SWIRLING FLOW ANALYSIS USING PIV

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Abstract. *In this experimental work Particle Image Velocimetry is employed in order to analyze the mean swirling air flow at the exit of a mixing chamber of a Lean Premixed Prevaporized Combustor - LPP. The combustor model comprises one swirler with a set of adjustable vanes where the swirl number may be controlled. The swirler is followed by the mixing chamber. Before reach the combustion chamber, the air stream experiments a sudden expansion. The flow within the combustion chamber, depending on the swirl number, is strongly recirculated. In this experimental set up the combustion chamber was removed to analyze only the swirl free jet flow at the exit of the mixing chamber . Using Particle Image Velocimetry two velocity components were firstly measured in the axial plane and, sequentially, two velocity components were measured in a transversal plane located at 10 mm of the outlet mixing chamber. The results of the velocity measurements show different regimes as the swirl number is varied. Particle image velocimetry shows considerable promise to analyze this complex turbulent flow.*

Keywords: *Combustor , PIV, Lean Premixed Combustor, Swirler Flow*

1. INTRODUCTION

The environmental protection rules, year after year, demand more restrictive legislations regarding pollutant atmospheric gas emissions, including the well known NO_x. The elevated petroleum costs affect the prices of all combustibles, and the search for more efficient combustor are inevitable. The advent of new instrumentation and process control presents deep implications in the new design methodologies, because the parameters that control the combustor operation may be well controlled in this new scenario. Among the variables that may be controlled the combustion temperature and gas composition may be cited. A better comprehension of the combustor is then justified, in order to get, besides a more flexible operation, an equipment more efficient and with less pollutant gas emissions. A combustor model, denominated by LPP - Lean Premixed Prevaporized is used in the present experimental work. It may be operated with gaseous fuel or prevaporized liquid fuel. To vaporize the liquid fuel, fraction of the hot combustion gases may be utilized. This LPP combustor comprises, as main components, a swirler with a set of mobile blades, a mixing chamber, a combustion chamber itself, and the combustion gases exit section that discharges the gases to the atmosphere. The turbulent swirling flow is produced by the rotation of the air flow inside the swirler, before the air reaches the mixing chamber. In the mixing chamber, air and fuel are mixtured , before the air-fuel mixture reaches the combustion chamber. The mixing chamber is a very important device in these combustor model. To better understand the LPP operation, and mainly to understand how the mobile blade angle in the swirler affects the flow at the entrance of the combustion chamber, and consequently the dynamic of the combustion process, particle image velocimetry is used to analyze the isothermal air flow, at the exit of the mixing chamber. To do this, the combustion chamber was removed, and the swirler flow was measured as a free atmospheric jet. Two distinct situations were analyzed. In the first, the laser sheet illuminated a horizontal plane in order to measure two horizontal components velocities, one of them is the longitudinal component and the other is a horizontal transversal component. In this configuration the digital camera was placed in a vertical position. In the secon, the laser sheet illumines a transversal section of the exit free-jet swirl flow and the CCD camera is placed in front of the mixing chamber. In this configuration, two components of the secondary flow is measured, one of them is the horizontal transversal component, and the other is the vertical transversal component of the air flow. The strong swirling flow present in the analyzed flow is produced by the swirler. The intensity of this rotating flow is controlled by the blade angles and a dimensionless parameter known as swirler number is an indicator of the intensity of this secondary flow. Anacleto *et. al* (2003) studied a LPP combustor model with and without reaction, using Laser Doppler Velocimetry and image analysis employing a high speed digital camera to make flow visualization. In this set up they have also used sensor to measure combustion temperature, pressure sensor and gas analyzer. The important dimensionless parameter present in this complex tridimensional and turbulent flow are the Reynolds Number, the Swirler Number and also the Strouhal Number due to the presence of a Precessing Vortex Core - PVC, present in this kind of flow. In the reaction analysis, propane gas is utilized. Liquid fuel is also tested and its vaporization is produced by hot air at 300^o. The flow measurements show that the flow enters the combustion chamber with the presence of a precession vortex for swirl number $S > 0.5$. The gas analysis shows that the concentrations of CO_2 and NO_x decay with the swirl number. The concept of combustion at poor inflammability limit as a mean to obtain ultra-low NO_x emission values, producing a low temperature reaction is something quite interesting to be explored, say the authors. The use of a very strong swirling flow produced by the mobile swirler blades induces a recirculating zone at the combustion chamber entrance. This permits to control the mixture residence time in the combustion chamber and, consequently, the burning of the CO and also a better control of the flame stabilization. The lean combustion regime may also produce combustion instabilities and the flame may sustain only in a very narrow operation band. The tested combustor model comprises a cylindrical mixture chamber with 50mm of inner diameter and 160 mm long. The combustion chamber, also having a cylindrical shape, presents inner diameter of 110 mm and 300 mm long. The combustor model may operate with gaseous fuel or liquid fuel. The whole combustor operates at atmospheric pressure. The Swirl Number $'S'$ is defined by:

$$S = \frac{2}{3}\left[\frac{1-(D_1/D_2)^3}{1-(D_1/D2)^2}\right] tang(\theta)$$

$D_1 = 90mm$ is the diameter of the cylindrical body that fixes the mobile blades
$D_2 = 120mm$ is the swirler diameter
$\theta =$ is the angle of the mobile blades.

The flow enters the combustion chamber, depending on the Swirl Number, with a precession vortex. The frequency of this precession vortex may be measured by the Fourier Analysis of a pressure sensor installed in the combustor model. The velocity components measured at the exit of the the mixing chamber and also in the combustion chamber are measured by Laser Doppler Velocimetry. The flame temperature was also measured utilizing a thermocouple and a chemical species analyzer was used to measure the combustion gas composition. The Reynolds Number based in the mean velocity at the combustor entrance and also with the diameter in the combustor entrance was equal to 10^5 in their experiment. The existence of a precession vortex in the flow generates a flow instability, with a frequency that may be quantified in a dimensionless form by the Strouhal Number, defined by $S_h = fd/U_o$, where $'f'$ is the precession vortex frequency, $'d'$ is the diameter at the entrance of the combustion chamber and $'U_o'$ the mean flow velocity in this position. The first phase of the experiments was held without combustion, in order to better know the flow conditions at the entrance of the combustion chamber. The results of the velocity measurements revel the presence of a primary zone in the combustor, with a near field region dominated by the presence of strong vortex and a central recirculating zone. The reversal velocity in this recirculating zone may be of the order of U_o, that is, the mean axial velocity at the entrance of the combustion chamber. This reversal flow is evolved by an axial and positive velocity field that defines the frontier of an external recirculating region. The presence of this external recirculating zone is crucial, in order to furnish lean and stable flames. The precession vortex action is present in the primary zone of the combustion chamber. The oscillations caused by the central portion of this precession vortex is responsible for the high turbulent intensity in this region that is not present in the outer shear layer. In their conclusion the authors say that the experiments with this strong swirling flow the enters in the primary zone of the combustion chamber show the presence of a precession vortex that rotates out of the symmetry axis, embracing the central recirculating zone. The frequency of this precession vortex is a function, among other factors, of the flow rate. It is also verified that the increasing in the Swirl Number promotes a decaying in the concentrations of NO_x and CO at the combustor exit. Fernandes *et. al* 2003, present an experimental investigation of a turbulent rotating flow without reaction of a combustor model. Flow visualization is made and Laser Doppler Velocimetry is employed to measure the flow velocity components and also the instabilities present in this kind of flow at the entrance of the combustion chamber. These instabilities are caused by the presence of a precession vortex originated in the mixing chamber and also by the sudden expansion between the mixing chamber and the combustion chamber. This precession vortex affects the whole flow and the combustion process. It may also modulate the heat liberation with oscillations frequency near the natural combustor frequency. In this case, noisy thermal-acoustics waves may produce quite intense sound and mechanical vibrations in the combustor structure. This operational mode is not good for the combustor and, consequently, it is not desired. It is important to study the dependence of those dimensionless frequency, the Strouhal Number, as a function of the Reynolds Number. The velocity measurements were made at the exit of the mixing chamber and the flow visualization by means of a high speed digital camera with capture rate of 10 000 frames/s. A mean temporal structure at the exit of the mixing chamber is presented for a Swirl Number $S = 1.05$ and Reynolds Number $Re = 2 \times 10^4$ indicating the presence of a jet with strong rotational movement , embracing a central zone with strong recirculation. These structure asymmetry may be explained by the presence of the precession vortex in the flow. A pressure probe installed at the entrance of the combustor detects periodical static pressure oscillations with the same frequencies present in the velocity field. In the conclusion the authors say that the pulsations observed in the combustion chamber induced by this high rotational and turbulent flow, may be related to the destruction of the precession vortex and with a consequent helicoidal movement the appears after this break down process. Cala 2006, studied the flow instabilities associated to the precession vortex, that frequent appears in this kind of rotational flow, both in natural and industrial processes. There are studies, says the author, on this subject, in combustors, cyclone type separators, mixture devices, Francis type hydraulic turbines, in this last case may produce a dangerous structural vibrations in the hydraulic turbine. The study of the precession vortex is also important in the hurricanes, associated to the atmospheric process. The study and effects of the precession vortex involve a series of important questions related to the instabilities in Computational Fluid Mechanics aiming to find precise answers for this non-steady state phenomenon. The experimental device used in his work generates stable pulsations in the turbulent flow, easily identifiable in the velocity and pressure signals. In the conclusion the author says that the flow of a swirling and non-steady jet was studied using the informations of a laser doppler velocimetry system and also the informations from a pressure sensor. He says that the non-steady character present in this flow is related to the presence of the precession vortex in the flow.

