Nd:YAG laser, a high resolution CCD camera and a centralized timing generator. Each laser head delivered a 120 mJ/pulse beam at a wavelength of 532 nm. The CCD camera captured the images of the illuminated particles at a resolution of 1360x1024 pixels, coinciding with the exhaust convergent-divergent nozzle, with an approximate area of 70 mm lenght and 54 mm wide, corresponding to the location of the primary combustion zone without confinement (Fig. 2). The images were processed using the PROVISION software package, provided by IDT Inc. This software uses an adaptive algorithm to obtain the velocity field (Lourenço e Krothapalli, 2000). The Reynolds numbers, based on the mean axial velocity at the inlet section of the combustor and the respective diameter (40mm), are of the order of 10^5.

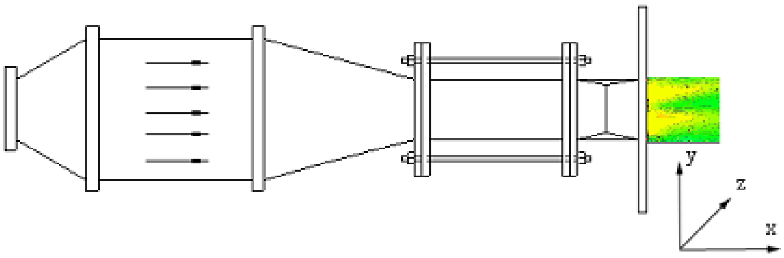


Figure 2. PIV measurement window.

The PVC frequency was obtained by fast Fourier-transform analysis of an instantaneous pressure signal acquired with acoustic probe system (Fernandes et al., 2005a, Fernandes et al. 2005b, Shtork et al. 2006 and Shtork et al. 2007) based on a B&K-4189 L condenser microphone placed in different positions along the axis of the combustor. The microphone signal was recorded at a rate of 20kHz by a a NI PCI-4474 board installed in a PC with 24 bit resolution, sampling of 102.4 kS/s. Also was studied the influence of confinement in a combustor exhaust using a cone with a smaller diameter of 50 mm, located in the axis of the combustor, as illustrated in Figure 3.

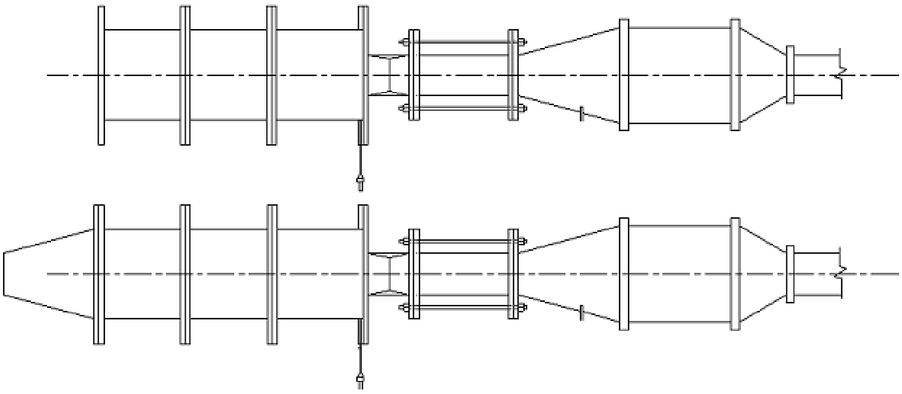
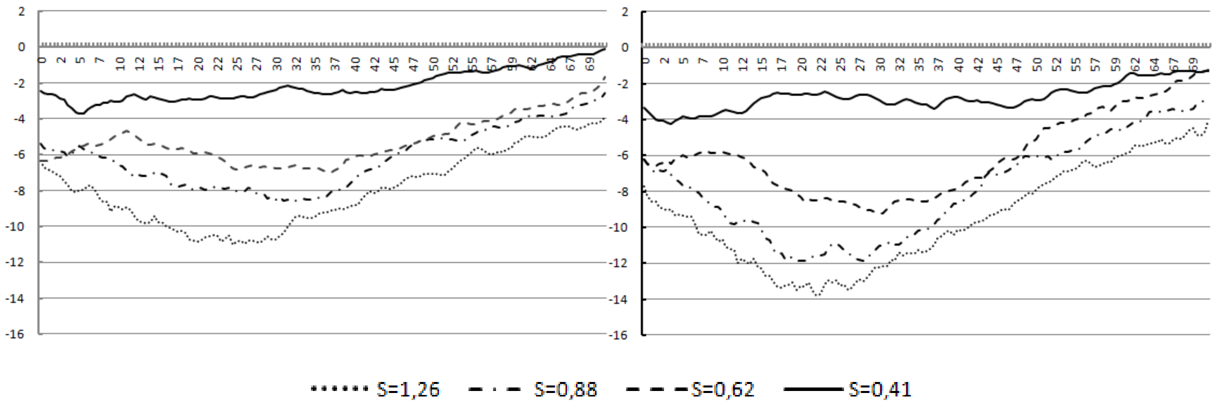


