Investigations of Large Coherent Structures in a Swirl Stabilized Gas-Turbine Combustor Using Time-Resolved PIV

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Abstract The present work details the analysis of the aerodynamics of an experimental swirl stabilized burner representative of a gas turbine combustor. This study has been performed using a High frequency PIV (HFPIV) system working at a high acquisition rate (12 kHz). For the last 25 years, Particle Imaging Velocimetry has been developed and improved so that the spatial resolution of PIV measurements has been increased. Nevertheless, up to now, PIV measurements are usually sampled at a low acquisition rate (about 10 Hz), so that only statistical quantities can be obtained and analyzed. However to better understand highly turbulent swirled flows, which are unsteady by nature, time resolved date are necessary. Thank to recent technical improvements, it has been possible to develop a PIV system working at 12 kHz to analyze the experimental combustor flow field. Using HFPIV, statistical quantities of the burner are obtained and analyzed, while a temporal analysis of the velocity field is carried out, indicating that large coherent structures periodically appear in the combustion chamber.

1. Introduction

Recently, environmental concerns have led to the development of lean premixed (LP) burners that reduce the amount of NOx produced. Lean premixed combustion permits to achieve lower NOx levels by reducing the fuel flow rate and thereby the peak flame temperature. Nevertheless, under lean conditions, flames tend to exhibit strong combustion instabilities, since the combustion in LP burners takes place near the lean blow-out limit which is more susceptible to unstable combustion dynamics. In order to enhance the stabilization of lean premixed flames, swirling motion is used, since it permits to control the flame stabilization through a swirled-induced recirculation of hot products near the nozzle (Syred, 2006). In addition, swirl-stabilized burners permit to achieve a reduced NOx emission level, by improving the mixing rate between fuel and oxidant streams. Unfortunately, it is difficult to ensure simultaneously good flame stability and low NOx emission in lean premixed swirl-stabilized burner, because the flame stability can be hindered by the same effects that lead to the reduction of NOx formation: efficient mixing, very lean conditions. It has been shown that turbulent swirled flows, like those encountered in industrial combustion devices, develop periodic large coherent structures which play an essential role in the dynamics of turbulent flames (Paschereit et al., 1999). Their interaction with the heat release process and the acoustic resonant modes of the combustor can cause undesirable instabilities in the system, which can cause flame extinction or led to the destruction of combustion device components (Candel, 2002; Nauert et al., 2007).

The problem of combustion dynamics and stability in lean premixed turbulent swirled burners has motivated many numerical (Roux et al., 2005; Sengissen et al., 2007; Schneider et al., 2008) and experimental studies (Kang et al., 2007; Meier et al., 2007; Ballester et al., 2008). In order to characterize and to better understand the complex interactions involved in these flames, turbulent lab scale swirl stabilized combustors have been developed and studied using a broad range of diagnostics: microphones, \( OH^* \) and \( CH^* \) emission sensors or laser diagnostics. Particle Imaging
Velocimetry (PIV) is now widely used to gain a deeper insight into various stabilization processes in turbulent flames or to better understand complex interactions involved in combustion instabilities.

As mentioned by (Adrian, 2004), PIV and its spatial resolution have been developed and improved in several stages, related to technical progresses in the fields of lasers, cameras and computers for the last 25 years. Many efforts have been made to develop more robust PIV post-processing algorithms. The basic method used to extract the velocity from two successively acquired pictures can be decomposed into several steps. First, the raw images pairs are divided into several windows (“observation areas”). Then, to estimate the average particle displacement within the observation area investigated, each pair of corresponding windows are cross-correlated using Fast Fourier transform algorithms (Scarano and Riethmüller, 1999). Finally, for each window, a velocity vector can be determined, since the time separation between the two pictures of one image pair is known.

To improve PIV algorithms, the spatial resolution and the measurement precision have been increased first (Adrian, 1991; Westerweel et al., 1997; Nogueria et al., 2001; Lavoie et al., 2007), while the uncertainties associated with the interrogation procedure are reduced by using iterative method (Scarano and Riethmüller, 1999).

