

# Mesures de compositions locales dans les flammes via plasma induit par laser

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## Résumé :

Afin de réduire les émissions toxiques des turbines à gaz, la combustion prémélangée offre une solution attractive. Néanmoins, en pratique, la qualité du mélange peut-être délicate à assurer et il faut recourir à des techniques capables d'effectuer des mesures locales et instantanées du rapport entre carburant et oxydant. Afin de fournir de telles données, une technique utilisant un laser Nd:YAG, focalisé via une lentille sphérique afin de créer un plasma local a été utilisée. Cette technique est connue sous le nom de spectroscopie plasma induite par laser (Laser Induced Plasma Spectroscopy; LIPS). Chaque molécule se trouvant initialement dans le volume de mesure est décomposée en atomes et ainsi l'émission du plasma permet d'accéder à la composition locale du gaz. En utilisant le rapport entre l'émission d'hydrogène (carburant) et celle de l'azote ou de l'oxygène (représentant l'oxydant), il est possible de remonter à la richesse locale. Cependant, différents problèmes doivent être pris en compte, comme par exemple le degré d'ionization du plasma ou encore la position exacte du plasma. L'ionization du plasma est déterminée dynamiquement par le rapport d'émissions entre deux raies d'hydrogène. Deux applications de cette technique sont présentées ici. Il est ainsi montré que des jets d'air secondaires utilisés pour la stabilisation de la flamme vont réduire localement la richesse du mélange initial. Cette technique a aussi permis de tester l'efficacité de deux types de mélangeur et de les comparer avec une méthode plus standard reposant sur une longueur de mélange plus importante.

## Abstract :

In order to reduce pollutant emissions from gas turbines, premixed combustion offers an attractive solution. However, in practical cases, the quality of the mixing may be difficult to assess and one need techniques to actually measure the local and instantaneous ratio between fuel and oxidizers. To provide such data, a technique was used that uses a Nd:YAG laser, focused through a spherical lens to create a local plasma. This technique is known as Laser Induced Plasma Spectroscopy (LIPS). Each molecule within the initial probe volume is decomposed into its fundamental atomic components and therefore the emission of the plasma will give a clear evidence of the local composition. Using ratio of hydrogen (representing fuel) versus oxygen or nitrogen (representing oxidizers), it is possible to retrieve the equivalence ratio information. Different cautions have to be taken however, like the degree of ionization of the plasma as well as the actual position of the plasma. Ionization is determined dynamically looking at the ratio between two hydrogen emission lines. Applications of this technique are shown in two different configurations. Fundamental flames have been investigated and the effects of dilution induced by secondary air jets used to stabilize the flame on the main mixture were clearly shown. Two different mixing devices were investigated as far as their mixing efficiency is concerned and compared with a more standard way to achieve mixing, using longer mixing length.

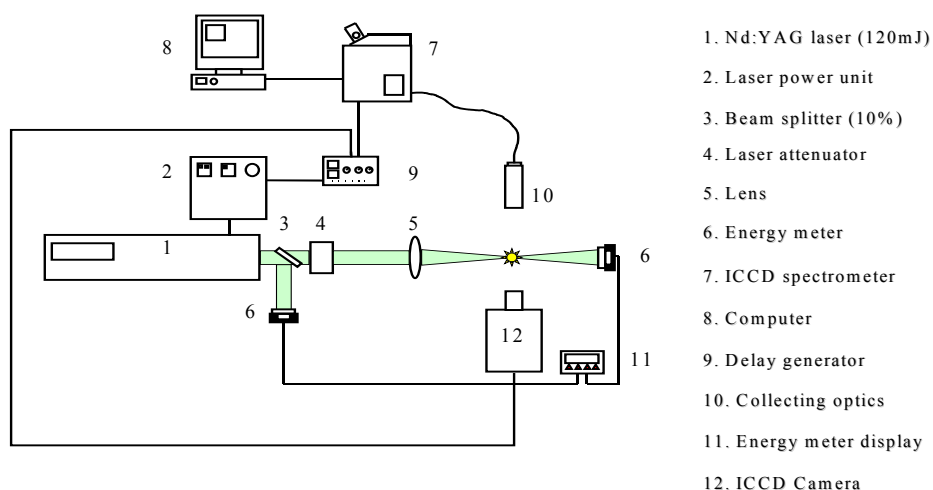
## Introduction :