Figure 3. Geometry of the combustion chamber without and with the exhaust cone

3. RESULTS AND DISCUSSION

3.1. Mean Velocity Field Data in Streamwise Plane

Figure 4 show the centerline normalized axial velocities for all swirl number and Re= 60000 and 70000. A central recirculation zone (CRZ) is present due to the fact that the axial adverse pressure gradient exceeds the forward kinetic forces, and the flow reverses its direction in the central region of the field. Figure 3 indicates that the length and strength of CRZ increase as the swirl number increases. For swirler S<0,62, very small CRZ is present, moves down and up and is not stable. Note that the values of the axial velocities are negative near the centerline at downstream of the exhaust sudden expansion. This indicates that the reverse flow in the central recirculation zone gets inside the nozzle, and hence the flow comes out as a hollow jet with high velocities near the duct wall. The peak value of negative axial velocities moves upstream as the swirl degree increases.



a) Re = 60000 b) Re = 70000

Figure 4. Axial velocity profile (vertical axis) on the combustor axis (horizontal axis) for (a) Re = 60000 and (b) Re = 70000.

Mean axial velocity map are presented in Fig. 5 for Re = 60000 and 70000 and S = 0,62, 0,88, 1,26 in the streamwise plane.

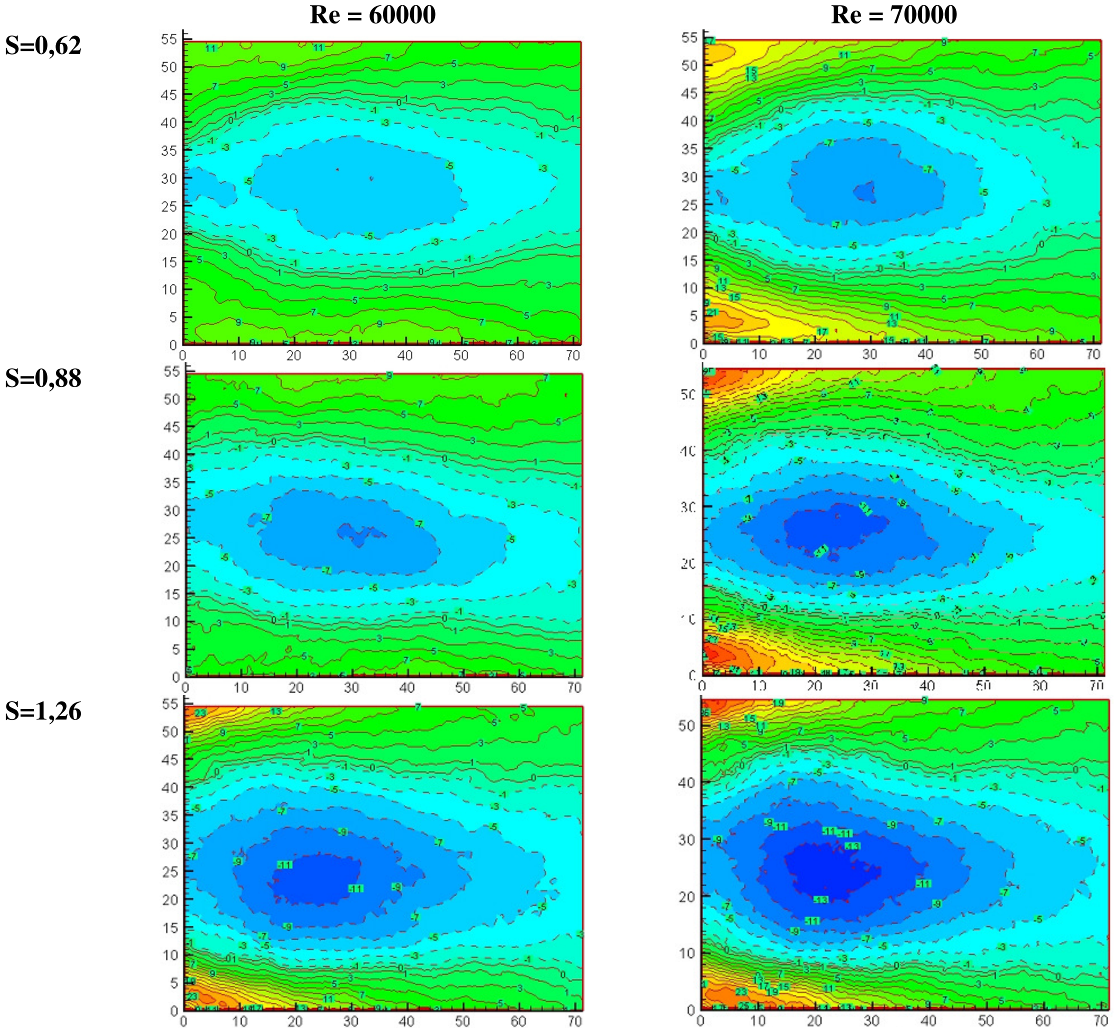


Figure 5. Mean axial velocity map

In all cases, the width of the recirculation zone increases and the peak value moves away from the centerline toward the duct walls as the swirl degree increases. Note that, for the same flow rate, as it increases the swirl number decreases the distance between the combustion chamber entry and the region of maximum axial velocity in the reverse flow as found by