Up to now, mainly due to laser technology limitations, the PIV measurements were sampled with a low acquisition rate (typically of few tens of Hz). A deeper understanding of swirled turbulent flames that are by nature strongly unsteady requires advanced measuring techniques with high spatial and temporal resolutions. Recently, commercial PIV systems working at 1 kHz were available thanks to camera and computer performance improvements. Nevertheless, these systems are not fast enough to help in understanding phenomena occurring in swirled turbulent flames. Thus, PIV systems operating at an acquisition rate up to 20 kHz have been used to analyze the wake in bluff bodies (Williams et al., 2003) or to obtain velocity fields for both cold and hot flows (Wernet, 2007). Williams et al. (2003) uses a system that consists in a copper vapor laser and a dump camera which induce a heavy post-processing work. For these reasons, this last system seems difficult to use to acquire a large number of velocity fields to study turbulent flame behavior.

In the present work, High Frequency Particle Imaging Velocimetry is carried out to analyze the reactive flow field of a gas turbine model combustor. These measurements are carried out at an acquisition rate of 12 kHz. It is expected from their analysis to gain insight into the interactions between large coherent structure and the turbulent surrounding flow.

The structure of the paper is as follows. The burner and the diagnostic are first described. Then, the mean reactive flow is detailed in section 3, so that the efficiency and the resolution of the new HFPIV system can be tested. Lastly, instantaneous flow fields and their analysis are presented in section 4.

2. Experimental Configuration

2.1. Experimental setup and diagnostic

Figure 1 shows a schematic diagram of the experimental burner. The setup is composed of a two-staged swirled injector, supplied with propane and air, representative of a gas turbine injector and a rectangular combustion chamber. The primary stage consists in a central duct fed with propane and a swirler supplied with air. The primary stage swirler has 18 vanes so that the swirler angle is maintained constant at 42°. The fuel and air are mixed together in a specific zone downstream the injection of propane and air. Fuel is delivered in the secondary stage by 15 holes, which are located on a circular hollow part fed with propane. The airflow of the secondary stage is injected through a swirler with 20 vanes. The angle of the secondary stage swirler is 35°. Both air and fuel mix together in the secondary stage before mixing with the primary fuel/air mixture and entering the combustion chamber. The airflow rate in the secondary stage is four times higher than the first stage.
one. A co-rotating motion is imposed to the flow. Both swirler are continuously supplied with air, while the fuel injections can be used separately. For the present study, for ease of illustration, only the secondary stage fuel injection is used. Air and propane mass flows are monitored with electronic massflow meters (Bronkhorst-Elflow).

![Detailed of the injector](image)

**Fig. 1** Schematic diagram of the experimental burner and the HFPIV system. A detailed of the experimental injector is proposed in the bottom of the picture.

Velocity fields are measured downstream the injection plane, on the axis of the combustion chamber using a High Frequency PIV (HFPIV) system. For such experiments, the top and bottom walls of the chamber, made of concrete, contain a rectangular silica window (25 mm wide and 120 mm long) that allows the laser sheet to cross vertically the combustion chamber. A schematic view of the HFPIV device is reported on Fig. 1. The light sheet is generated by a system of two Nd:YAG lasers (Quantronix). Both lasers emit a pulse at 532 nm with an energy of 6 mJ and a duration of 160 ns. Optics are used to combine both beams along the same trajectory. A set of lenses (Melles Griot) is used to transform the laser beam into a planar light sheet 60 mm wide and 0.3 mm thick. A high-speed camera (Photrom Fastcam, 1024×1024 pixel at a rate of 2000 frames per second) equipped with a 105 mm F/1.8 Nikkor objective is placed perpendicularly to the burner axis to acquire the image pairs.

![Time diagram](image)

**Fig. 2** Time diagram of the high frequency PIV system. The time delay between two successive pulses is \(\Delta t = 6 \, \mu s\), while the time delay between two pulses emitted by laser 1 (resp. laser 2) is \(1/\nu = 83 \, \mu s\).
The two lasers working at a frequency \( f \) of 12 kHz and the camera operating at \( 2f = 24 \) kHz are synchronized using a pulse delay generator (BNC 555 pulses/delay generator), as shown in the time diagram of Fig. 2. Following an estimation of the maximum velocity to be measured, the time delay between two pulses is chosen equal to \( \Delta t = 6 \) \( \mu \)s.

