MIXING AND COMBUSTION ANALYSIS OF NON-PREMIXED TURBULENT FLAME SUBMITTED TO ACOUSTIC FORCING USING SIMULTANEOUS ACETONE AND OH LASER INDUCED FLUORESCENCE

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Abstract

Simultaneous planar laser induced fluorescence measurements of the OH radical and the acetone for different flame structures submitted to acoustic forcing are presented here. This kind of diagnostic allows to quantify the influence of the acoustic excitation on the mixing of reactants and on the distribution of the burnt gases. Both effects are major mechanisms on the flame stabilization and should be taken into account to develop and validate combustion models and numerical simulations such as Large Eddy Simulations (LES). The combustion chamber used for this study is specially designed both for easy optical diagnostics (two dimensional configuration) and easy numerical simulations. In order to investigate the flame response to longitudinal acoustic perturbations, a key ingredient to predict and analyze possible combustion instabilities, the air flow is modulated by plane waves induced by two loudspeakers plugged in the inlet duct. The mixing layer is visualized by adding acetone vapor as a tracer in the propane flow whereas the OH radical fluorescence displays the reacting area and the burnt gases. The mixing distribution and the burnt gases locations are found to strongly depend on the excitation frequency.
Introduction

Large eddy simulation (LES) where the largest turbulence structures are explicitly computed whereas only the effect of the smallest ones is modeled appears to be a promising tool to predict combustion instabilities. These instabilities result from a coupling between large scale flow motions, acoustic waves and unsteady heat release. To efficiently and precisely validate large eddy simulations is also a challenge for experimentalists. This validation requires accurate experimental data (ideally, instantaneous time resolved three dimensional velocity and scalar fields would be welcome), as shown, for example, by Nottin et al. (2000). The objective here is to describe the flame behavior in a partially premixed burner to validate the large eddy simulations performed by Léger et al. (2000) Léger et al. (2001) using the Dynamically Thickened Flame model (DTFLES). Our combustion chamber has been especially designed to facilitate both optical diagnostics (two dimensional configuration) and numerical simulations. Planar laser induced fluorescence (PLIF) on acetone vapor added in the fuel flow and OH radical are simultaneously used to visualize both the fuel mixing and the reaction zone and burnt gases. OH radical PLIF has become a popular technique for comprehensive 2-D imaging investigations in flames and is a proven approach for non-intrusive measurements Clemens et al. (1997), Eckbreth (1996). On the other hand, PLIF on acetone used as tracer in mixing layers has been also improved and tends to become a robust technique. In non reactive flow fields, Lozano et al. (1992), Meyer (2001) have shown that the CH$_3$COCH$_3$ PLIF may provide quantitative scalar measurements. In combustion flows, the same procedure may be used upstream the flame before the acetone pyrolysis, using an excitation wavelength that reduces the temperature dependence of the fluorescence signal Thurber (1990). A detailed review of the acetone pyrolysis modeling can be found in Sato and Hidaka (2000). The combination of both PLIF technics in reactive flows is possible because of the acetone broadband UV absorption feature and the non overlap emission spectra of these species. In the following, the application of this technique to describe a non premixed flame behavior submitted to harmonic forcing is presented.

![Figure 1: Burner geometry: a propane flow is injected through two slits into a coflowing air stream. Two backward facing steps generate recirculation zones. Optical access allow the laser sheet to pass through walls. A microphone measures the inlet pressure for conditional imaging.](image)


**Experimental set up**

**Experimental rig**

The combustion chamber has been especially designed to facilitate both optical diagnostics (two-dimensional configuration) and numerical simulations (simple coarse grid meshes). A propane flow is injected through two slits into a coflowing air flow [Fig. 1]. Two backward facing steps generate recirculation zones to ensure the flame stabilization in a large range of inlet velocities. Lateral walls are made in artificial quartz to allow flow visualization whereas laser sheets are introduced into the burner through narrow windows in the top and bottom ceramic walls. The air flow may be modulated by planar pressure waves induced by two loudspeakers plugged in the inlet duct. Moreover, this acoustic forcing provides a reference signal for PLIF conditional imaging.

**Experimental apparatus**

The instantaneous structure of the reacting mixing layer is visualized combining OH/CH$_3$COCH$_3$ PLIF imaging techniques. The propane flow is seeded by acetone vapor upstream the injector slits. This vapor is generated from a liquid acetone spray in propane flow inside a heated plenum. The plenum temperature is kept larger than the acetone vaporization temperature (329 K) to ensure that only acetone vapor is present in the propane flow [Fig. 2 a].

