Time-resolved PIV measurements applied to a non-reactive dodecane-air mixture in a two-staged multi-injection burner

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Abstract

Lean premixed prevaporized burners seem good candidates to reduce pollutant emissions from gas turbines. Indeed, lean combustion regimes result in lower temperatures and therefore a reduction on the NOx emissions, major pollutant species. However, these burners are very sensitive to combustion instabilities (flashback, flame extinction or pressure oscillations). To face this problem, multi-injection staged combustion is envisaged first to keep the good fuel-air mixture and second to control the fuel distribution. To fully understand the flame's behavior while using a two-phase flow, it is necessary to characterize the non-reactive flow at the same operating conditions in order to detect any instability. Time-resolved Particle Image Velocimetry will be used to characterize the droplet dynamics and the effect of fuel distribution on the resulting spray.

1. Introduction

Because of environmental concerns, permissible pollutant emissions of gas turbine plant or aircraft engines have decreased significantly in recent years (Correa [1998]). Combustion in gas turbines was traditionally based on diffusion flames because of their stability. Unfortunately this type of combustion leads to an important production of large quantities of pollutant emissions (NOx, CO, etc...). In order to face this problem, Lean Premixed Prevaporized combustors have been designed to control the pollutant emissions (Ticina [1990], Lefebvre [1995] or Moore [1996]). This concept consists in providing a uniform mixture of fuel and air that burns at lower temperature than diffusion flame, reducing thermal NOx emissions. However, it has been shown that reducing the NOx emissions often results in a higher production of CO. In addition, gas turbines operating in lean conditions often present combustion instabilities such as flashback, self-ignition and blowout (Lieuwen and Yang [2006]). Indeed the coupling of heat release and pressure oscillations in the combustor may produce self-excited oscillations of such amplitude that they cause damages to the combustor (Candel [2002], Nauert et al. [2007], Lefebvre [1999]). Ducruix et al. [2003] have also shown that these acoustic resonance phenomena tend to develop more easily in well-mixed combustion systems such as the LPP. To overcome those problems, secondary fuel injection has been proposed, for which a small amount of fuel is injected as a pilot. This secondary injection can also be modulated so as to reduce coupling between heat release and pressure (Tachibana et al. [2007]) while keeping reduced NOx emissions.

Multi-injection staged injectors used for fuel injection are now considered as potential candidates for real engine operations. However, the study of their dynamics is still required to prevent any potential instability and to optimize spatial distribution. A study of a multi-injection system, at a lab scale, using a gaseous fuel (Barbosa et al. [2009]) has shown that depending on the relative distribution of fuel, combustion instabilities can be encountered.

The present research concerns the study of a similar multi-injection system but using liquid fuel in order to get closer to deal with two-phase flow physics. The use of a liquid fuel adds new parameters such as droplets size and evaporation that can influence the combustion process. Indeed, Batarseh et al. [2009] showed that depending on the atomizer used for fuel injection, fluctuations of the spray could be encountered in the resulting spray. These fluctuations cause a self-induced
modulation of the spray's shape and velocity at a given frequency.  
This paper focuses on the characterization of the non-reactive two-phase flow in a lab scale injector and dynamics of droplets will be discussed using time-resolved particle image velocimetry in transverse plans and Mie scattering analyses. In the second section, the setup used is described. Third section deals with measurement techniques and averaged quantities whereas fourth section is devoted to the study of the dynamics inside the combustor.