The airflow is seeded with TIO2 particles with a nominal diameter \( d = 1 \) \( \mu \)m. As their melting point is higher than the adiabatic flame temperature, these particles are present both in fresh and burnt gases.

The raw image pairs are then exported and an off-line image processing is performed with an adaptive cross-correlation program ("Flow-Manager" by Dantec) using Fast Fourier Transform algorithm. This PIV post-processing software is designed and optimized to deal with high velocity and density gradients, providing a peak finding error of less than 0.1 pixel. The raw image pairs are divided into square interrogation areas whose final dimensions are 8\times8 pixels with an overlap of 25 \%, so that the flow field spatial resolution is 1.07\times1.07 mm\(^2\).

### 2.2. Operating conditions

The structure of the flow field is examined in the operating conditions reported on table 1. The fuel flow rate injected in the primary and the secondary stages are respectively \( (Q_{C3H8})_p \) and \( (Q_{C3H8})_s \), while the global airflow rate is noted \( Q_{air} \). \( \Phi \), \( \Phi_p \) and \( \Phi_s \) are respectively the global and the local equivalence ratios in the primary and secondary stages. The power associated with this regime is \( P = 94 \) kW and may appear low compared to industrial devices. Nevertheless, it is already a high quite power for a laboratory scale combustor.

<table>
<thead>
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<th>( Q_{air} )</th>
<th>( (Q_{C3H8})_p )</th>
<th>( (Q_{C3H8})_s )</th>
<th>( \Phi )</th>
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**Table 1** Operating conditions for PIV measurements.

In the following sections, the notations \( x^* \) and \( y^* \), defined by \( x^* = x/D \) and \( y^* = y/D \) are used. \( D \) is the diameter of the outlet divergent of the injector; \( x \) refers to the horizontal direction and \( y \) to the vertical one.

In order to estimate the efficiency of the high frequency PIV system and to study the combustor aerodynamics, PIV images are acquired in the combustion chamber, near the injection plane, using two complementary observation areas. The first one (Region 1), 512 pixel high and 128 pixel wide, permits to visualize and analyze the vertical velocity distribution (\( 0 < x^* < 0.4 \) and \( -0.7 < y^* < 0.9 \)). The second window observation (Region 2), 128 pixel high and 512 pixel wide, focuses on phenomena taking place in the top part of the combustion chamber between \( 0 < x^* < 1.8 \) and \( 0.4 < y^* < 0.87 \).

The program Flow-Manager is used to process the raw images. A peak-height validation and a moving-averaged validation methods are used to validate or reject each calculated vectors. The peak-height validation principle is to compare the value of the highest peak in the correlation plane with the value of the second highest peak using the delectability criterion, \( k \), while the moving-averaged validation permits to compare each vector with its neighbors using an acceptance factor, \( \alpha_f \). A parametric study has shown that the values \( k = 1.2 \) and \( \alpha_f = 0.1 \) are the most adapted to the
present measurements (Barbosa et al., 2008). The effects of the validation method parameters on the PIV results have been analyzed and it has been shown that they introduce a maximal uncertainty of 11% in the region of maximal velocity. This difference is quite acceptable as the reactive flow is very turbulent.

3. Mean velocity fields in a reactive situation

In order to evaluate the efficiency of the HFPIV system to analyze the flow field within the combustor, the mean and RMS velocities (RMS for “root mean square”) are calculated. The mean velocity components, \( U_{\text{mean}} \) and \( V_{\text{mean}} \), and the RMS velocity components, \( U_{\text{rms}} \) and \( V_{\text{rms}} \), are obtained by processing \( N = 12000 \) successive instantaneous velocity fields and are defined by:

\[
U_{\text{mean}} = \frac{1}{N} \sum_{i=1}^{N} u_i \quad \text{(resp. } V_{\text{mean}}) \tag{1}
\]

\[
U_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (u_i - U_{\text{mean}})^2} \quad \text{(resp. } V_{\text{rms}}) \tag{2}
\]

The same definitions apply to \( V_{\text{mean}} \) and \( V_{\text{rms}} \). The notations \( u \) and \( v \) refer respectively to the horizontal and vertical velocity components.

