Experimental investigation of a spray swirled flame in gas turbine model combustor

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ABSTRACT

Dynamical processes in gas turbine combustors play a key role in flame stabilization. Those phenomena were investigated in a gas turbine model combustor for a partially premixed kerosene/air flame at atmospheric pressure. The large optical accesses of the combustion chamber enable the application of laser diagnostics. Stereo-PIV, Planar laser induced fluorescence (PLIF) of OH at 10 kHz and simultaneous particle image velocimetry (PIV) at 5 kHz have been implemented. The flow field was characterized by PIV in front view and stereo-PIV in a horizontal plane while the flame structure was visualized by OH-PLIF. Simultaneous OH-PLIF/PIV measurements were used to investigate the interactions between the flow field and the flame. POD and image processing tools were developed to analyze images. Temporal analysis of the results demonstrated the development of a local flame extinction mechanism.

1. Introduction

Since many years, air traffic is maintaining a strong growth trend, which is expected to last for the next few decades. The need arises to reduce noise, fuel consumption and pollutant emissions of future aeroengines. In this context, environmental concerns and legislative regulations are increasingly more stringent. The reduction of pollutants is then one of the driving forces in the development of modern gas turbines (GT). To further reduce pollutant emissions, the concept of lean premixed (LP) combustion was introduced and is considered as one of the best solution to significantly reduce NOx emissions (Correa, 1993) (Lefebvre, 1998). However, lowering emissions of NOx by reducing the flame temperature will compromise the flame stability and may lead to very weak conditions increasing drastically CO and HC emissions (Huang & Yang, 2009) (Lieuwen & Yang, 2005).

Interactions between flow field and sprays and flame play a key role in GT combustors. Often, in lean premixed gas turbines, it is common practice to stabilize flames by inducing a swirling flow. Because of the sudden expansion at the exit of the injector and the vortex breakdown, a recirculation zone is created (Gupta, et al., 1984). This recirculation zone transports hot products
to the root of the flame enhancing the local ignition and therefore the stability of the flame. Between the inflow and recirculation zones, shear layers allow the mixing between fresh and hot gases. It is of first importance to investigate and understand the unsteady phenomena and the complex interactions between turbulence and reactive chemistry for further studies on pollutant formation (NOx and CO).

Detailed studies have been conducted using laboratory scaled models of GT on CH4/air flames at atmospheric pressure using high-speed (kHz) repetition rate laser diagnostics measurements for studying flame shape and flow structure (Meier, et al., 2010) (Stopper, et al., 2013), the flame stabilization and ignition (Boxx, et al., 2013), flame-vortex interaction in CH4/air flames (Stöhr, et al., 2011) (Boxx, et al., 2012) (Stöhr, et al., 2012) (Oberleithner, et al., 2015), thermos-acoustic oscillations/flow field interactions (Boxx, et al., 2010), fuel/air mixing (Stöhr, et al., 2015) (Slabaugh, et al., 2015) and (Boxx, et al., 2015) examined the flame and the flow field structures in elevated pressure conditions.

To the knowledge of the authors, simultaneous high-speed OH-PLIF/PIV has never been applied to this industrial configuration using liquid kerosene fuel. The present work will be carried out on a GT model combustor at atmospheric pressure. The combustion chamber is equipped with a LP gas turbine injector supplied by TURBOMECA. This swirl injector is fueled with commercial Jet-A1.