Wang et al (2004). Figure 5 shows that the ZRC gets stronger as it increases the flow and/or the number of swirl, since larger angles and flow rates to the value of negative axial velocity increases. As seen in Fig. 4, the peak value of negative axial velocities moves upstream as the swirl degree increases

Urms values (Fig. 6) increase with increasing flow rate and angle, being more evident with increasing flow, also observed by Martinelli et al (2007). The highest value of axial turbulence lies approximately between the limits of ZRC and the outline of the region of high velocity has a cone shape and decreases on the "x" axis. This behavior was found by Anacleto et al (2003) and Shtork et al (2007), attributing this result to the presence of PVC.

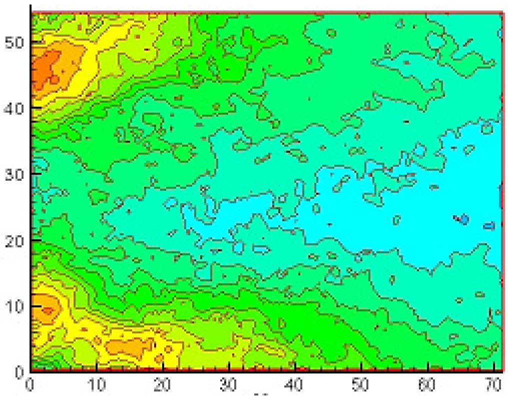


Figure 6. Urms field at exhaust convergent-divergent nozzle for Re=70000 and S=1,26.

3.2. Instantaneous Velocity Field Data in Streamwise Plane

Figure 7 represents the axial-radial velocity vectors for instant random time for a flow with Re = 50000 and S = 0,62. Large vortical structures along the shear layer are clearly shown in this instantaneous image, in red circles. These large vortices are most likely to be PVC and its associated eddies as was identified by Fick et al. (1997). Fick et al. (1997) stated that PVC was represented by the point of zero velocity in the tangential flow. PVC is a helical structure that develops when the central core of the vortex precess around the axis of symmetry of a well-defined frequency, distorting the entire flow, including the ZRC, which rotates and moves radially with respect to the central axis. The center of the coherent structures coincides with the limits of ZRC similar to that reported by Fick et al (1997).