3.1. Statistical quantities

The vertical distribution of the mean axial and radial velocities, \( U_{\text{mean}} \) and \( V_{\text{mean}} \), obtained in a plane containing the chamber axis are reported on Fig. 3. The top and the bottom limits of the observation window are respectively at the distance \( y^* = 0.87 \) and \( y^* = -0.7 \), while the top and the bottom wall of the chamber are at the distance \( y^* = +/- 1 \) and the edges of the injector correspond to \( y^* = +/- 0.5 \).

Fig. 3 Contours of mean axial and radial velocities, \( U_{\text{mean}} \) and \( V_{\text{mean}} \), downstream the injection plane, on the axis of the combustion chamber. Measurements have been carried out using the first observation window, Region 1. Mean quantities are obtained by processing \( N = 12000 \) successive velocity fields. The edges of the injector are drawn in black.

Figure 3 indicates that, as expected, the vertical distribution of \( U_{\text{mean}} \) is symmetric, while the \( V_{\text{mean}} \) one is anti-symmetric around \( y^* = 0 \). Second, a penetrating annular conical jet of fresh gases, where the maximum levels of the mean axial and radial velocities are observed, is visible on both sides of
the view. The jet internal boundary is situated at the distance $y^* = +/-0.4$ for $x^* = 0$, meaning that the flame is probably stabilized within the outer divergent of the burner. Assuming that the mean flame front is associated with the annular conical jet boundary, an estimation of the mean flame front angle, $\beta$, is: $\beta = 20^\circ$. Lastly, an inner backflow region, characterized by a negative mean axial velocity, is observed around the chamber axis. This recirculation area is characteristic of swirling reactive flows and provides the major mechanism for flame stabilization in the combustor.

In order to analyze phenomena occurring near the annular jet, the camera is focused in the top part of the combustion chamber (Region 2). The mean velocity field and associated streamlines are displayed on Fig. 4 (left). The central backflow region, well revealed by the streamline plot begins at $x^* = 0.5$ for $y^* = 0.4$ and does not seems to be completely ended at $x^* = 1.8$. A second weak recirculation area is also visible in the superior part of the horizontal observation area. The annular jet, characterized by positive velocity vectors, separates these two back-flow regions. The profiles of $V_{mean}$ and $U_{mean}$ obtained with the vertical observation area (Region 1) and the horizontal one (Region 2) are plotted in Fig. 4 (right) for the vertical cut $x^* = 0.1$. These mean velocity components are still obtained by processing $N = 12000$ successive velocity fields. This figure shows that the profiles are very similar whatever the region used to measure them. In the superior part of the combustion chamber, the profiles present a peak at $y^* = 0.53$ both for $U_{mean}$ and $V_{mean}$. The maximum level of the axial velocity is close to 54 m.s$^{-1}$ for both regions, while a difference of less than 7% is observed in the zone of high radial velocity, which is a quite acceptable difference.

![Fig. 4](image)

The distribution of mean axial and radial velocities, is reported on Fig. 5(a) and Fig. 5(b) for the vertical cut $x^* = 0.2$. The profiles of $U_{mean}$ and $V_{mean}$ present two peaks at $y^* = +/-0.53$ corresponding to the annular jet of fresh gases. The $U_{mean}$ maximum value is 54 m/s, while the $|V_{mean}|$ maximum level is 22 m/s, indicating that the maximum level of $U_{mean}$ is almost 2.4 time higher than the $V_{mean}$ one. Between the two peaks of $U_{mean}$, a large negative mean axial velocity, corresponding to the inner backflow region described before, extends between $y^* = -0.38$ and $y^* = 0.38$.

In order to compare the distributions of mean and RMS velocity components, the profiles of the axial and radial velocities, RMS, $U_{rms}$ and $V_{rms}$ are also reported on Fig. 5(a) and Fig. 5(b) for the vertical cut $x^* = 0.2$. First, the lower levels of $U_{rms}$ and $V_{rms}$ are obtained, as expected, in the inner recirculation area. Second, the annular conical jet of fresh gases induces an inner and an outer shear layers, which coincide with $U_{rms}$ and $V_{rms}$ peaks as visible on Fig. 4(a) and Fig. 4(b). The profile of $U_{rms}$ reaches its maximum level ($\approx 18$ m/s) at the distance $y^* = +/-0.46$, i.e in the mixing region between the central recirculation area and the positive streamwise velocity flow. These two $U_{rms}$ maxima coincide with two local $V_{rms}$ peaks. The global maximum levels of $V_{rms}$ (almost 22 m/s), are reached at $y^* = +/-0.59$, corresponding to the location of an external shear layer also induced by the fresh gas jet.
Fig. 5 (a) Profiles of $U_{\text{mean}}$ (black line) and $U_{\text{rms}}$ (gray line) for the vertical cut $x^* = 0.2$. (b) Profiles of $V_{\text{mean}}$ (black line) and $V_{\text{rms}}$ (gray line) for the vertical cut $x^* = 0.2$. These results are obtained using Region 1.