With the actual regulations on emissions, it is common to run combustors in lean premixed modes. In land-based turbines, the mixing section dimension is not as crucial as in aircraft design. However, rapid mixing is a key parameter and a proper evaluation of the properties of the mixture has to be available to designers in order to improve or validate the new mixing devices. It is relatively easy to achieve qualitative characterization of mixing using for instance tracers to see where the fuel is actually injected. However, quantitative measurements remain a challenging issue (see [Schulz and

Sick, 2005] for recent advances on tracer LIF techniques). Those techniques require either the introduction of a seeding molecules at known concentration to measure the concentration within the combustor or the use of several excitation schemes (hence lasers and cameras). An alternative method to obtain quantitative measurements of local gaseous composition is presented here and a practical case is discussed where local gradients of mixture fraction exist. This method may be applied to any type of fuel without addition of seeding molecules. The first part will aim at presenting the Laser Induced Plasma Spectroscopy technique. The second part will present the burner used and the effects of secondary swirling air jets on the main mixture. The third part will deal with quantitative measurements of local equivalence ratio at different height above the burner for two different mixing devices. Their relative efficiency will be compared. Finally conclusions are drawn.

## Laser Induced Plasma Spectroscopy

The technique used here is not new as trials were already reported in early 80's (see [Schmieder, 1982]). However, with recent development in lasers and cameras it becomes attractive as good signal to noise ratio can be obtained. To achieve a local plasma, the second harmonic of a Nd:YAG laser is used coupled to a lens (NADL-30-200PY2 from Sigma Koki ) with a focal of 200mm. The collecting light probe is a lens with focal length of 300mm coupled to a fiber optics. The fiber optics is then connected to a spectrometer (MS-257 from Oriel) and measurements are made with an ICCD (Andor) and a slit of 50 $\mu$ m. The time delay between the formation of the spark and the measurements is a key parameter as well as the exposure time [Zimmer et al., 2005]. The frequency was set to 1Hz (for the Q-switch but keeping flash lamps at 10Hz). The actual measurement volume is limited to the volume of the spark as the natural emission is limited during the exposure time. To precisely measure the position of the plasma, an ICCD camera is used, synchronized with the laser. Each spark position is therefore precisely known as well as the possible occurrence of multiple sparks. Those multiple sparks have to be rejected because they are not spatially localized and furthermore, the energy used to form each individual plasma cannot be measured. Together with the position, each time the spark energy is also measured, because it has been shown that the energy is an important parameter for LIPS technique ([Phuoc and White, 2002]). A typical sketch of the experimental facility is shown in Figure 1.