2. THE EXPERIMENTAL SET UP

The aim of the present experimental work is centered in the swirling turbulent flow that occurs at the exit of the mixing chamber, installed between the swirler and the combustion chamber of a Lean Premixed Prevaporized Combustor Model - LPP, operating without reaction, which means that the air flow occurs isothermally. The Particle Image Velocimetry - PIV permits the simultaneous measurement of two velocity components in a plane illuminated by pulsed laser light sheet. Firstly, the laser sheet illuminates a horizontal plane and the axial flow may be measured. Secondly, a transversal section is illuminated , the camera is placed perpendicularly to the axis of the mixing chamber, and the secondary flow may now be measured. The LPP combustor model used in the present work is shown in the Fig.1.

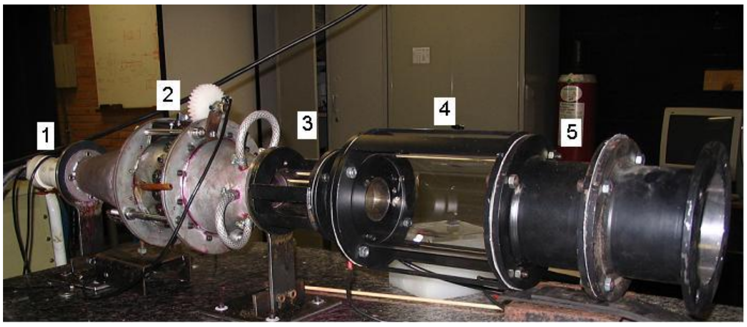

Figure 1. Combustor. 1- Air Inlet; 2- Swirler ; 3- Mixing Chamber ; 4- Combustion Chamber; 5- Combustion Gas Exit