2. Experimental Setup

2.1 Injector

A multi-injection staged injector is designed and placed inside a plenum where air and dodecane are injected. The injector is composed of two stages where air and fuel may be both used. The first stage, called the ‘Pilot stage’ is made from a pressurized nozzle for fuel and a swirler for air injection. The pressurized nozzle generates a solid cone and fuel can be injected at a maximum rate of 6.3 liters per hour (its flow number is equal to 1.4 l/h/bar⁻⁰.⁵). The swirler is composed of 18 vanes and it is geometrically designed so that 20% of the global air rate is injected through this stage. The second stage, called the ‘Takeoff stage’, is composed of a multi-injection system and a swirler for fuel and air injection respectively. The multi-injection system is composed of 10 equally spaced holes (0.3 mm in diameter). The swirler is composed of 20 vanes and its geometry has been designed so that 80% of the global air rate is injected through this stage. Both swirlers are co-rotating and designed so that the swirl number S is close to 1. A schematic view of the injector is shown in Figure 1(a) and 1(b). In order to have a good atomization of the liquid fuel, air is preheated at 473 K when fuel is injected through the Pilot stage only, and at 453 K, when fuel is injected partially or totally through the Takeoff stage, to avoid an early evaporation in the feeding lines.

The main feature of this type of injector is the fuel distribution. Therefore, to define the relative amount of fuel injected through the Pilot stage, a staging parameter \( \alpha \) is defined as:

\[
\alpha = \frac{m_{fuel, pilot}}{m_{fuel, global}} \times 100
\]

Its value will be zero in case all fuel flows through the multiple injection system and 100% for all fuel injected through the pressurized nozzle.
2.2 Diagnostics

A High Speed Particle Image Velocimetry (HSPIV) system is used to measure velocity fields in the combustion chamber (150x150x500 mm). A schematic view of the HSPIV system is shown in Figure 2.

The laser sheet is generated by a system consisting of two Nd:YAG lasers (Quantronix). Both lasers emit a pulse at a wavelength of 532 nm with energy of 5 mJ and a temporal width of 120 ns. An optical system (Melles Griot) is used to convert the laser beam into a planar light sheet 100 mm wide and 1 mm thick. Both sides of the combustion chamber contain rectangular silica windows allowing the laser sheet to cross horizontally the chamber, transverse to the non-reactive flow. A mechanical table is used to translate the laser sheet through the chamber, as well as the camera to keep images focused.

A fast speed camera (Photron Fastcam, 1024 x 1024 pixels at a rate of 6000 frames per second) equipped with a 105 mm F/2.8 Nikon Nikkor objective is placed at 90° from the laser sheet. The two lasers work at half of the camera's acquisition frequency and are synchronized by a pulse delay generator (BNC 555 pulse/delay Generator) as shown in Figure 3. The study is carried out for 3
different positions in the combustion chamber. As getting further away from the injector's exit, a bigger size of the camera picture is needed to capture all the spray so a reduction in the acquisition frequency is used, as shown on Table 1. No additional particles will be used to seed the flow, as we are only interested here by the two-phase flow velocities. The optimal time delay between two pulses has been estimated at $\delta t = 15 \, \mu s$.

![Figure 3 – Time diagram for the time-resolved PIV.](image)

<table>
<thead>
<tr>
<th>Sheet position d</th>
<th>0.2D</th>
<th>0.3D</th>
<th>0.6D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image size (pixels)</td>
<td>512 x 472</td>
<td>512 x 472</td>
<td>704 x 584</td>
</tr>
<tr>
<td>Cam. pitch (mm/pixel)</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Frame rate (kHz)</td>
<td>20</td>
<td>20</td>
<td>17.5</td>
</tr>
<tr>
<td>Nb. of raw images</td>
<td>11843</td>
<td>11843</td>
<td>9831</td>
</tr>
<tr>
<td>Initial window size</td>
<td>128 x 128</td>
<td>128 x 128</td>
<td>128 x 128</td>
</tr>
<tr>
<td>Final window size</td>
<td>32 x 32</td>
<td>32 x 32</td>
<td>32 x 32</td>
</tr>
<tr>
<td>Overlap</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>

**Table 1** - PIV acquisition and processing parameters. The sheet position $d$ corresponds to the distance to the injector’s exit and D is the outer diameter of the injector.

### 2.3 Operating conditions

The following table summarizes the operating conditions where HSPIV is tested.