The objective of the present study is to investigate the flow and flame structure, and their dynamical interactions. Large optical accesses of the combustion chamber allow the application of laser-based diagnostics. First mean flow field where measured in front view and top view using respectively PIV (5 kHz) and stereo-PIV (5Hz). The results enable us to understand the main flow structures inside the combustor. Then, simultaneous PIV and planar laser induced fluorescence of OH radical (OH-PLIF) were performed on our burner at multi-kHz repetition rates in a complex two-phase reactive flow field with high velocities. The global flame and flow structures were studied using averaged results whereas the flow and the flame interactions were investigated using simultaneous results. To take advantage of the acquired high-speed measurements post-processing tools were developed. Nonlinear filtering and active contour method based on a level set formulation were specifically used to extract flame contour from the OH-PLIF images. Coherent structures of the flow were visualized by the application of proper orthogonal decomposition (POD) on the velocity field. Mechanism of local extinction of the flame by vortices was highlighted with the temporal analysis of instantaneous measurement sequence.
2. Experiments
   a. Swirled Burner and Operating Conditions
   An overview of the experimental facility is given in Fig. 1. The burner is equipped with a TURBOMECA LP, industrial swirl injector. The combustion chamber consists in a 100 mm² square cross section and is 230 mm long, equipped with three large fused quartz optical accesses (80x200 mm²). The exhaust directly opens on the ambient air with a 56 mm in diameter nozzle, equipped with a gas sampling probe. The wall structure of the burner is cooled by water circulation.
   Several non-reacting and reacting conditions have been studied with this set-up but this current study focuses on a single test condition. The swirling kerosene/air flame that is investigated has a thermal power of 65.6 kW with an overall equivalence ratio $\phi = 0.7$ ($m_{\text{air}} = 30 \text{ g/s}$, $m_{\text{fuel}} = 1.417 \text{ g/s}$). All reacting conditions are running with commercial Jet A1 liquid fuel thus providing a realistic configuration. For seeding the flow, a part of the main inlet air is by-passed and is injected through a fluidized bed filled with ZrO₂ particles. The seeded air is injected in the plenum, and is mixed with the preheated air before the injection system. In order to meet closer operating conditions encountered in industrial GT, the air inlet is preheated so that the temperature of the air in the plenum reaches the target of 473K.

![Image of atmospheric swirled burner](image)

**Fig. 1:** Atmospheric swirled burner

b. Laser diagnostics
   i. Stereo-PIV at 5Hz
   The stereo-PIV system consists in a dual-cavity Q-switched Nd:YAG laser running at 5Hz providing two 532nm laser pulses delayed of 2µs in time. A horizontal laser sheet is formed using a spherical lens ($f=1000\text{mm}$) and two cylindrical lens ($f_1 = -20\text{mm}$, $f_2 = 500\text{mm}$), resulting in a 70mm in width laser sheet and 500 µm thick, to minimize particle drop out of volume
measurement that occurs due to high axial velocity. Mie scattering from solid zirconium oxide (ZrO$_2$) particles seeded into the flow and kerosene droplets are imaged using Dantec Dynamics FlowSense 4M cameras. To minimize the potential Mie scattering signal from kerosene droplets, the laser sheet is set 25mm above the burner where ZrO$_2$ particles and droplets have the same order of size. Cameras operate with a 2048x2048 pix$^2$ resolution, and are mounted with a Nikkor f/1.2 50mm lens. The collection systems are mounted with Scheimpflug adaptors between lenses and cameras as they are tilted with an angle of 35° (Fig. 2). A bandpass filter centered at 532 nm with a 10nm spectral width, is placed in front of the lens in order to suppress the flame emission (not represented on the schema). A calibration of the two cameras is required to compensate the perspective distortion and images are corrected (dewarping) before determining the velocity fields. Images are then post-processed using commercial software (Dynamics Studio, Dantec) with a multipass adaptive window cross-correlation leading to a final window size of 64x64 pixels and a 50% overlap. The three-components (U along x, V along y and W along z) of the velocity are determined in the (x, y) plane, at an axial distance of 25 mm above the burner (Fig. 2).

![Fig. 2: Schematic representation of the camera configuration for top view stereo-PIV](image)

### ii. High-Speed PIV and High-Speed OH-PLIF diagnostics

Spatial flame front location and associated instantaneous flow field are obtained from high-speed OH-PLIF at 10 kHz repetition rate combined with high-speed PIV at 5 kHz. The OH-PLIF system consists in a Nd-YAG-laser operating at 527 nm wavelength, generating pulses at 10 kHz repetition rate, with an average power of 105 W. The laser pumps a tunable dye laser (Sirah Credo with Rhodamine 590 solved in ethanol). At 10 kHz, the resultant output pulse energy is 350 µJ/pulse in the probe volume. The wavelength is tuned to the Q(t(5) line of the $A^2Σ^+ ← X^2Π(0,1)$ transition of OH ($\lambda = 282,675$nm). This wavelength is adjusted using the fluorescence signal emitted by a laminar CH$_4$/air flame. The laser beam is superimposed with the PIV beam, using a dichroic mirror and is expanded through a set of fused silica lenses ($f_1 =$...
1000 mm, \( f_2 = -20 \) mm, \( f_3 = 500 \) mm) to form a laser sheet of 50 mm in height (Fig. 3). Fluorescence signal is collected using an external image intensifier (High-Speed IRO, LaVision) mounted on a CMOS camera (Fastcam SA5) operating with a 896x848 pix² resolution. A B.HALLE UV lens (Nachfl. GmbH 100mm f/2) is mounted on a Scheimpflug system as the camera is tilted by 27.5° in configuration 1 (Fig. 4 Left) and 13.5° in configuration 2 (away from the laser sheet normal). Intensifier gate is set to 100 ns, with an intensifier gain set around 65, and background noise (especially elastic and Mie scattering) is reduced using a high-pass Schott WG295 filter and a bandpass Schott UG11 filter.