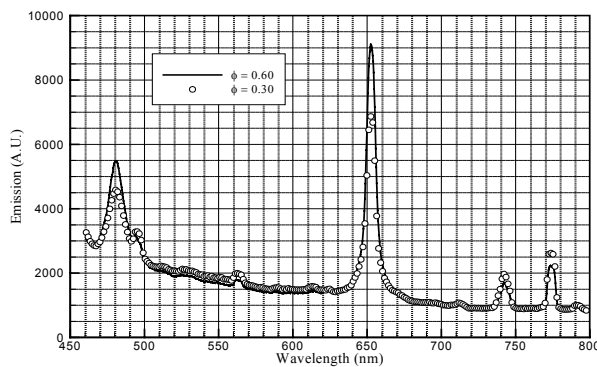


**Figure 1** Sketch of the experimental technique

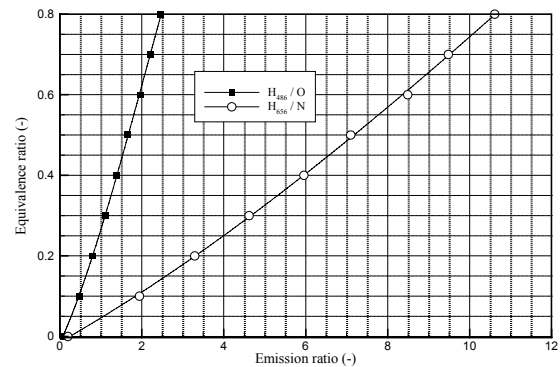
To measure the local equivalence ratio, emission lines corresponding to the fuel atomic composition and those corresponding to oxidizers have to be clearly identified. Afterwards, ratio of two or more of those lines can be linked to equivalence ratio. A proper choice in the line will clearly influence the accuracy and sensitivity of the technique. In order to show the how the technique works, typical examples are chosen to illustrate the basis of the technique. The present spectra were taken with an integration of 3,000ns 300ns after the plasma formation. The spark is located 10mm above the exit

of the burner and no swirling air jets are used. Therefore, one may assume that the inner part of the jet is exactly at the preset equivalence ratio and therefore, the spectra obtained do represent the imposed stoichiometry. In Figure 2, two spectra are represented, one for an equivalence ratio of 0.30 and the other one for 0.60. The spark energy was kept constant and was 20mJ. One can clearly notice four main peaks. The two first one represent the hydrogen emission (Balmer series) with distinctive emission at 486 and 656nm. The third peak represents the nitrogen emission (746nm), whereas the last one represents the oxygen atoms (777nm). Based upon the examination of those two spectra, it turns out that indeed an increase of equivalence ratio resulted in an increase in the emission of hydrogen, whereas the emission for nitrogen and oxygen atoms decreased. However, it is very difficult to rely on absolute values and therefore, for the calibration purpose, one will rather look at ratio.

It is possible to use at least two independent ratio to relate each spectra to a given equivalence ratio. One will be done with the hydrogen emission at 486nm with the emission of oxygen and the other one between the second hydrogen peak (which is the strongest here at 656nm) and the nitrogen emission at 746nm. Typical calibration curves obtained are shown in Figure 3. From those two curves, it seems quite unambiguous that the emission ratio can be linked to the equivalence ratio. It is worth noting that both calibration and results are performed in fresh gases. The reason to use two independent ratios is to have increase accuracy. A spark will therefore lead to a successful measurement if and only if the stoichiometry as measured by the two methods coincides with each other. An important parameter is the spark energy. For different spark energies, even though the equivalence ratio is kept constant, the ratio will change due to changes in ionization levels. To avoid this kind of problems, two strategies are simultaneously used. The first one is to actually measure the spark energy, using the two power meters as shown in Figure 1. The other one is to actually estimate the ionization level of the hydrogen atom. This is possible as two different transitions are measured (emission at 486 and 656nm) and therefore this ratio provides an alternative to the measurement of the actual spark energy. This ionization estimation would be preferable in practical situation for which the measurement of the spark energy may not be straightforward due to limited optical access.



**Figure 2** Mean spectra for equivalence ratio of 0.30 and 0.60



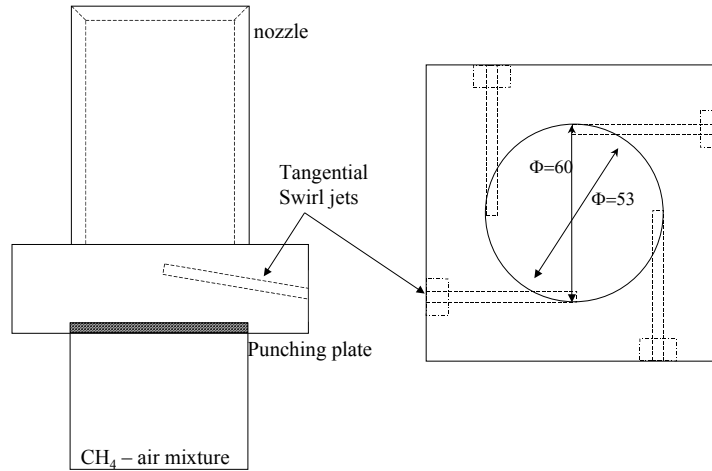
**Figure 3** Example of calibration curve obtained for two different ratios