The air is fed by a rotating ventilator. The ventilator electrical motor speed is controlled by a frequency inversor. The air flow rate is measured by a rotameter. The swirler comprises a set of mobile vanes. The vane angle may be adjusted and is measured by a protractor installed in the axis of one of the gears that control the vane movement. When the combustion process is present, the fuel is injected downstream of the swirler, at the entrance of the mixing chamber, in different injection points. Between the mixing chamber and the combustion chamber the air flow experiment a sudden expansion. A recirculating zone is then present in this process. Both, the mixing and the combustion chamber present a cylindrical shape. The mixing chamber has an inner diameter of 50 mm and length of 110 mm. The combustion chamber has an inner diameter of 90 mm and length of 200 mm. The bluff body placed in the central part of the swirler presents also a cylindrical shape, its extremities are conical. It has an outer diameter of 90 mm and total length of 120 mm. During the measurements using PIV the sections placed after the mixing chamber were removed. Consequently, the air at the exit of the mixing chamber flows as a rotating free jet, flowing at atmospheric pressure. The horizontal axial flow was measured in a section of 60 mm by 60 mm. The rotating flow, in a vertical plane, was measured in a distance of 10 mm of the exit section of the mixing chamber.

3. PARTICLE IMAGE VELOCIMETRY - PIV

The Particle Image Velocimetry differs from the other velocimetric methods due to the fact that this technique utilizes a CCD camera in order to capture the positions of a group of very tinny particles positions injected in the flow (seeding particles). This seeding particles, chosen in an adequate form, must follow the fluid flow appropriately. Two pulsed laser cavities illuminates a horizontal plane in the test section. The laser ray passes to a cylindrical lens in order to produce a fine laser sheet. The seeding particle positions are frozen in a first PIV image when the first laser cavity is triggered. When the second laser is triggered it illuminates the seeding particles in another position. The Fig.2 shows how this process occurs.

The flow occurs upwards. The time interval between the two laser pulses is known. There is a time hub that triggered the laser's signals with the CCD camera in each capture instant. Laser cavities and CCD camera operates in a synchronized form. A sequence of image-pairs are transferred and saved in a computer. An appropriate software controls the whole acquisition system and the image acquisition process. During the post-processing, the image section of $60mmx60mm$ is divided in small sections, known as interrogation areas. For each interrogation area it will be associated a velocity vector in the image plane. To obtain this vector a cross-correlation process is made in each interrogation area. The interrogation area may be seen as a binary image, where the presence of a particle in a position means "zero" and the absent of a particle

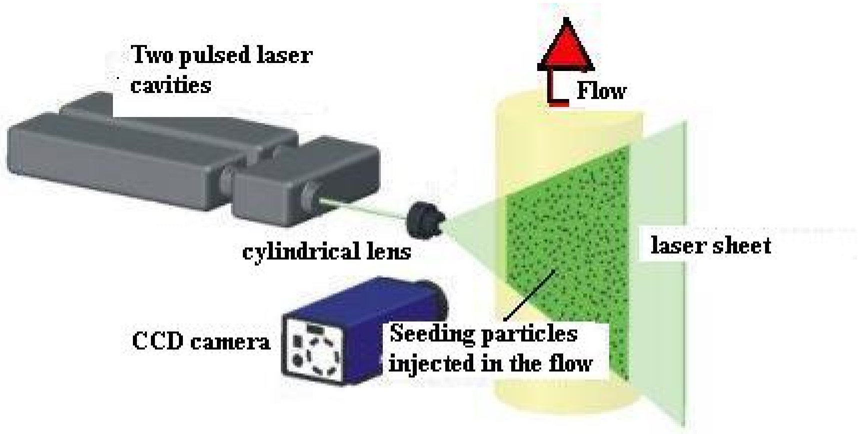

Figure 2. PIV operation principle - adapted from La Vision.

means "one". In this mathematical process it is calculated the maximum x-displacement and y-displacement that give a maximum in the cross-correlation of the two sequential interrogation areas in the same image position, in the sequential instant of time. With the x-displacement and the time interval between the two laser pulses it is possible to evaluate the V_x component in the plane. With the y-displacement and the pulse interval between the two laser cavities, it is possible to evaluate the V_y component. That is, in general terms, the philosophy of PIV. Figure3 shows a schematic view of the test section and how to use PIV to measure two velocity components in the horizontal axial plane, one of them is the axial velocity component V_x and the other the transversal and horizontal component V_y. In this configuration the laser cavities illuminates a horizontal plane and the camera axis is placed vertically.