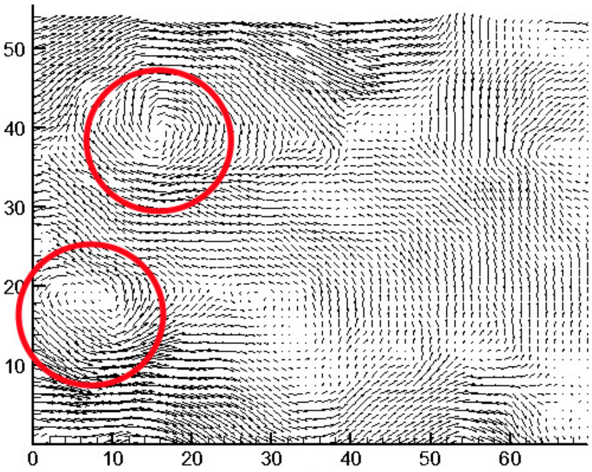


Figure 7. Axial-radial velocity vectors for a instant random time for Re = 50000 and S = 0,62.

Figure 8 shows the instantaneous axial velocity fields with the boundary of the recirculation zone in red, at random times, with a ZRC that changes in size, shape, position and strength, influenced primarily by the phenomenon PVC, as explained by Froud et al (1995) , Syred et al (2004). It changes dramatically in size and position, making the flow very unstable and hence the combustion as well. As the angle and flow rate increases ZRC gets stronger, the variation in size and shape is less pronounced even more persistent, maintaining its characteristic to precess around the axis, typical flow with PVC, but with higher values of negative velocities, which ensures greater stability.

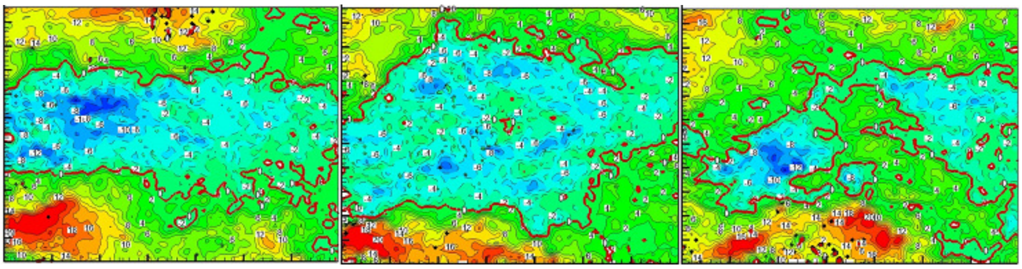


Figure 8. Instantaneous axial velocity fields for a instant random time for Re = 50000 and S = 0,62.

3.3. Spectral data of LPM model.

The PSD results are presented in Fig. 9 for two radial position in the premixing chamber for Re = 70000 and S = 0,88, on the axis (in red) and wall (black), perpendicular to the axial velocity. The spectra show a single high-energy peak at a frequency of 458Hz, corresponding to the PVC. Since the energy in the center of the flow is greater. For Re = 60000 and 64000 the behavior is analogous. The frequency increases slightly with increasing Re, but the Strouhal number remains almost constant with a weak function of Re, as observed by Syred (2006).

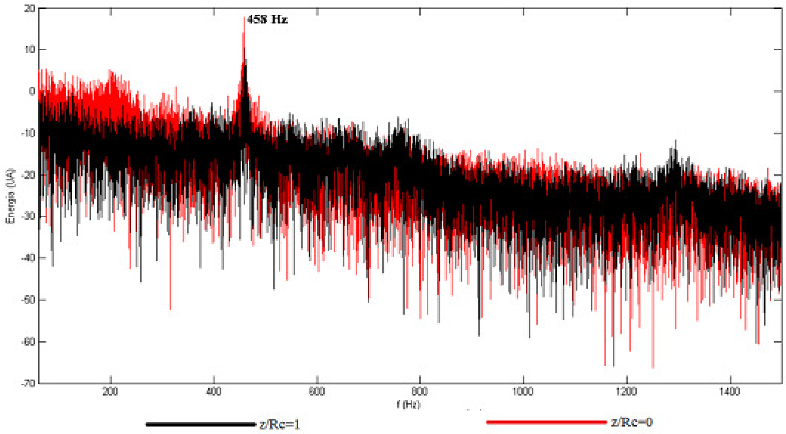


Figure 9. PSDs for Re = 70000 and S = 0,88 measures in premixing chamber, on the wall (z/Rc = 1) and on the axis (z/Rc = 0).