For high-speed PIV, the laser system consists in a double cavity Nd:YLF Laser, DarwinDual, Quantronix operating at 527nm, generating doubled pulses with a pulse energy of 6mJ/pulse. The Mie scattering signal from droplets and ZrO\(_2\) is collected with a Photron SA1.1 camera equipped with a Nikkor 80mm, f/1.4 operating at 10 kHz, with images (single frames) separated by 5\( \mu \)s in configuration 1 or 2.5 \( \mu \)s in configuration 2 (time between pulses) and with a 768x768 pix² resolution. A bandpass filter centered at 532nm is also placed behind the lens. The images are then imported and post-processed with Dynamics Studio software. A multipass adaptive window cross-correlation with a final window size of 16x16 pixels and a 50% overlap is applied. No filter is used on PIV results, only spurious vectors (in x and z component velocity) are suppressed.

**Fig. 3**: Schematic representation of the dual kHz measurement technique

### a. Pressure oscillations

Pressure fluctuations are recorded with a Kistler 7001 piezoelectric pressure sensor at 20 kHz to evaluate the stability of the flame. The pressure sensor is mounted on a waveguide system in the combustion chamber at 30mm above the injector.
Fig. 4: Collection system in configuration 1 (Left) and region of interest (ROI) in configuration 1 and 2 (Right).

<table>
<thead>
<tr>
<th></th>
<th>Acq. Rate</th>
<th>Resolution</th>
<th>Configuration</th>
<th>Magnification ratio</th>
<th>ROI (LxH)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OH-PLIF</strong></td>
<td>10 kHz</td>
<td>896x848 pix²</td>
<td>Conf. 1</td>
<td>0.0857 mm/pixel</td>
<td>76x50mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Conf. 2</td>
<td>0.0615 mm/pixel</td>
<td>50x30mm</td>
</tr>
<tr>
<td><strong>PIV</strong></td>
<td>5 kHz</td>
<td>768x768 pix²</td>
<td>Conf. 1</td>
<td>0.1100 mm/pixel</td>
<td>76x50mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Conf. 2</td>
<td>0.0794 mm/pixel</td>
<td>50x40mm</td>
</tr>
</tbody>
</table>

Table 1: Experimental characteristics of the kHz collection system

3. Image processing

The main objective of the current study is to investigate the flame/turbulence interactions. It is of particular interest to extract the flame front from OH concentration fields and coherent structures from velocity fields. To do this, image processing tools have been developed to automate the filtering process and flame front detection. Also, POD is applied on velocity fields to identify vortices in the flow.

a. Correction of the raw OH-PLIF images

The raw OH-PLIF images are first corrected to remove distortion produced by the lens and the effect of perspective. This procedure is performed using the commercial software Lavision Davis. In a second time, noise and spatial distribution of energy in the laser sheet is taken into account. For noise correction, acquisitions were realized without laser. To obtain the spatial energy distribution of the laser, the combustion chamber was filled with a homogeneous mixture of acetone vapor and air.
Fluorescence on the acetone vapor is carried out to obtain the energy profile of the laser sheet. Images were corrected using the following relation:

\[ I_{\text{corrected}} = \frac{I_{\text{raw}} - <I_{\text{noise}} >}{<I_{\text{acetone}} > - <I_{\text{noise}} >} \]  

(1)

Where \(<, >\) is the temporal averaging operator.

b. Nonlinear diffusion filter

A main difficulty in high-repetition rate OH-PLIF lies in the very limited energy per pulse (350µJ/pulse). Local maxima of OH concentration gradient are good markers of the flame front location. Because of noise features, the position of the flame front cannot be easily extracted from raw images. Corrected OH-PLIF images (Fig. 5-Left) need to be filtered before executing the contour detection routine. Also, high-speed diagnostics generate huge datasets. So, the computational time for the filtering procedure must be reasonable, and must be applied on the different images with fixed parameters.