<table>
<thead>
<tr>
<th>$m_{\text{air}}$ (g s$^{-1}$)</th>
<th>$m_{\text{fuel,global}}$ (g s$^{-1}$)</th>
<th>$T_{\text{air}}$ (K)</th>
<th>$T_{\text{fuel}}$ (K)</th>
<th>$\alpha$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>1.3</td>
<td>473</td>
<td>298</td>
<td>100</td>
</tr>
<tr>
<td>28</td>
<td>1.3</td>
<td>453</td>
<td>298</td>
<td>40 to 60</td>
</tr>
</tbody>
</table>

**Table 2** – Operating conditions for the PIV measurements
3. Results

3.1 Post-processing

As described in the previous section, for each experiment, a continuous acquisition of \( N \) raw images has been performed corresponding to a physical time of 0.5 seconds (\( N \) depends on the laser sheet position). From these raw images, \( N/2 \) image pairs are processed to determine the mean velocity components \( u \) and \( v \), using Dantec's software Dynamic Studio. In addition to the processing parameters defined on Table 1, two validation routines have been used to perform data analysis:

- **Peak-height validation** validates or rejects individual vectors based on the value of the peak height in the correlation plane where the vector displacement is measured. This method computes the ratio of the highest validation to the second one and rejects the vectors if the value is less than the detectability criterion \( k \). Keane and Adrian [1992] have shown that 1.2 can be considered as a good value for \( k \). When the vector is rejected, it is replaced by a new one using the moving average method, which calculates the average of the vectors in a rectangular neighborhood.

- **Velocity range validation** rejects vectors that are outside a certain range of velocities in the flow. An estimation of the velocity magnitude is done by analyzing its temporal evolution at different zones of the spray. The maximum value is chosen as a threshold value for the velocity range validation.

Figure 4 shows an example of the resulting mean velocity magnitude field and the mean Mie scattering intensity.

![Figure 4 - Mean velocity magnitude (left) and mean droplet intensity (right), for \( \alpha=100\% \) and \( d=0.2D \).](image)

3.2 Average analysis of the spray

In order to analyze the mean behavior of the spray, the evolution of the mean velocity component \( u \) and the mean droplet's Mie scattering intensity along the vertical axis (Figure 4) are plotted and reported on Figure 5. The mean intensity profile has been computed in 32 \( \times \) 32 windows identical to the ones used in the PIV processing and normalized by its maximum value for each staging parameter \( \alpha \). As the spray shows an average symmetry, only half of the axis is plotted for the Mie scattering profiles.
Figure 5 - Mean velocity component $u$ (left) and mean Mie scattering intensity (right), for four staging values and three transverse plans.
These results show a common global shape of the spray. Even though the nozzle used for fuel injection in the Pilot stage generates a solid cone, the resulting spray is a hollow cone. This shape is the result of the inner and outer recirculation zones (IRZ and ORZ) present in the combustion chamber (Gupta et al. [1984]). This is why profiles show lower velocities at the center and at the spray's periphery. From the mean Mie scattering profiles, one can see that the IRZ and ORZ tend to confine the droplets into one specific region, where profiles show an increase in both droplet's velocity and intensity. This clearly shows that most of the fuel is concentrated in one region only. In addition, the shape of the spray is influenced by the staging factor α, mostly visible when going from one stage injection to two-stage injection. When α=100%, more droplets are encountered in the IRZ near the injector's exit as the Pilot stage generates a central solid cone injection. When the Takeoff stage is used, as less fuel is injected through the Pilot stage, less droplets are encountered in the IRZ. In addition, reducing the amount of fuel through the Pilot stage causes a reduction in the droplet's injection velocity and lower u velocities are encountered. Even though profiles show a null velocity at the center of the spray, droplets do show a slightly asymmetric behavior in both sides of the spray. For example, for y=-0.8D and d=0.6D, droplets present a velocity close to 0 while for y=0.8D, velocities are close to -5 m/s. This particular behavior has not been explained yet, and to do so, more information on the aerodynamics and the droplets (diameter) is needed.

Due to evaporation and thus lower diameters, far from the injector's exit, u velocity profiles show faster droplets for all staging values. As for the fuel distribution, the Mie profiles show a global expansion of the spray, with a faster expansion for the lower staging values. Figure 6 shows the evolution of the thickness of the spray along the chamber for all staging values. This thickness has been computed using the Mie profiles and using the full width half maximum as a threshold for the spray's detection.