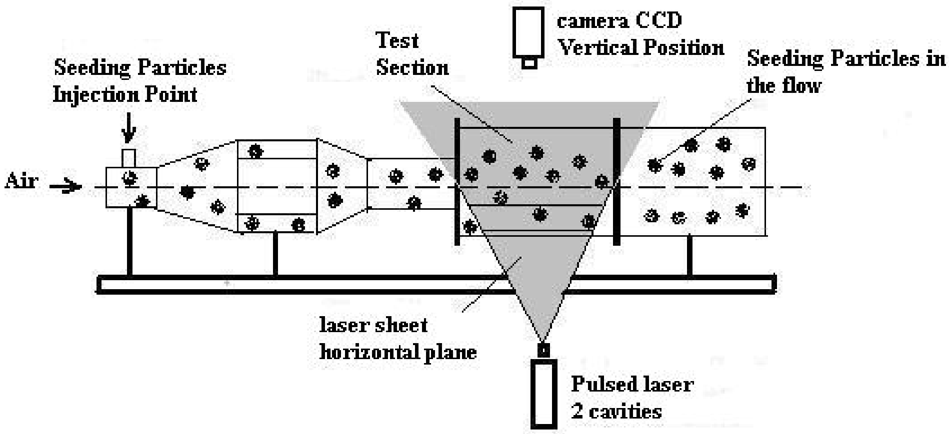

Figure 3. Esquema de uma montagem para velocimetria por imagem de partículas em um combustor LPP.

The two pulsed laser cavities employed in this PIV instrumentation are denominated by Nyodim-YAG, with wave length of $\lambda = 532nm$, color green, with maximum frequency of 15 Hz. The digital CCD camera is a SharpVISION progressive scan, with high transfer rate, wiht three operate modes: continuous, triggered, and double exposure. The last one is fundamental for the PIV process. The energy released per laser pulse is equal do 120 mJ. The acquisition and control process software is produce by IDT - Systems (http://www.idtpiv.com/systems/index.shtml) .

4. RESULTS

The experimental results were obtained following the sequence bellow:

1. With the whole equipment adjusted, laser, camera, sincronizer, and the software of command, control and acquisition, the CCD camera was set in focus in the desired image plane;

2. A known image from a millimetric paper was initially placed in the position where the laser illuminates the plane in

order to get a calibration scale to convert pixels displacement in the image in metric displacement in the real flow;

3. The air from the ventilator and the seeding particle are set on. A homogeneous mixture of seeding particles and air flow together to the test section;

4. A sequence of image-pairs are acquired and recorded in the computer:

5. Initially, with the camera axis in the vertical position, the longitudinal flow is measured, in an area of 60 mm x 60 mm at the exit of the mixing chamber (horizontal fraction of the free rotating jet);

6. A set of 200 image pair, at a frequency of 6 Hz are recorded. The air flow rate is kept in 27 normal cubic meters per second in the test section;

7. Finishing the measurements in the horizontal plane, the laser sheet is moved to illuminate a transversal section at 10 mm from the exit of the mixing chamber, the CCD camera is placed in front of this test section and protected against the seeding particles by a transparent surface, and the measurements of the rotating jet are done;

8. The set of 200 image-pairs are processed and the bidimensional velocity field present in the illuminated plane is obtained. With those results, it is possible to evaluate the mean velocity filled in those horizontal and transversal planes. Only the mean velocity fields are presented is this work.