Fig. 5: Corrected image (Left), Filtered image (Center), Intensity profile from corrected and filtered images (z=32mm) (Right)

In many cases, Gaussian filtering is applied on images. However, this type of filter has two drawbacks: blurring effect on the whole image including edges and delocalization of contours (Weickert, et al., 1998). To avoid those limitations, a non-linear diffusion filtering process is used in the current work. The nonlinear filter is applied on the corrected OH-PLIF images in order to improve the signal-to-noise ratio (SNR) while preserving edges. This approach presents the advantage to smooth the noise locally by diffusion flow while stopping diffusion flow at edges. As a result, flame contours are enhanced and physical gradients are sharpened. Hence, the detection of the boundaries is simplified. Previous studies already used nonlinear filtering on OH-PLIF images (Abu-Gharbieh, et al., 2001) (Malm, et al., 2000) (Boxx, et al., 2010). In this work, a new feature, the additive operator splitting (AOS) is implanted, compared to those previous works in order to reduce the computational time.
This method based on the work of (Perona & Malik, 1990) and (Catté, et al., 1992), consists in solving the following partial derivative equation (PDE):

\[
\frac{\partial u}{\partial t} = \text{div}(g(|\nabla u_\sigma|^2)\nabla u)
\]

\[ u_0 = u(x,y,t = 0) = I \tag{2} \]

The basic idea of this filtering procedure is to reduce the diffusivity at edges. Edges are detected by $|\nabla u_\sigma|^2$. A diffusivity function $g(|\nabla u_\sigma|^2)$ is introduced and its definition is based on the work of (Perona & Malik, 1990):

\[
g(|\nabla u_\sigma|^2) = \frac{1}{1 + \left(\frac{|\nabla u_\sigma|}{\lambda}\right)^2} \tag{3} \]

$u_\sigma$ is a Gaussian smoothed version of $u$, where $\sigma$ is the standard deviation of the Gaussian kernel used for the convolution. The aim of this Gaussian smoothing is a spatial regularization of the PDE solving procedure (Catté, et al., 1992). Spatial regularization guarantees that the solution converges to a constant steady-state. Also, spatial regularization makes the filter insensitive to noise at scales smaller than $\sigma$ (Weickert, 1998). The parameter $\lambda$ is called the contrast parameter. Lower gradient intensity values than $\lambda$ are diffused.

The numerical implantation of this filter requires a discretization of the previous PDE (eq.2) and solves it using an iterative process. The simplest approach is based on explicit scheme, but for stability reason, this method is severely restricted to very small time steps. The introduction of a semi-implicit scheme would be a good alternative.

In matrix notation, the discretized PDE can be re-written as follow:

\[
\frac{u^{t+1} - u^t}{\Delta t} = \mathcal{A}(u^t)u^{t+1} \tag{4}
\]

Where $\mathcal{A}(u^t)$ is a matrix defined as:

\[
\mathcal{A}(u^t) = \begin{bmatrix} a_{i,j}(u^t) \end{bmatrix}
\]

\[
with \ a_{i,j}(u^t) = \begin{cases} 
\frac{g_i^t + g_j^t}{2} & j \in \mathcal{N}(i) \\
-\sum_{n \in \mathcal{N}(i)} \frac{g_i^t + g_j^t}{2} & j = i \\
0 & \text{otherwise}
\end{cases} \tag{5}
\]

A reformulation of the (eq.4) gives:

\[
u^{t+1} = (I - \Delta t \mathcal{A}(u^t))^{-1} u^t \tag{6}
\]

$u^{t+1}$ can be solved directly but this method is computationally inefficient because of the numerous linear system of equations to solve. Considering an image of size $M \times N$, the linear
system to solve would have a size \((M \times N) \times (M \times N)\). A solution to this issue is the AOS (additive operator splitting) method proposed by (Weickert, et al., 1998)

\[
 u_{i}^{t+1} = \left( I_d - \Delta t \sum_{l \in \{x, y\}} A_l(u^t) \right)^{-1} u^t
\]  

Finally, \(u_{i}^{t+1}\) can be calculated by solving two linear systems of \(M \times N\) equations. Using semi-implicit scheme with AOS, the computational cost is increased, compared to the explicit scheme but time steps are no more limited. Thus, the global computation time is reduced.