Figure 10 shows the PSD for the same conditions of Fig. 9, for the combustor with and without exhaust cone measured in wall premixing chamber. As has been previously characterized, high-energy peak corresponds to the PVC frequency. Note that, for the combustor with exhaust obstruction, the energy of PVC is higher, while the frequency that characterizes it is smaller, as already reported by Syred (2006), although in general both have the same energy-level for almost any frequency band. Valera-Medina et al (2009) found that for a contraction cone-shaped, PVC has a lower frequency of rotation while it increases in size, both length and width.

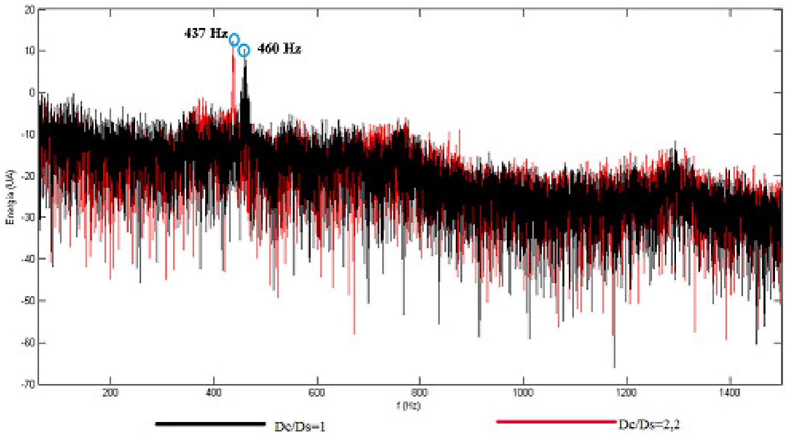


Figure 10. PSDs for Re = 70000 and S = 0,88 measures in wall premixing chamber for combustor with (red) and without (black) exhaust cone.

In the combustion chamber itself, the embedded energy in the frequency that characterizes the PVC decreases, but can still found that characterizes the peak. For a distance of x/D = 1,8 is found only a single low-amplitude peak that represents the PVC, measured on the wall of the combustor while it is not possible to identify the PVC on the centerline of the combustor for the same distance (Fig. 11).

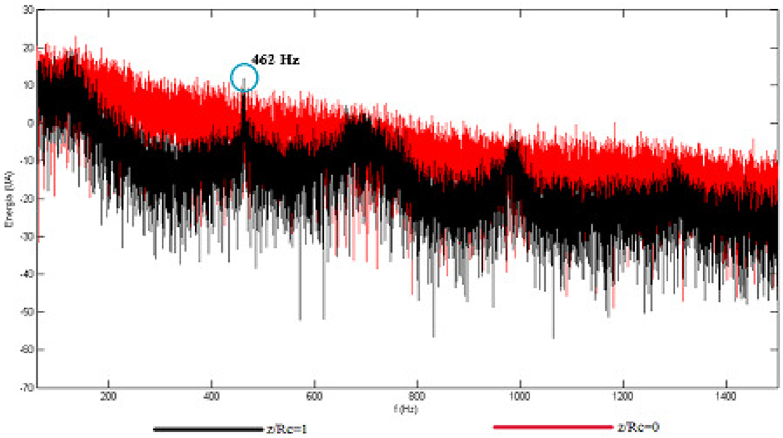


Figure 11. PSDs for Re = 70000 and S = 0,88 measures in combustion chamber at x/D=1,8, on the wall (z/Rc = 1) and on the axis (z/Rc = 0).

Anacleto et al. (2003) quantified the axial development of this PVC structure for the same combustor, through measurements of amplitude of pressure oscillations along the outer boundary of jet, for isothermal and reacting conditions with and without the combustor. Regardless of the working mode, the PVC structure loses intensity around z/D=0,5, coinciding with maximum radial jet spreading and maximum reverse flow, being that the distance of x/D = 1,8 was dissipated in small turbulent structures.