As a first step of the burner behavior analysis, the statistical data reported on Fig. 3, Fig. 4 and Fig. 5 permit to gain insight into the reactive flow structure and the flame front position. Nevertheless before going deeper in the study of the burner behavior, the coherence of experimental results has to be checked. In this objective, the experimental massflow rate is calculated using the vertical distribution of $U_{\text{mean}}$ and compared with the value given by the massflow controller.

### 3.2 Estimation of the injected flow rate

The fluid flow rate is estimated using the vertical distribution of $U_{\text{mean}}$ taken at the distance $x^* = 0.05$. The flow rate is calculated assuming that the flow is symmetric and using the following definition:

$$Q = \int \int_S u \cdot n \, dS$$  \hspace{1cm} (3)

where $u$ is the axial velocity vector, $S$ is the section of the annular jet that is delimited by the region of positive mean axial velocity.

For the present study, the imposed flow rate is $Q_{\text{th}} = 147 \text{ m}^3\text{h}^{-1}$, while the experimental flow rate calculated using PIV measurements is found to be $Q_{\text{exp}} = 141 \text{ m}^3\text{h}^{-1}$. The relative error between $Q_{\text{th}}$ and $Q_{\text{exp}}$, which is about 4 %, can be due to the precision of the mass flow meters, the precision of PIV measurements or the assumption of the flow axisymmetry. Nevertheless, the relative error is weak and experimental measurements seem consistent.

This estimation of the flow rate injected in the combustion device indicates that HFPIV measurements seems to give a good description of phenomena taking place on the combustion chamber in a quantitative point of view.

It is now possible to use HFPIV measurements to increase the understanding of the aerodynamical burner behavior. Indeed, the main characteristic of this diagnostic (its high acquisition rate) can be used to investigate the development of coherent structures in the combustion chamber and their interactions with the combustion process and the combustor acoustics. The temporal evolution of instantaneous velocity fields is described in the following sections.

### 4. Aerodynamical behavior of the burner

A natural choice to extract coherent structures from PIV measurements is to analyze instantaneous vorticity fields, whose peaks coincide with vortices. Instantaneous 2D vorticity fields are obtained by processing instantaneous velocity fields using the following definition:

$$\omega = \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}$$  \hspace{1cm} (4)
However vorticity is very sensitive to shear regions so that vorticity peaks do not necessarily correspond to a vortex center. In complex flow fields, vortices are often “masked” by regions of significant shear (Jeong and Hussain, 1995), making extremely difficult to use a vorticity map to identify coherent structures and to determine their contribution to the overall flow. New methodologies based on the analysis of the velocity gradient tensor have been developed during the last decades to differentiate the swirling motion of a vortex from pure shearing motion; see Kolar (2007) for a review.

In the following sections, one of these methodologies, the \( \lambda^2 \) criterion proposed by Jeong and Hussain (1995) is used to study the development of coherent structures in the combustion chamber. With this criterion, a vortex is defined in terms of eigenvalues of the tensor \( S^2 + \Omega^2 \), where \( S \) and \( \Omega \) are the symmetric and antisymmetric parts of the velocity gradient tensor \( \nabla \mathbf{u} \). As \( S^2 + \Omega^2 \) is a symmetric tensor, it has only real eigenvalues ordered as follow: \( \lambda_1 > \lambda_2 > \lambda_3 \). According to this criterion, a local minimum of \( \lambda^2 \) is associated with a local pressure minimum. Since this pressure minimum is usually met in vortex cores, the \( \lambda^2 \) criterion indicates the location of each vortex center, while the vortex diameter is defined by the zero contours of \( \lambda^2 \).