During the experiments, different positions of the swirler vanes may be adjusted, and consequently different swirl numbers may be tested. In order to obtain a set of velocity field informations regarding to this mean air flow, at the exit of the premixing chamber, 200 image pairs were acquired and storaged in the computer. The time delay between the two image pair, which will produce a specific velocity field information, in a specific instant of time, is quite low (something around 20 to 60 microseconds, according to the specific swirl number). The time delay may be well controlled in this specific aspect. Unfortunately, the PIV instrumentation operates with two pulsed laser cavities, each one presenting a maximum pulsed frequency of only 15 Hz. In this manner, it is possible to get a pair of images in a very low time interval (it is possible to "freeze" the air flow with the PIV technique). But, on the other hand, it is not possible to obtain pair of images in a very high frequency, that would make possible the measurement and visualization of turbulent instabilities that are presented in this free turbulent jet, at the exit of the premixing chamber, of the LPP combustor model. It is possible, when one observes the sequence of 200 image pairs, in slow motion, the presence of a rotating flow (similar to a solid body rotation) with a precessing vortex superimposed to this main air movement. Its frequency, unfortunately, can not be measured using the PIV technique. We are trying to make this frequency analysis using Hot Wire Anemometer. This free turbulent jet at the exit of the premixing chamber presents different movements and many instabilities are presented, as already reported by Anacleto *et al* (2003), Cala *et al* (2006), and also by Fernandes *et al* (2006). The air flow that comes from the ventilador experiments an axial flow until the swirler is riched. The set of swirler vanes, depends on the angle of the vanes, will transform this pure axial flow in a mixture of axial flow - that transports the main air flow - with a rotating flow. Superimposed to this rotating flow, another important instability may be presented, depending on the swirler number. This instability is known as the Precessing Vortex Core, which may be presented in many other flows in fluid mechanics, including the exit of the Hydromachines, as a Francis Hydroturbine. We have already observed the presence of this precessing vortex at the entrance of a diffuser model, in one of our experimental set ups, after the water flow has crossed an swirler of fixed angles. The water flow, originally purely axial, at swirler downstream, presents a rotational flow and, depending on the flow rate, may also presents a precessing vortex instability in the central part of the water flow. The air flow in the premixing chamber is a turbulent flow, presenting, three main movements - one axial transporting the air flow, the second is a rotating movement (as a solid body rotation) and the third is a precessing vortex movement. This complex flow at the exit of the premixing chamber will experiment a sudden expansion to the atmosphere, where the atmospheric air is at rest in the present set up. Due to the effect of the rotation, the central zone of the jet presents a low pressure value. Consequently, a large recirculating zone will appear due to this rotation flow. Besides this, in the outer region, where the free jet flow is in contact with the atmospheric air, other kind of instabilities may be presented, due to the strong shear stresses presented in these interface where a stream of air is in contact of atmospheric air at rest. The air flow may also receive some fraction of air from the atmosphere due to the entrainment behavior.

The Fig. 4 presents the longitudinal and transversal flow in the horizontal and transversal planes. In the horizontal plane in (a) one has the axial flow and in (b) the transversal flow. In the transversal section in (c) one has the horizontal velocity component and in (d) the vertical component. The directional blades in the swirler, in these configuration, were set for an angle $\theta = 30^o$.

This mean flow shows, in a global form, the presence of a large recirculating zone, with negative axial velocity in the order of -4 m/s. This may be consired as a good flow characteristic for the combustion process. The flame may be well anchored by this flow characteristic. One can also observed a region of axial and positive flow next to exit of the mixing chamber, characterized by elevated values of axial velocity, in the order of 15 m/s in the external part of the jet. The interface of those two regions, with negative axial velocity in the central jet zone, with positive axial velocity at the outer