### Application to a turbulent burner

To validate the ability of the LIPS technique to actually measure inside turbulent burners, a series of experiments have been conducted in a low-swirl burner type. The low-swirl burner is a burner that enables the stabilization of a turbulent flame under moderate and intense turbulence without recirculation zone. It is used for fundamental studies of turbulent premixed flames. A sketch of the facility is displayed in Figure 4. The main changes compared to the LSB as presented in [Chan et al., 1992] are the turbulence generating mechanisms. Rather than using two slots, a punching plate is used. Another important different is that the nozzle is made of glass to allow optical access also inside the burner. This is of crucial importance for CFD simulations that require boundary conditions to be well described.

It is worth noting that the flame is not confined and therefore there may be some gradients of mixture fraction due to mixing with surrounding air and swirling jets. The flow rate of the swirling

jets will enable to change the lifted height of the flame as well as the turbulent characteristics at the flame front [Tachibana et al., 2004]. An increase in the swirling strength will induce three-dimensional effects and mixing between the main core and the surrounding jets may become possible.



**Figure 4** Sketch of the LSB burner

Therefore, local measurements of equivalence ratio should be performed to quantify precisely the impact of the swirling jets in terms of stoichiometry. The measurements presented in the following are taken 10mm above the exit of the burner. This location is always in non-reacting gases for the different conditions chosen here. It is important also to note that the flame cannot be stabilized for very low swirl numbers but that the mixing can be faithfully quantified using LIPS technique. A series of tests were done with a mean stoichiometry of 0.60 and changing the swirl number from 0 to 1.80. The total flow rate is set to  $662\text{NL}\cdot\text{min}^{-1}$ , which induces a mean bulk velocity of  $5\text{m}\cdot\text{s}^{-1}$  at the exit of the burner. The geometric swirl number is defined as

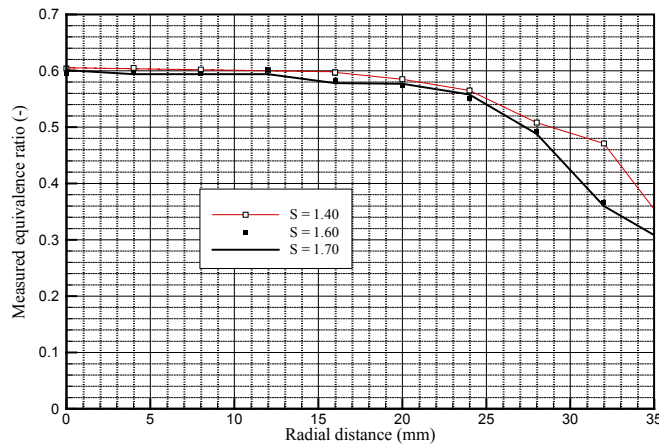
$$S = \frac{\pi R^2 Q_j^2 \cos \alpha}{4\pi R_j^2 (Q_j + Q_m)^2}$$

where the subscript j represents the swirling jets (radius and flowrate) and  $\alpha$  being the angle between swirling jets and main mixture (in the present case  $\alpha = 20^\circ$ ),  $R_j=1\text{mm}$  and  $R=26.5\text{mm}$ .