However, the calculation of a \( \lambda^2 \) field requires the velocity field and its variation in the three directions \((x, y, z)\). With 2D-PIV, only the two components of the velocity fields contained in the laser sheet plane and their variations in this plane are available. Assuming that the flow is locally two-dimensional, which is a strong assumption here, the following definition of the \( \lambda^2 \) criterion can be used (Anthoine et al., 2003; Schram et al., 2004):

\[
\lambda^2 = \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial x} \frac{\partial u}{\partial y} \right)
\]  

(5)

Based on this criterion and on the selectivity in space and scale of the wavelet transform of each instantaneous \( \lambda^2 \) field (Schram et al., 2004), a detection algorithm is developed to perform an analysis of each instantaneous velocity field. It provides the center of detected vortices and an estimation of their convection velocity components \((U_c; V_c)\), which are calculated by averaging the velocity vectors, contained in the structures.

To complete the aerodynamical burner behavior analysis, each PIV recording is post-processed to obtain the Power Spectral Density (PSD). In the present study, the velocity fields acquisition frequency is \( f = 12 \, \text{kHz} \), while the number of samples is \( N = 12000 \), giving a Shannon frequency of 6 kHz and a spectral resolution of 1 Hz.

4.1. Instantaneous flow fields

In order to illustrate the temporal evolution of the flow field vertical distribution in the whole combustion chamber, a succession of four velocity and associated vorticity fields are reported on Fig. 6. The fields, which correspond to Region 1, are taken on the vertical symmetry axis of the chamber \((y^* = 0)\). A time delay of \( \Delta t = 83 \mu \text{s} \) separates each field from the following one.

Figure 6 shows that the instantaneous velocity fields exhibit large deviations from the mean velocity field described in Fig. 3. Still, a large central backflow region, characterized by a negative velocity and a low vorticity level, and an annular conical jet remain clearly visible. The location of the boundary of the annular jet changes dramatically from one image to the others, illustrating that the flow is very turbulent. Maximum levels of vorticity coincide with the jet boundaries, i.e the places where the flow is characterized by a great shear rate. Finally, a well-formed structure is visible in the top part of the chamber at the point called \( A_0 \) \((x^* = 0.2; y^* = 0.4)\). The vortex center corresponds to a local maximum of \(|\omega|\). This structure is deformed and convected toward the right
end of the observation window as visible on the four other frames of Fig. 6

Fig. 6 Instantaneous velocity vector and associated vorticity fields for five successive recordings. On each frame, the injection area is drawn in black.

Figure 6 illustrates well that a vorticity peak can coincide with a coherent structure or a high shear rate region. This is why the detection algorithm described in the previous section is now used to analyze the development of vortices in the combustion chamber. In this case, the frame size is 512 pixel wide and 128 pixel high so that only phenomena taking place in the superior part of the combustion chamber ($0 < x^* < 1.6$ and $0.4 < y^* < 0.87$) are analyzed. A set of eight successive velocity fields colored by their associated $\lambda_2$ fields are reported on Fig. 7.

Fig. 7 Eight successive vector fields colored by the wavelet transform of the $\lambda_2$ field, normalized by the minimum negative value. The observation window called Region 2 is used. The injection area is drawn in black.
As expected, the $\lambda_2$ criterion is not sensitive to shear region and only vortices are visible. Thus $\lambda_2$ is a Gallilean invariant, so that small vortices, which are difficult to see directly on the vector fields due to the high levels of velocity encountered in the chamber, can be detected. Several peaks of $\lambda_2$, corresponding to vortices, are detected, and two structures are clearly visible on the first frame of Fig. 7. At the time $\Delta t = 0 \mu s$, a first structure is located in the mixing region between the annular conical jet and the central backflow region. The axial position of this vortex increases from the initial value of 0.26 to a final value of 0.68, while its radial position increases from an initial value of 0.4 to a final value of 0.69. Using the detection algorithm, the axial and radial velocity speeds of the structure, $U_c$ and $V_c$, are estimated. For $\Delta t < 332 \mu s$, $U_c$ is about 30 m.s$^{-1}$ while $V_c$ is about 15 m.s$^{-1}$, explaining the displacement of the structure towards the right end and superior part of the observation area. When $\Delta t > 332 \mu s$, the convection speed becomes negative: about $-8$ m.s$^{-1}$ for $U_c$ and about $-1$ m.s$^{-1}$ for $V_c$, explaining that the structure stays almost at the same position as it is visible on Fig. 7. At the time $\Delta t = 0 \mu s$, a second structure is detected in the external shear layer induced by the fresh gases jet at the location $C_0$ ($x^* = 0.34$; $y^* = 0.67$). The displacement of this vortex can be followed in three successive frames. It is convected toward the top part of the observation window, which is consistent with the estimated axial and radial convection speed components: $U_c \approx 35$ m.s$^{-1}$ and $V_c \approx 15$ m.s$^{-1}$.