![Diagram of Experimental Apparatus](image)

**Figure 2:** (a) Heated plenum used to produce a gaseous mixing of propane and acetone. (b) Experimental spectrum of the OH $A^2\Pi^+ \rightarrow X^2\Sigma$ electronic transition and the laser beam distribution used for OH PLIF.

The implementation of the simultaneous OH/acetone PLIF imaging system is displayed in Fig. 3. A single, 7 ns, 15 mJ pulse issued from a frequency doubled Nd:YAG pumped dye laser (Spectra Physics Quanta Ray PDL3 / WEX 1) is used to pump the $Q_{1,6}$ transition of the (1,0) band of the $A^2\Pi^+ \rightarrow X^2\Sigma$ system of OH at 282.75 nm. Figure 4 compares the experimental spectrum of the OH radical corresponding band and the dye laser beam distribution used for laser induced fluorescence. These spectrum are obtained from a Cromex 500 IS Imaging Spectrograph spectrometer with a 0.07 nm resolution in a reference premixed flame. Because of the large absorption spectrum of the CH$_3$COCH$_3$ molecule (250 nm → 350 nm), the same wavelength could be theoretically used for acetone PLIF.
Figure 3: Experimental setup used for simultaneous $\text{OH}/(\text{CH}_3)_2\text{CO}$ PLIF.

In the present experiments, the fourth harmonic of a Spectra Physics Quanta ray Indy Nd:YAG laser (266 nm) is used to increase the signal to noise ratio. This laser provides a pulse with an energy (70 mJ) about five times higher than the energy of the OH PLIF dye laser. A single laser sheet is obtained from the two lasers using a 45° mirror on the 266 nm adjusted to minimize the angle formed between the two beams. A single 25 mm focal length cylindrical lens generates both laser sheets which are then focused in the middle of the combustion chamber by a 800 mm spherical lens. Each fluorescence signal is recorded on a separate intensified Princeton Imax camera. The WG305 and UG5 filters association is used for OH whereas the 415WB90 and CG400 combination filters the acetone emission. This filters mounting allow to cut both laser wavelengths and to avoid overlapping of the fluorescence band of both species [Fig. 4 a]. A gate of 25 ns width is used to record OH fluorescence on the intensified camera. This gate is reduced to 10 ns for acetone signal to record only fluorescence and not phosphorescence. Both lasers and cameras are synchronized using a DG 535 delay generator and when phase measurements are performed, the generator is externally triggered by the microphone pressure signal at the burner inlet.

Figure 4: (a) Filters mounted on OH and acetone intensified cameras. (b) Calibration curve used to quantify the $\text{C}_3\text{H}_8$ mass fraction.
Quantitative measurements for acetone PLIF

For a weak excitation, the fluorescence signal $S_F$ is expressed in number of collected photons as Thurber (1990):

$$ S_F = \frac{E}{hc/\lambda} \eta_{opt} dV_c \left[ \chi_{acetone} P \right] \sigma(\lambda, T) \psi \left( \lambda, T, P, \sum_i \chi_i \right) $$

(1)

where $E$ is the laser fluorescence ($J/cm^2$), $hc/\lambda$ is the energy of a photon at the excitation wavelength $\lambda$, $\eta_{opt}$ the overall efficiency of the collection optics and $dV_c$ the collection volume. The bracket term is the acetone number density $[cm^{-3}]$, given as the product of mole fraction $\chi_{acetone}$ and total pressure $P$ divided by the Boltzmann constant $k$ times the temperature $T$. The final two quantities are $\sigma$, the molecular absorption cross-section of the tracer $[cm^{-2}]$ and $\psi$ the fluorescence quantum yield. The quantification of the acetone mole fraction and hence of the propane mole fraction implies different assumptions:

- The pressure $P$ in the combustion chamber is uniform and close to the atmospheric pressure.
- The molecular absorption cross section, $\sigma$, does not depend on $T$ for the 266 nm excitation wavelength Thurber and Hanson (2001).
- The molecular diffusivity is neglected compared to the turbulent diffusivity.
- The effect of the composition variation on the fluorescence yield is neglected and only the 266 nm wavelength is considered Thurber and Hanson (2001), so $\psi = \psi(T)$.