### Mixing between main flow and secondary air swirling jets

As depicted by Figure 1, another ICCD camera is used to monitor the position of the plasma. It is used in gate mode with an integration time of 10ns following the emission of the laser. A filter is used (Band pass  $431\text{nm}\pm 10\text{nm}$ , typically used to monitor  $\text{CH}^*$  emission) to attenuate the emission and the smallest aperture is used ( $f=32$ ). One of the answers provided by this ICCD is to give precisely the localization of the induced plasma. A traverse system is used to simultaneously move the lens and the collecting lens in a horizontal plane so that the measurement point will be moved along a radial axis. The other information provided by this ICCD is to give the exact nature of the spark. In a flowing condition, presence of small dust particles may change the position of the plasma as well as create multiple sparks. Three swirl numbers are used for an overall equivalence ratio of 0.60. Plots are shown in Figure 5. Those profiles are averaged profiles over 4mm in space and correspond to the mean values obtained at a radial point (both from left and right side). Typically 200 shots are averaged to provide statistically converged mean values. The measured equivalence ratio is the one inferred by the LIPS ratios and radial distance denotes the distance from the center of the burner. One can see that in the core of the jet, values close to the one fixed (0.60) are indeed measured. However, for radial distances higher than 15mm as far as swirl number of 1.60 and 1.70 are concerned, one has values slightly lower than 0.60 (around 0.58). This reduction of actual equivalence ratio becomes more evident for radius of 20mm and further. One can also notice that even for swirl numbers of 1.40, this reduction is measured, but for a slightly higher radial coordinates (typically around 20mm in the present case). Clearly, LIPS technique can show local mixture fraction variation and this variations have a strong impact as this burner is generally

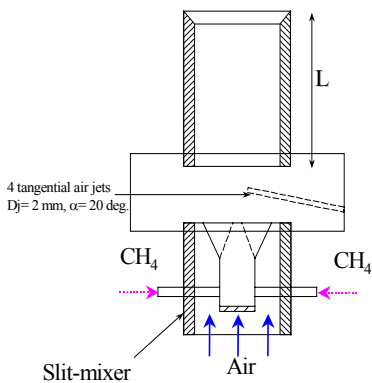
used to quantify properties of premixed flames. As typically 200 shots are averaged to get those profiles, the relative uncertainty is quite small (see Zimmer and Tachibana, 2004).



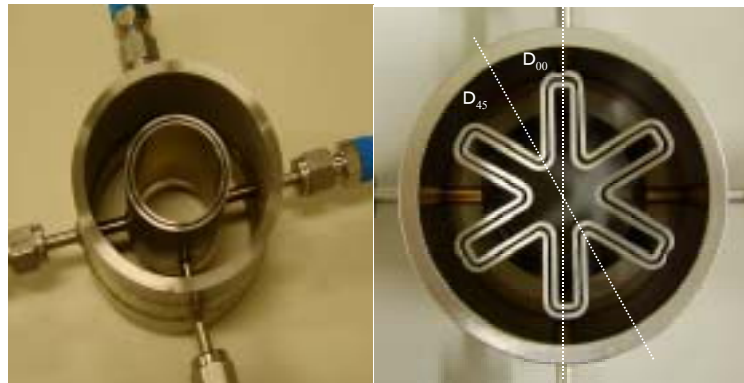
**Figure 5** Evolution of local equivalence ratio with swirl

### Quantification of mixing devices using LIPS technique

In this application, two mixing devices are investigated to characterize their mixing efficiency. The strategy is to place the mixing upstream of the swirl injection, as shown in Figure 6. The two injectors are displayed in Figure 7. On the left, is a simple circular slit from which the methane is injected. The second one is a lobed shaped slit. This lobed shaped should increase the mixing capacity and therefore allow better mixing for a similar spatial extension. The important parameter is the length of the nozzle  $L$ . In the following, only a length of 90mm will be used.