A filtered OH-PLIF image can be observed in Fig. 5-Center. The effect of the nonlinear filter can clearly been seen on Fig. 5-Right. For comparison purposes, profiles of pixel intensities at \(z=32\) mm are extracted from the corrected and the filtered images, and then are plotted on the same chart. The parameter \(\lambda\) is chosen in order to smooth noise in the low intensity regions while it preserves high gradients of the image corresponding to the flame front. In the luminous regions (high concentration of OH radical), the noise is less smoothed but this is not an issue for flame detection.

c. Flame front detection

After the filtering process on the corrected images, a contour detection procedure is applied. Classical approaches to extract the position of the flame front position are based on the magnitude of gradients. Images are previously filtered, and in spite of that, classical procedure found in literature failed to define the flame front location.

In medical studies, researchers are often faced with the challenge to segment noisy images in order to identify blood vessel, tumor... An emerging solution concerning the segmentation of medical images especially medical resonance images (MRI) is active contour based on level-set method. In this work, active contours using level set method are used to extract the position of the flame front.

The basic idea of active contour is to initiate a first curve around the object to be detected; this curve moves towards to its interior normal and has to stop on the boundary object. The initial curve \(C_0\) is represented implicitly within a higher dimension function. Usually \(C_0\) is embedded as the zero level set of a function \(\phi(x)\) by using the signed distance function. In the interior region \(\phi(x) < 0\), and outside \(\phi(x) > 0\). A PDE is governing the time evolution of the function \(\phi\) and at each time the zero level set of this function gives the contour. The PDE to solve depends on the chosen active contour model.

The method used in our work is a geodesic region-based level set segmentation method. In geodesic active contour (GAC) introduced by (Caselles, et al., 1995), the basic idea is to start with
a curve around the object to be detected, the curves move towards to its interior normal and has to stop on the boundary object. Image gradients are used to construct an edge stopping function to keep the contour evolution within the boundary. The Chan-Vese region-based level set model (Chan & Vese, 2001), assumes two different homogeneous regions to be partitioned. (Rousson & Deriche, 2002) proposed a modification of the energy functional to take into account second order variation. Then, regions are characterized by statistical properties such as mean and standard deviation.

The image segmentation is based on the minimization of a variational functional. To minimize the problem, the level set $\phi(x)$ is introduced and the resolution is done by taking the Euler-Lagrange equations and update the level set function $\phi(x)$ by the gradient descent method. The final evolution equation for the level set function $\phi(x)$ is given by:

$$\frac{\partial \phi}{\partial t} = \nabla \cdot ( \nabla \phi ) + \log \left( \frac{\sigma_1^2}{\sigma_2^2} \right) - \frac{(I(x) - \mu_1)^2}{\sigma_1^2} + \frac{(I(x) - \mu_2)^2}{\sigma_2^2}$$

(8)

Where $v$ is weight factor. The subscripts 1 and 2 correspond to the interior and exterior region. The means $\mu_{1,2}$ and standard deviations $\sigma_{1,2}$ are updated while the level set is evolving. The PDE is evaluated numerically on the whole image domain. The first term of the right handed side of (eq.8) is numerically resolved semi-implicitly using the AOS method described previously.

On the Fig. 6-c and Fig. 6-d, an application of the level set method is illustrated. The blue circles correspond to the initial contours. Those contours evolve to create the final contour (red). The level set method is compared to the Otsu’s method for the flame front extraction (Fig. 6(b)). This second method fails to locate with accuracy the flame front. Locally, on OH-PLIF images, it is possible to find very close gray levels in the recirculating burned gases and fresh gases. It induces wrong flame front detection. Methods based on the gradient of the image are not presented in this paper but they also go wrong with the flame front detection. In fact, the flame contour is represented by high gradient magnitude but it is difficult to extract this information because of high gradients produced by noise. In the best case scenario, flame front can be extracted but with substantial discontinuities. Nonetheless, the level set method is an attractive alternative to cope with problems mentioned below. This method detects the flame contour with a better accuracy than the previous method. On the Fig. 6-d, the contour proposed seems to be in accordance with expected flame front boundary. The presented level set method is designed to be more robust to deal with spatial non-uniformity, weak boundaries and complex flame topology on OH-PLIF images and without any modification.
d. Proper Orthogonal Decomposition

The proper orthogonal decomposition (POD) was first introduced in the context of fluid mechanics by (Lumley, 1967). The POD is a statistical tool used for the identification and the extraction of coherent structures in flows. The POD is a method which gives a better understanding of turbulent flows. The POD consists in determining a set of basis of linear functions, the so-called proper orthogonal modes which optimally represent the fluctuating part of the velocity in terms of energy. Details about the POD can be found in the review by (Berkooz, et al., 1993). The present proper orthogonal decomposition presented here is based on the snapshot method introduced by (Sirovich, 1987).