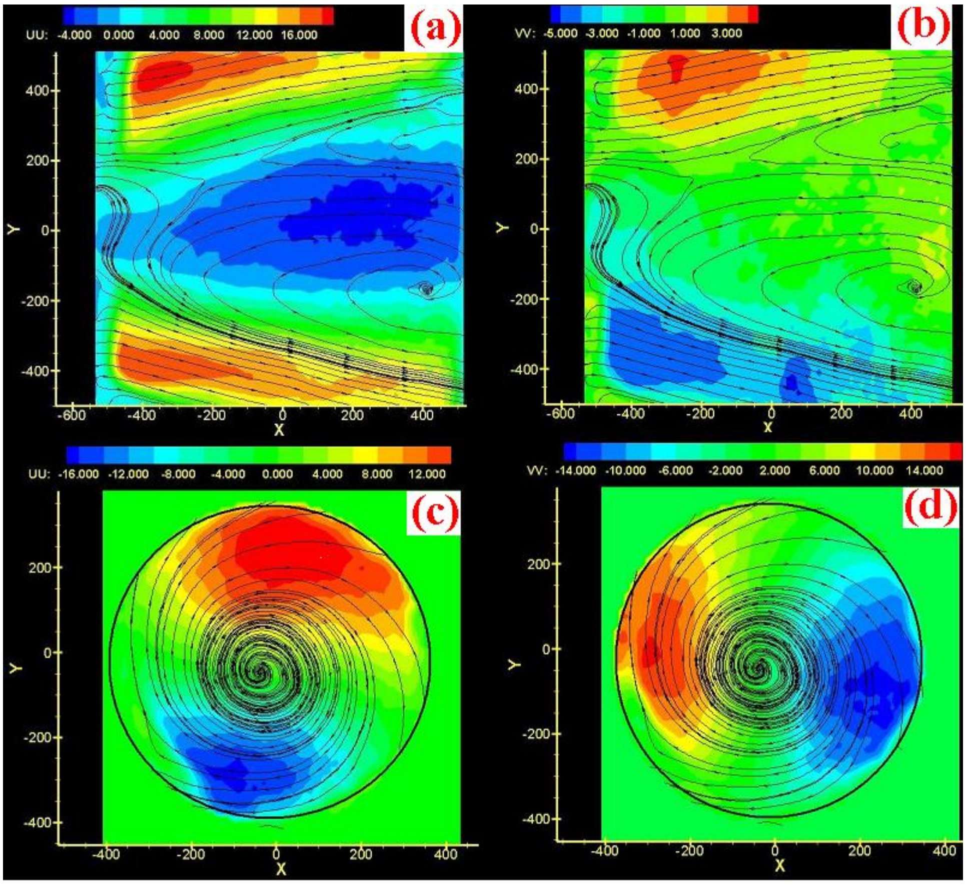

Figure 4. Flow velocity for $\theta = 30^o$. (a)- axial component in the horizontal plane; (b)- transversal component in the horizontal plane; (c)- horizontal component in the transversal plane at 10 mm of the exit mixing section ; (d)- vertical component in the transversal plane.

zone characterizes interfaces of strong shear stresses in this jet flow and this counterflow may produce regions of strong instabilities. Another instability zone with high shear stresses, may be presented in the interface between the outer jet flow, with positive axial velocity, in contact with the atmospheric air, that is at rest. In this region there is air entrainment, where the atmosphere feeds the jet with some air fractions.

The two components of the secondary flow in the cross section of the jet placed at 10 mm of mixing chamber exit are shown in (c) and (d). This frontal flow view, when one observed the flow along the mixing chamber axis, shows very clear the presence of a strong rotating flow, with a centrifugal action. There is also a radial velocity component, superimposed to the tangential velocity component, that makes the mean flow, with an helical movement. The observed flow is similar to that one that occurs when one superimposed a vortex flow with a sink flow, in a potential flow model. The centrifugal effect then appears. The presence of a large recirculating zone may cause flow instabilities, and the presence of a precession vortex may be responsible by the non-steady state characteristic in this complex turbulent and swirling flow, presented in these LPP combustor model.

5. CONCLUSIONS

Particle Image Velocimetry was used to analyze the velocity field at the exit of a mixing chamber of a LPP combustor model. With this technique, many aspects of the flow, may be observed, by the fact that more than a million of sensor in the CCD camera device is working simultaneously. Unfortanately, the acquisition frequency is not high - its maximum value is fixed in 15 Hz, and in this particular case the image pairs were acquired in only 6 to 8 Hz. But the information density is enormous. When one tries to compose the longitudinal and the transversal mean flows, it is possible to conclude that the flow, as a whole, is a tridimensional flow with a helicoidal shape, rotating clockwise. Other flow configurations of the same flow may be well analyzed using the same procedure and technique.

6. ACKNOWLEDGMENTS

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