Figure 6 - Evolution of the spray's thickness along the chamber. $\varepsilon^* = \varepsilon/D$ where $\varepsilon$ is the real thickness of the spray.
3.3 Temporal analysis of the spray

Frequency analysis

For this analysis, velocity vector $u$ has been decomposed in radial and tangential components, $u_r$ and $u_t$, and a frequency analysis has been carried out in two regions of the spray (A and C) as shown in Figure 7(a). Both instantaneous velocity fields and Mie scattering images have been used for this analysis. For the Mie images, the analysis has been done in a 32 x 32 window with a 50% overlap corresponding exactly to the one chosen for the instantaneous velocity field calculation so that they could be compared. Figure 7(b) shows the power spectral density of the intensity and the velocity component $u_r$ at the region A for $\alpha=100\%$ and at $d=0.2D$.

Results show a peak at 1520 Hz and the same analysis has been done for the other values of $\alpha$ and a peak at 1420 Hz is found for all the three values (Figure 8). The same peaks were encountered at $d=0.3D$, however at $d=0.6D$, no peak was found. These results show the presence of a three-dimensional structure such as the Precessing Vortex Core (PVC), often encountered in swirling flows (Syred [2006]). In addition, as it was shown in the mean behavior analysis, decreasing the staging value $\alpha$ results in an expansion of the spray and thus an augmentation of its mean radius, which can explain the decrease in the frequency value. This decrease can also be related to the change in air preheating temperature for the two operating conditions defined on Table 2.
Phase-Locked analysis

From the previous results, a phase-locked method has been computed to find the spray's mean phase behavior at \( d=0.2\text{D} \). The phase-locked average fields were reconstructed every \( 45^\circ \pm 10^\circ \) from approximately 500 instantaneous fields each. The mean phase velocity components \( u_r \) and \( u_t \) and intensity fluctuations have been computed in the opposite regions A and C. Results are reported on Figure 9.

Results show an opposite behavior at the two regions for both velocities and intensity fluctuations. The same behavior has been found at \( d=0.3\text{D} \) and for all staging values. This result clearly shows that the two regions of the spray have a phase shift of \( 180^\circ \). As this result concerns only two regions of the spray, random regions along a constant radius were analyzed in order to compute the phase shift as a function of the circumference angle \( \gamma \). The phase shift is computed using the Mie intensity fluctuations (de la Cruz Garcia et al. [2009]) and is reported on Figure 10. Its evolution confirms the
presence of a phenomenon generated by the aerodynamic flow as no influence of the fuel
distribution has been found in these results. In addition, phase delay was computed in the radial
direction and results showed no difference, meaning that if the spray oscillates in this direction, the
oscillation does not present such phase shift.

Figure 10 - Evolution of the phase shift as a function of the circumference angle $\gamma$
for all the staging values and for $d=0.2D$.

4. Conclusions

Time-resolved PIV has been used to characterize the dynamics of a non-reactive two-phase flow in
a lab scale injector. Analysis were done mainly close to the injector's exit as droplet's may not be
present further in reactive conditions. In section 3, the mean analysis gave us the global behavior
and shape of the spray when the fuel distribution in the injector was changed. In section 4, a
temporal analysis was done and revealed the presence of a PVC at 1520 Hz and 1420 Hz when
using the Pilot stage and both stages respectively. The difference of frequencies was found to be
related to the increase of the mean radius of the spray and also to the change in air temperature.
Furthermore, a phase-locked averaging method was used and established that the PVC's behavior
was not influenced by the fuel distribution. These results were all found in regions close to the
injector's exit and farther in the combustion chamber ($d=0.6D$), no frequency was detected. As
analyses were done using the Mie intensity fluctuations, the absence of frequency may be related to
the droplet evaporation.
However, in order to fully understand and characterize the dynamics of the spray, information on
droplet's diameters and aerodynamic flow are needed.

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