Let's consider a dataset of \( N \) velocity vector fields \( \overline{u}_i(\overline{x}_k) \) \((i = 1, \ldots, N)\) measured at \( M \) positions \( \overline{x}_k \) \((k = 1, \ldots, M)\). Velocity vector fields are first decomposed (Reynolds decomposition) into an average and a fluctuating part. The analysis will only consider the fluctuating parts of the velocity components. The mean velocity field can be considered as the 0-th mode of the POD.

\( u \) and \( v \) are denoted as the fluctuating part of the two velocity components measured and need to be rearranged in a single array as follow:
The autocovariance matrix is created as:

\[
\tilde{C} = U^T U
\]  

(9)

Then, the following Eigen mode problem has to be solved:

\[
\tilde{C}A^i = \lambda^i A^i, \quad \lambda^1 > \lambda^2 > \ldots > \lambda^N
\]  

(10)

Where \( A^i \) and \( \lambda^i \) are respectively the eigenvector and the eigenvalue of the i-th mode.

The eigenvectors are used to calculate the normalized POD modes \( \phi^i \):

\[
\phi^i = \frac{\sum_{n=1}^{N} A^n_i u^n}{\|\sum_{n=1}^{N} A^n_i u^n\|}
\]  

(11)

And the time-dependent coefficients for each mode are determined using:

\[
a^i = \phi^i u^n
\]  

(12)

Reconstruction of the snapshots using N modes can be done by applying:

\[
u^n = \bar{u}_i + \sum_{i=1}^{N} a^n_i \phi^i
\]  

(13)

4. Results and discussion

In the following section, all the results presented have been measured at atmospheric pressure with a 30g/s air flow rate preheated at 473K and with an overall equivalent ratio \( \phi = 0.7 \). The burner operates on stable conditions.

4.a. Aerodynamic of the burner (averaged flow field)

For a better understanding of aerodynamics and to calculate statistical converged values, kHz PIV measurements have been used. Indeed, due to windows fouling induced by solid ZrO2 particles in reactive case, the time available to perform the measurements is only few seconds. High-Speed PIV enable to obtain quickly large amount of data in a focused zone of interest (configuration 1). The large number of velocity fields enables to obtain converged physical quantities. Main flow structures can be identified from the mean velocity streamlines in front view (Fig. 7-Top, Right) and are typical averaged flow field of enclosed swirl burners (Meier, et al., 2010). The unburned air and fuel mixture enters from the nozzle of the injector with a cone shape. The magnitude of axial velocity is important in this zone and can exceed the 150m/s. A
large inner recirculation zone (IRZ) is developing caused by the induced-swirl vortex breakdown. Furthermore, an outer recirculation zone (ORZ) is created due to the sharp change of cross section between the nozzle and the chamber. Two shear layers of high strain rates are formed between the inflow and the IRZ/ORZ, namely the inner shear layer (ISL) and outer shear layer (OSL). Those zones are characterized by strong velocity fluctuations and highly turbulent structures as shown by the instantaneous flow field (Fig. 7- Left). A schematic representation of the averaged flow field in the combustion chamber under reactive conditions is presented by Fig. 8.

![Diagram](image)

**Fig. 7: Top:** (Left) Instantaneous velocity flow field colored by axial velocity (1 vector over two is plotted), (Right) Streamline of the mean flow field colored by norm of velocity. **Bottom:** (Left) Mean Vorticity; (Right) Mean Turbulent Kinetic Energy

The flow field has been also investigated in top view by using stereo-PIV with horizontal laser sheet. Both non-reactive and reactive flows have been explored. In (Fig. 9), results in reactive conditions are presented. Results show that a small asymmetry of the flow field exists. This behavior can be explained by the fact that the injection system is a complex industrial device and a small defect in the centering of the injector can induce large effects on the resulting flow field. Good agreement between the classical PIV in vertical plane and the stereoscopic-PIV have been
demonstrated in the horizontal plane at $z = 25$ mm above the burner. According to the top view measurements, this flow can be defined as a medium swirl flow with large magnitude of tangential and radial component velocity.