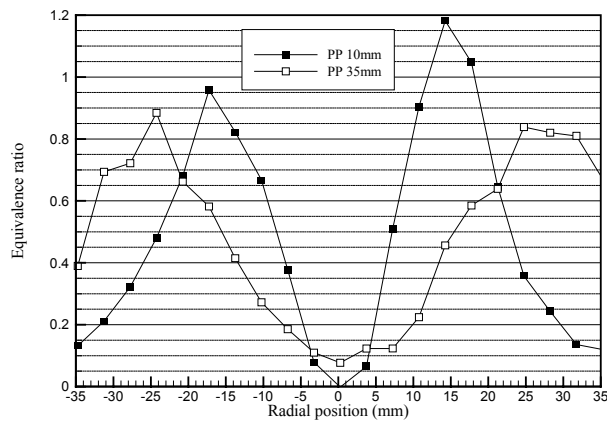


**Figure 6** Sketch of the injection position

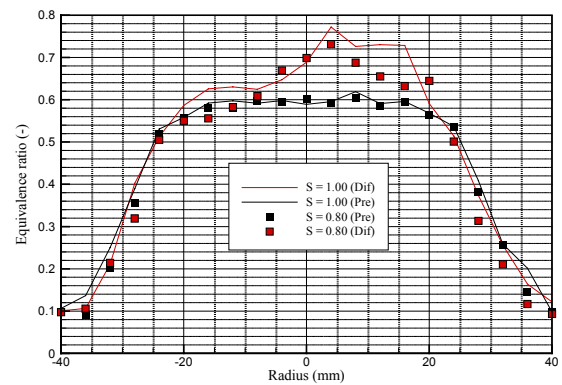


**Figure 7** Direct photograph of the two injectors

The results are plotted in Figure 8 for the slit mixer, with measurements performed 10 and 35 mm above the exit of the burner. One can notice that the inner side of the burner does not contain any fuel for a height of 10mm, as the measured equivalence ratio drops to 0. One can also see two sharp regions in which fuel is detected to a relatively high concentration as measured equivalence ratio reaches values above 1.0. Afterwards, the outer part of the flow exhibits a decrease in the local mixture fraction. Measurements performed further downstream (35mm) show that the fuel is spreading (due to divergence of the main flow) and that it mixes with air as measured equivalence ratio tends to become lower than unity. Nevertheless, the fuel can still not efficiently penetrate inside the core of the mixture in the center the equivalence ratio is only 0.10, for an overall equivalence ratio of 0.60. Measurements performed with the lobed shaped injector (see Figure 9) do exhibit a complete different behavior. To illustrate the mixing efficiency of such an injector, measurements were also taken with a static mixer located 2m upstream.



**Figure 8** Profiles of the fuel for the slit mixer



**Figure 9** Profiles for the lobed slit mixer

Those measurements are referred as Pre in the plot whereas those obtained using the lobed shaped injection for fuel supply are denoted as Dif. Highest values reached for the equivalence ratio is 0.76 for a distance of 10mm above the burner, which is much better than the slit injector. Furthermore, one can notice that the fuel is more distributed. However, non-symmetry is a very important problem. The reason for an overall increase of the equivalence ratio measurement for radius higher than 0 comes from manufacturing issues that do not allow at the present stage a complete symmetry of the lobed shaped slit. Therefore the right side corresponding to a slightly higher gap provides more fuel than the left side and therefore overall equivalence ratio is increased in this region. Nevertheless, the performances of the lobed shaped injector are very good for rapid mixing efficiency and it may be fruitful to overcome the manufacturing issues to provide a new and fast way for mixing fuel and air within limited space.

### Conclusions

A Laser Induced Plasma Spectroscopy has been studied and applied to characterize mixing occurring in turbulent flames. It uses the emission of the plasma to infer the local composition, hence local equivalence ratio. It has been used to characterize the influence of the swirling air jets on the main mixture. It clearly showed the influence of the tangential air jets on the main mixture fraction. It has also been used to characterize two injectors. The lobed shape injector has clearly an overall better efficiency than the slit injector as fuel mixes faster, even though symmetry was hard to achieve. Further measurements of the LIPS technique may include temperature estimation using the emission of the plasma.

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