Equation (1) then reduces to:

$$ S_F \propto \chi_{acetone} f(T) \text{ where } f(T) = \left[ \frac{\psi(T)}{T} \right] $$

(2)

The fluorescence signal depends on the temperature $T$ only through the $f(T)$ function. The temperature variation in flames is estimated from a 1D single step chemistry simulation of a premixed flame with the AVBP code [Fig. 5]. The distance $\delta$ needed for the temperature to increase from the fresh gases temperature (300 K) to the acetone pyrolysis temperature (1000 K) is about $\delta = 0.3$ mm. Accordingly, regions where the fluorescence signal depends on the temperature are very thin and this temperature dependence will be neglected. According to these assumptions, $S_F$ is directly proportional to the acetone mole fraction, hence $S_F = \beta \chi_{acetone}$ where $\beta$ is determined by calibration. A perfect acetone/propane/air mixing is studied to derive the propane mass fraction from the acetone fluorescence signal. A known acetone flow rate is injected in a propane/air mixture for different global equivalence ratios at $T_0=300$ K. The calibration curve is then built averaging one hundred fluorescence frames [Fig. 4b]. The $\beta$ constant is determined and the propane mass fraction is given by:

$$ Y_{C_3H_8} = \epsilon \beta S_f(T_0) \text{ with } \epsilon = \frac{\chi_{acetone}}{Y_{C_3H_8}} $$

(3)

where $\epsilon$ is the acetone dilution ratio in the propane flow, known for each operating point. $\beta$ is the slope of the $S_f$ function versus $Y_{C_3H_8}$ in Fig. 4. The propane mass fraction field is then deduced from fluorescence images using relation (3).

Experimental results

This burner exhibits two main operating regimes summarized in terms of air and fuel mass flow rates in Table 1 in which Re is the Reynolds number, $\dot{m}$ the mass flow rate, $\phi$ the global
Figure 5: 1D simulation of a premixed flame using a single step chemistry to determine the fluorescence signal temperature dependent region.

equivalence ratio and $A$ the inlet velocity fluctuation amplitude. For low flow rates the flame is anchored in the vicinity of the propane injector lips ("anchored flame" regime). For higher reactant flow rates and higher global equivalence ratio, the flame lifts rom the injectors and is stabilized downstream in the vicinity of the recirculation zones ("lifted flame" regime). For both regimes, the fluorescence of acetone vapor added as a tracer in the propane flow provides a powerful way to visualize the mixing layer between reactants whereas the OH radical fluorescence displays the reacting area and the burnt gases. Flame stabilization mechanisms may then be studied. The air flow is forced by sinusoidal acoustic waves to determine the mixing and combustion responses to perturbations, a key ingredient in combustion instabilities CROCCO and CHENG (1956). The amplitude of the acoustic perturbation is measured using an hot wire. The velocity at the burner exit ($x_0$) is given as $U(x_0, y, t) = U(x_0, y)[1 + A \sin(2\pi ft)]$. Two different excitation frequencies have been investigated here, $v = 100\text{Hz}$ and $v = 350\text{Hz}$. The stoichiometric iso-surface of the propane / air mixture is determined in fresh gases and appears as a white line on the following figures (fuel mass fraction $Y_{C3H8} = 0.058$).

![Graph showing normalised scale versus x (mm) with labelled axes and data points]

**Table 1: Operating conditions**

<table>
<thead>
<tr>
<th>Operating point</th>
<th>$m_{air}$ (g/s)</th>
<th>$m_{C3H8}$ (g/s)</th>
<th>$\varepsilon$</th>
<th>Re</th>
<th>$\phi$</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifted flame</td>
<td>70</td>
<td>4.5</td>
<td>0.05</td>
<td>40000</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Anchored flame</td>
<td>33.4</td>
<td>0.36</td>
<td>0.05</td>
<td>25000</td>
<td>0.17</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Flame regime without excitation**

In the lifted flame regime displays in [Fig. 6], the propane mass fraction is maximum in the fuel stream at the burner inlet and decreases downstream where the mixing increases. The acetone’s signal disappears when the OH radical signal appears, where the combustion takes place. In this regime, the reactants partially mix before reaching the flame and most of reaction zones are found for equivalence ratios lower than the stoichiometric value. The mixing layer between air and propane exhibits large coherent structures due to Kelvin-Helmotz instability and the flame dynamic depends on this vortices motions. The burnt
gases roll-up close to the recirculation zone might contribute to the flame stabilization by heating the reactant before reaching the stagnation point.

![Figure 6](image)

Figure 6: Lifted flame regime without acoustic excitation. (a) propane mass fraction field, (b) OH radical fluorescence field and (c) superimposed fields with stoichiometric surface (white line).