![Fig. 8: Schematic representation of the aerodynamic in the burner](image)

Unsteady structures are not showed up in the mean field. These structures can be investigated applying Proper Orthogonal Decomposition (POD) on instantaneous velocity field as a method to identify dynamical structures. POD is a useful tool in turbulence analysis that extracts information via a statistical analysis of the set of velocity field. In our case, 3750 velocity fields are used to conduct the POD analysis. It enables to investigate large scale structure in turbulent flow. This analysis is applied on the flow field measured in a focused region of interest, centered on the left jet (configuration 2) since the behavior of the flame is symmetric. The corresponding contribution of POD modes to the total fluctuating kinetic energy are shown in Fig. 10-Left. One can observe that the contribution of the most energetic modes is quite low and decrease slowly. This result is also confirmed by applying spectral analysis on the pressure signal in the combustion chamber. As shown by Fig. 10-Right, the Power Spectral Density (PSD) is spread around some range of frequencies but no single value is predominant preventing from applying phase averaging. This behavior can be explain by the fact that the analysis is performed on a stable operating point representative of standard conditions of use of this injection system.
In this study, POD reconstruction is used to reproduce experimental flow fields. This enables to identify large coherent structures that cannot be clearly observed on direct experimental results. POD reconstruction can be seen as a filter removing small fluctuations and keeping only the most energetic vortices. Flow field reconstruction with the 20 first modes enables to reproduce the main behavior of the stream as they contain 60% of the fluctuating kinetic energy. As shown in Fig. 11, reconstructed POD flow field are representative of experimental instantaneous flow field (only 1 vector over two is plotted for better readability).

Unfortunately, coherent structure cannot be temporally followed in such flows at a recording rate of 5 kHz. Indeed, integral length scale is found to be about 3.6 mm in the ISL and 3.2 mm in the jet zone at z = 25mm where mean axial velocity is around 60 m/s in the ISL and 80m/s in the fresh gases inflow. Between two snapshots, the order of magnitude of displacement is around 10mm in both zones, which is three times larger than the integral length scale. As shown by the time sequence of POD reconstructed snapshot presented in Fig. 11, it is complex to follow automatically any coherent structure.
Fig. 11: (Top) Instantaneous axial velocity, (Bottom) Instantaneous vorticity, (Left) measured flow field, (Right) POD reconstruction. (1 arrow over 2 is plotted).

Fig. 12: Five consecutive POD snapshots time-spaced by 200µs colored by vorticity.

a. Flame structure
Flame structure along the all cross section of the burner, at \( z = 25\text{mm} \) have been studied using OH-PLIF in configuration 1. As mentioned in section 3.a, OH-PLIF images are corrected by laser sheet profile deduced from the data processing of 1000 images of acetone fluorescence. An instantaneous corrected image is shown on Fig. 13-Left, and enables to distinguish three separated zones. The black region corresponds to the jet zone where fresh gases composed of air and kerosene vapors and droplets are mixed. The reaction zone is located between fresh gas and
regions with high-level of OH* (white zone), where gradient of luminosity is important. This zone is located from either side of the jet. A third zone composed of OH at equilibrium, previously formed in the reaction zone, is also present in the IRZ and ORZ, due to the burned gas recirculation (gray to white level, with low gradient). Fig. 13-Right presents the mean flame with an M shape for the investigated operating point, and point out those three main zones.

When comparing average OH-PLIF images and the averaged velocity flow field (Fig. 14), one can observe that the peak of OH concentration is located between the inflow and the inner/outer recirculation zone. As matter of fact, this region presents high turbulent kinetic energy and good mixing between burned and fresh gases occurs, promoting ignition and flame stabilization.

**Fig. 13:** (Left) Instantaneous flame shape by OH-PLIF images, (Right) Mean OH-PLIF image

**Fig. 14:** Superposition of mean OH-PLIF and mean flow field streamline (colored by TKE).

b. **Flame and aerodynamic interactions**

In order to give a better understanding of the flame/aerodynamics interactions, instantaneous OH-PLIF images and velocity fields are superimposed. In the present configuration, it is difficult
to follow temporally flame roll-up or local extinction. Indeed, successive OH-PLIF images are often uncorrelated due to the important out of plane velocity component and relatively low repetition rate of OH-PLIF laser compared to the order of magnitude of velocity in the jet zone. However, for some time-series of images, it is possible to follow the temporal evolution of the flame front and the analysis of those images can reveal isolated phenomenon. The following analysis focuses on the left side of the fresh gases jet (ROI 2) and point out a flame splitting with the release of a large pocket of unburned gases. Fig. 15 presents OH-PLIF time-series images with the flame contour and are overlaid with PIV field colored by axial velocity. Fig. 16 (left) shows the interaction between flame structure and vortices by using POD reconstruction on the experimental flow field. Influence of the strain rate of the velocity field on the flame is also presented by Fig. 16 (right).