### 4.3 Coherent structures frequency

The vortex frequency is an important parameter to better understand the effect of these vortices on the combustion process or the combustor acoustics. Two methods are used to determine the vortex frequency.

With the first one, the number of vortices that cross a square observation area 3 mm wide centered on the point of coordinates $B_0$ ($x^* = 0.5$; $y^* = 0.6$) is counted during a given time (1 second of physical time for the present study). For this analysis, a vortex is detected when $|\lambda_2|$ is higher than a given threshold value. The peaks of $|\lambda_2|$ detected with this method are plotted versus time on Fig. 8(a). This temporal analysis indicates that the vortex frequency is $f_0 \approx 330$ Hz (+/- 25 Hz).

![Fig. 8](attachment:image.png)

**Fig. 8** (a) Vortices detected within a square observation window centered on $B_0$ ($x^* = 0.5$; $y^* = 0.6$). The peaks of $|\lambda_2|$ are normalized by the maximum value. (b) Axial velocity PSD amplitude at $B_0$. (c) Radial velocity PSD amplitude at $B_0$.

With the second method, the power spectral density (PSD) of the instantaneous axial and radial velocities is calculated for each point of the velocity grid. The PSD amplitude of the two velocity components calculated at the point $B_0$ are plotted versus frequency on Fig. 8(b) and 8(c). The axial velocity PSD amplitude presents a strong peak at a frequency $f_u \approx 340$ Hz, while the main peak value of the $v$ spectrum is also observed at a frequency $f_v \approx 340$ Hz, even if this peak is less well marked. These values of $f_u$ and $f_v$ are consistent with the value of the vortex frequency $f_0$.

Finally, these aerodynamical frequencies have been compared with the frequency of combustion instabilities. Indeed with these operating conditions (table 1), strong combustion instabilities are observed within the burner at a frequency $f_{ac}$ of 336 Hz, that can be associated with the quarter
wave mode of the combustion chamber, estimated at about 320 Hz. This comparison indicates that two phenomena coexist in the combustor: the first one associated with the acoustic wave propagation and the second one related to vortex convection. For this regime, it seems that the two phenomena match and one can imagine a scenario in which the flame heat release rate is pulsed by strong aerodynamical structures, whose frequency is the same as the one of the quarter wave mode of the combustion chamber.

5 Concluding Remarks

The objective of the present work was to evaluate the efficiency of a High Frequency Particle Imaging Velocimetry operating at 12 kHz. Statistical quantities such as mean and RMS velocities are calculated to characterize the burner. The mean velocity field exhibit the feature of a swirling flow with a large recirculation area of hot products surrounded by an annular conical jet of unreacted gases. The mean velocity field is used to check the coherence of the velocity measurements, since they permit to calculate the flow rate entering in the combustion chamber. Comparing this experimental flow rate and the value given by the mass flow controllers, a difference of 4 % is found, which is very low error for such complex system.

The present work also shows that temporally resolved velocity fields are necessary thanks for a deeper understanding of turbulent swirled flames. For the present operating conditions, the analysis of instantaneous velocity fields indicates that vortices appear periodically within the combustion chamber. Their frequency is determined and compared with acoustic measurements, so that it can be related, for the present combustion regime, to the quarter wave mode of the combustion chamber.

To achieve high temporal resolution, it has been necessary to find a compromise between spatial and temporal resolutions, due to technical limitations of cameras at the present time. Nevertheless, the present work shows that the quite low spatial resolution is still high enough to characterize the flow and to detect large coherent structures. Increasing spatial resolution will be possible in a near future thanks to recent developments of high-speed cameras.

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