The anchored flame structure exhibits a completely different behavior [Fig. 7]. In this case, the OH radical fluorescence signal is found in the wake of the injector lips and the propane jet mixes very rapidly with the air stream. Flame stabilization is also found for this regime in the lean side of the mixing layer after a relatively fast premixing.

![Figure 7](image)

Figure 7: Anchored flame regime without acoustic excitation. (a) propane mass fraction field, (b) OH radical fluorescence field and (c) superimposed fields with stoichiometric contour.

Flame regimes under acoustic excitation

The mixing layer motions are strongly modified by acoustic forcing. For both regimes, the low frequency 100 Hz forcing induces different combustion processes. Six snapshots taking every 60 degrees of the acoustic cycle are displayed in Fig. 8 for the lifted flame regime. A huge premixed gases pocket is generated at the beginning of the cycle and plays an important role in the combustion process (see phases 0°, 60°, 120°). Indeed, for \( \phi = 0° \), the mixing layer is amplified and exhibits a disturbance at \( x \approx 50\text{mm} \) and most of the reaction zone is constrained downstream. At \( \phi = 60° \), this pocket is convected downstream and growths inducing a high local equivalence ratio at the end of the frame. Because of the rich flammability limit, the reactants cannot burn at this location and are convected upstream by the recirculation zone motion. For \( \phi = 120° \) and \( \phi = 180° \), burnt gases and reaction zones interact with the propane stream between two successive structures. For
\( \phi = 180^\circ \), the flame is still stabilized by the tip of the huge convected structure at \( x \approx 80 \text{mm} \) in the vicinity of top and bottom walls. At the end of the acoustic cycle, \( \phi = 240^\circ \) and \( \phi = 300^\circ \), the largest coherent structures are convected and the reaction may then develop. The OH radical fluorescence signal is very intense for these last phases, probably because of the mixing layer preheating during the previous steps.

The structure of the anchored flame regime is completely affected by the 100 Hz acoustic forcing [Fig. 9]. In fact, the flame is no more anchored and becomes lifted. Moreover, for some phases, the mixing layer symmetry is broken and one of the two propane flows is stopped by the acoustic waves. At the beginning of the cycle, the mixing layer exhibits a disturbance interacting directly with the recirculation zones. Between \( \phi = 0^\circ \) and \( \phi = 120^\circ \), the propane jet follows the rotating motion imposed by the backward facing step. At the same time, the flame lift distance increases as displayed by the OH radical field. From \( \phi = 120^\circ \) to the end of the cycle, the flame comes back towards the anchored position whereas the propane jet penetration decreases. A global trend may be extracted from these snapshots. Assuming the velocity and pressure signals are in quadrature, the mixing layer motions may be explained as follows. If \( \phi_p \) denotes the phase of the inlet acoustic pressure wave and \( \phi_v \), the phase of the inlet velocity signal, the quadrature assumption requires \( \phi_v = \phi_p - \pi / 2 \). Under sinusoidal forcing, the inlet air flow velocity increases until \( \phi_p = 180^\circ \), reaches its maximum value and finally decreases until \( \phi_p = 360^\circ \). This scheme explains why the anchored flame is lifted before 180 degrees and seems to reach the injector lips beside this value. The spatial distribution of the coherent structure observed in the different

Figure 8: Lifted flame regime submitted to a 100 Hz acoustic excitation. Phases are based on the inlet acoustic pressure signal. Propane mass fraction and OH radical fluorescence signal fields are superimposed. The white line displayed the stoichiometric surface.
cases may be explained following the Ho and Huang (1982) theory (Varoquie et al. (2002) for details).

![Diagram of anchored flame regime submitted to a 100 Hz acoustic excitation. Phases are based on the inlet acoustic pressure signal. Propane mass fraction and OH radical fluorescence signal fields are superimposed. The white line displayed the stoichiometric surface.](image)

Figure 9: Anchored flame regime submitted to a 100 Hz acoustic excitation. Phases are based on the inlet acoustic pressure signal. Propane mass fraction and OH radical fluorescence signal fields are superimposed. The white line displayed the stoichiometric surface.

### Conclusion

The simultaneous laser induced fluorescence on the OH radical present both on reaction zones and burnt gases and the acetone added as tracer in the propane stream appears as an useful way to visualize the mixing and the combustion dynamics under acoustic excitation. The mixing distribution and the burnt gases locations are found to strongly depend on the excitation frequency. Moreover, the comparison of phase-averaged images allows a better understanding of the combustion process under acoustic excitation. A post processing treatment will allow a comparison of experimental results with large eddy simulation.

### Acknowledgments

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References