![Fig. 15: OH-PLIF time series images overlaid with velocity field colored by axial velocity. Red lines: contour of the flame](image)

The analysis of the flame extinction starts at the reference time $t = 0$ ms which correspond to the beginnings of the observed phenomenon. This event is initiated by an intense release of kerosene droplets observed on PIV seeding images (not shown). Due to the dramatic velocity of the fresh
gas jet, a pressure drop is located in this zone and two opposite vortices are formed from either side of the jet. Those vortices bring hot burned gases and ignite the root of the fresh gas jet (t = 0.1 ms) as shown by the raise of OH signal on the right side. Flow field recorded at t = 0.2 ms shows that the two counter-rotating vortices have migrated upstream. Flame continues to roll-up in those zones where good mixing between fresh and burned gases occurs. In the meantime, the top part of the fresh gas jet starts to be isolated. Indeed, important strain rate is located between the two main zones of fresh gas, between the two vortices. Generally, high strain-rate is located around the flame front where there is a rapid expansion of gases through the flame front but in this case, it is located among the inflow. This seems to predict that the jet will split. Finally, at t = 0.3 ms, a large pocket of unburned gases is released at the top of the image (not perfectly detected) whereas the remaining fresh gases continues to burn quickly as shown by the large quantities of OH in a vortex on the right.

**Fig. 16: (Left)** Streamlines of POD reconstructed velocity fields colored by vorticity and **(Right)** Strain rate of experimental PIV measurements. Red lines represent the contour of the flame.
This kind of events can be observed at various moments in both configurations and follows each time the same mechanism. The various steps occurring in the flame splitting are summarized by Fig. 17. This behavior of the flame is suspected to be responsible of some pollutant releases at the outlet of the combustor.

High-speed OH-PLIF has also been applied at the nozzle exit to study important flame/droplets interactions. However, successive images are completely uncorrelated and spatial resolution is strongly affected by droplets which prohibit flame front detection and comprehension, despite robust post-processing and optical filtering to remove Mie scattering. Under the stable operating point studying in the current study, no PVC has been detected. PIV could not be applied at the exit of the burner because intense Mie scattering signals from kerosene droplets hide ZrO₂ particle signals. Nevertheless flame/droplets interaction at the nozzle exit should be taking into account in the analysis of this type of injector system since the disparity of droplet release seems to affect combustion dynamic and efficiency. Future studies should focus on this interaction, coupled to pollutant measurements in order to determine physical mechanisms responsible of pollutant formation.

5. Conclusion and prospects
A gas turbine model combustor equipped with an innovative industrial LP injection system, supplied by liquid kerosene has been investigated using non-intrusive laser based measurement. First, interactions between flame and aerodynamics of the burner under stable operating
conditions have been studied by “classical” PIV and OH-PLIF diagnostics. The M-shape of the flame and the aerodynamics in the chamber are typical of enclosed swirl flames. The generation of large inner recirculation zones and good mixing between fresh and burned gases in the inner shear layers enable to ignite and stabilize the flame in those regions.

In a second part, high-speed PIV coupled to high-speed OH-PLIF measurements were implemented in a focused region of interest to investigate instantaneous flame/turbulence interactions. To extract instantaneous and statistical values from high-speed measurements, efficient post-processing methods were developed like flame front extraction using nonlinear filtering and level set method segmentation or POD analysis on velocity flow field. POD of the velocity fields shows that in stable operating conditions, no modes are predominant. We also observed that PIV and OH-PLIF measurements, in most of cases, are not temporally resolved at 10 kHz. But time-series images can be isolated and some events such as flame extinction or inhomogeneous combustion can be analyzed. In the current study, the origin of a local extinction, resulting in a large release of unburned reactant was analyzed. An inhomogeneous release of droplets, turbulence and their interaction with the flame govern this phenomenon.

Future measurements will be based on standard low-speed measurement like OH-PLIF, NO-PLIF and CO-PLIF at 10Hz. The aim of the future work will be to correlate flame front, and pollutant formation.

Effect of pressure will also be analyzed using a new high-pressure optical combustor facility to meet more realistic aeronautical operating conditions.

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7. References


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