When an obstruction is placed in the exhaust combustor the flow behavior in the axis of the combustor changes clearly, and the signal was very similar to that found on the wall for almost the entire frequency range analyzed (Figure 12). In this case the energy peak corresponding to the signal of PVC is also found in the center of the combustor, indicating that for this configuration has not yet been dissipated. The two measurements are nearly the same level of turbulent energy in almost the entire spectrum.

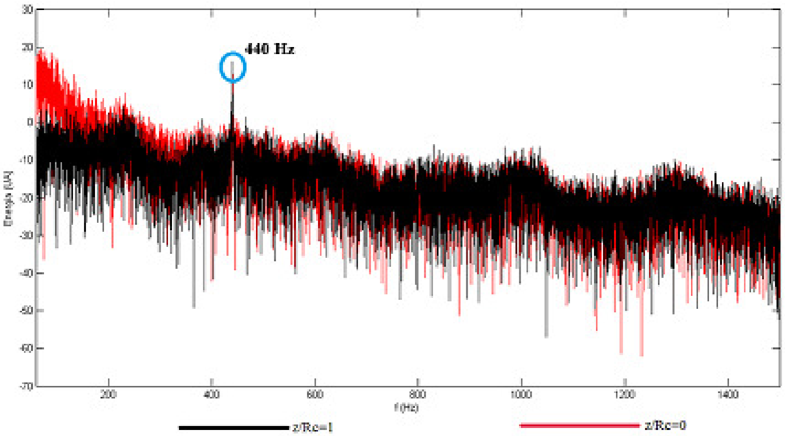


Figure 12. PSDs for Re = 70000 and S = 0,88 measures in combustion chamber with exhaust cone at x/D=1,8, on the wall (z/Rc = 1) and on the axis (z/Rc = 0)

As reported by Dawson et al (2000), Lucca-Negro and O'Doherty (2001), Syred (2006) and Valera-Medina et al (2009), any confinement in the combustor exit can cause a significant change in the flow. In most studies, it was found that the ZRC, depending on configuration of obstruction, changed shape, from elliptical-shaped to annular-shaped (or toroidal, usually found in gas turbines) as the downstream pressure induces a flow positive in the center of the combustion chamber. This does not mean that the PVC is suppressing. Valera-Medina et al (2009) observed that PVC has increased its size in both width and length, and Syred (2006) reports that in some studies in combustors with outlet obstruction coinciding with the center of the combustion chamber, found two PVCs. we can supposed that the shape of

ZRC and associated PVC must have changed, specifically the increased width and/or length, explained in the similarity of the spectra in Fig. 12.

4. CONCLUDING REMARKS

This work studies the typical structures found in a swirling flow generated in LPM model also studied by Anacleto et al (2003), Fernandes et al (2005a, b), Shtork et al (2007) and Shtork et al (2008), through two measurement techniques: PIV to measure velocity fields and pressure probe connected to a microphone to measure the dynamic pressure.

In the velocity fields is found a well established ZRC for Reynolds number greater than 60000 and swirl number greater than 0,62, with shear layers that lie between the contours of zero speed and high speed regions. Around this recirculation zone observed a vortex precession (PVC) which causes the ZRC change the size and shape, precess around the axis of symmetry at a well-defined frequency. Compared to the mean flow, which shows only a pair of vortices in its structure, with the instantaneous flow can note that the average velocity field represent partially of the global trends of the flow, fluctuations in the instantaneous field governing the flow fields in real time and have a great impact on the performance of combustion. PVC is the dominant frequency, and therefore modulates the flow dynamics, causing the variations found in the instantaneous axial velocity fields, as also observed by Anacleto et al (2003), Fernandes et al (2005a and 2005b) and Shtork et al (2007) and Shtork et al (2008).

Spectral results also show the energy peak corresponding to the PVC. By increasing the flow rate increases the flow velocity and therefore the PVC frequency, as explained earlier by Shtork et al (2008). The obstruction cone at the combustor exit caused that ZRC had increased in width or length, increasing the length of the PVC associated, as the characteristic sign of that is found at a distance of x/D = 1.82, but with a slightly lower frequency of precession.

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