Laser Induced Plasma Spectroscopy for Local Composition Measurements Inside a Low Swirl Burner.

L. Zimmer, S. Tachibana
Aeroengine testing technology center, Japan Aerospace Exploration Agency, Tokyo, JAPAN
Corresponding author: zimmer.laurent@jaxa.jp

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). 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. The first part will aim at presenting the Laser Induced Plasma Spectroscopy technique. The second part will present the burner used as well as visualization to show qualitatively the effects of swirls. The third part will deal with quantitative measurements of local equivalence ratio 10mm from the exit of the burner. Finally, conclusions will be drawn from the current experiments and direction for further investigation will be suggested.

Laser Induced Plasma Spectroscopy

The technique used here is not new as trials were already reported in early 80's (see [Schmieder, 1982]). 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 50µm. 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 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. 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 Fig.1.

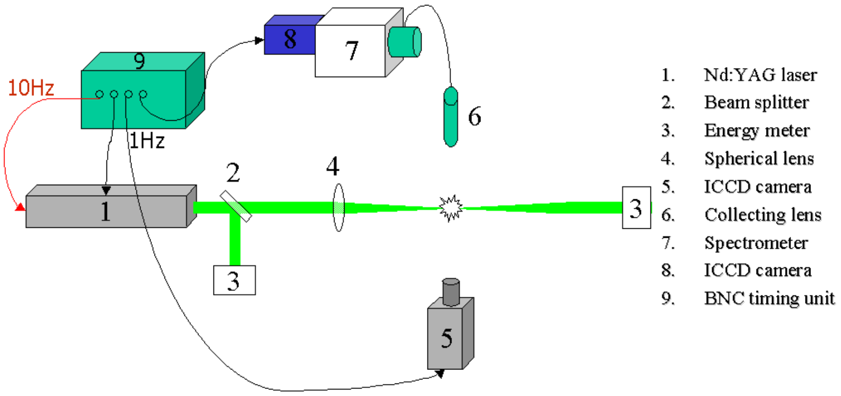

Figure 1. Sketch of the experimental technique

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 location 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 Fig.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.

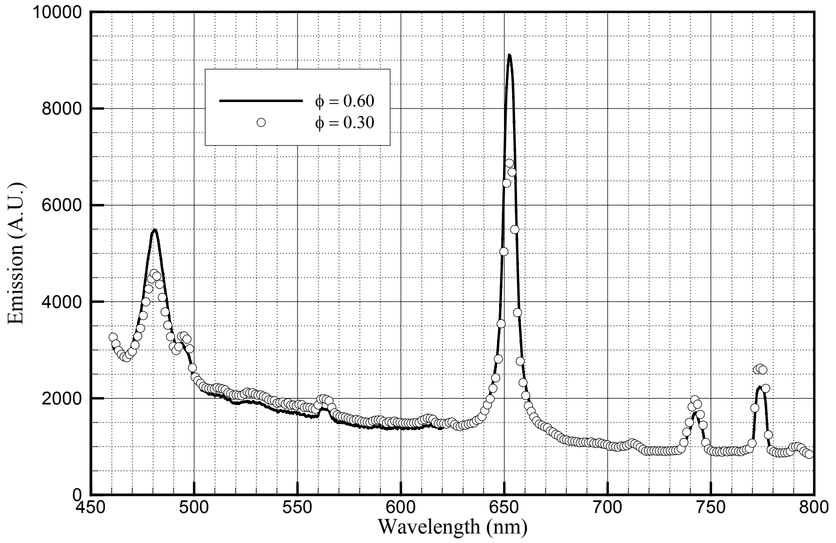

Figure 2. Mean spectra for equivalence ratio of 0.30 and 0.60

It is possible to use at least fully 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 Fig.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 unburnt 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 Fig.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.

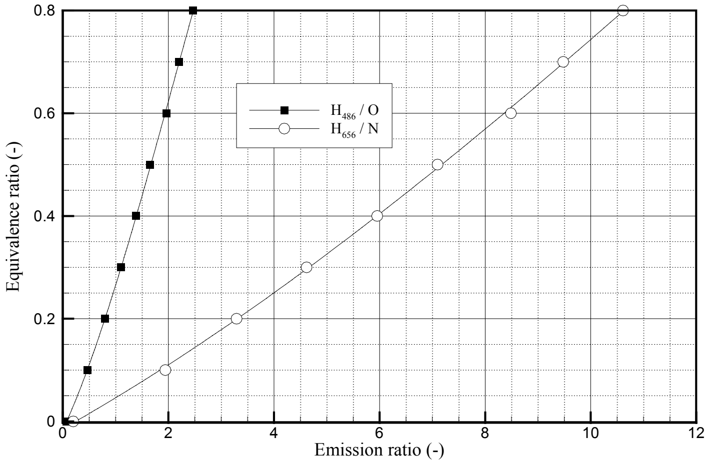

Figure 3. Example of calibration curve obtained for two different ratios

Application to 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 Fig.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, punching plates are 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.

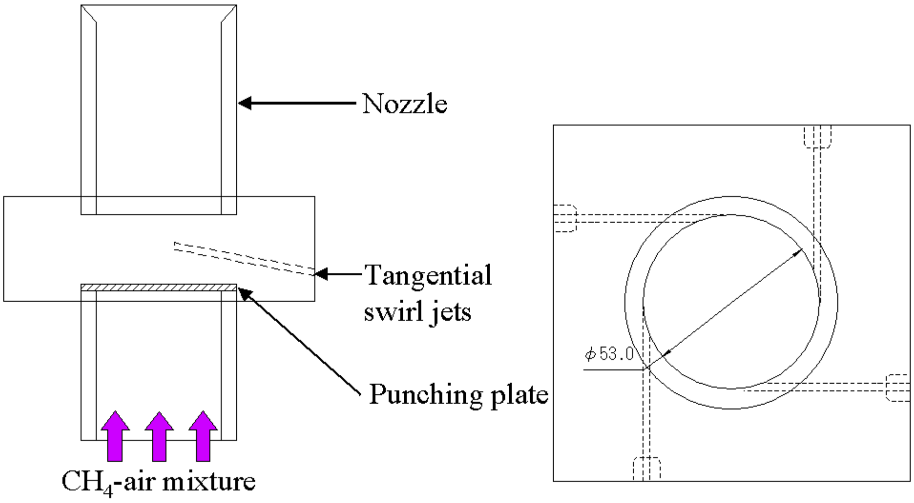

Figure 4. Sketch of the LSB burner

The main changes compared to the LSB as presented in [Chan et al., 1992] are the turbulence generating mechanisms. Rather than using two slots, punching plates are 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.

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 on a mean stoichiometry of 0.60 and changing the swirl number from 0 to 1.80. The total flow rate is set to 662Nl.min^{-1}, which induces a mean bulk velocity of 5m.s^{-1} at the exit of the burner. The 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 α being the angle between swirling jets and main mixture (in the present case α = 20°), R_j=1mm and R=26.5mm.

Visualizations

Prior to quantitative measurements of local equivalence ratio, the regions where the swirling air jets are penetrated have been visualized. For this purpose, the four swirling jets were seeded with DEHS oil droplets using six-jets atomizers from TSI. Seeding was injected in both non-reacting and reacting conditions. In this later case, one may have some influence of the droplet on the main combustion pattern. However, ought to the limited mass flowrate (only three jets were used), it is expected that the modifications remain limited. To realize visualization, a CCD camera (2048x2048, 12 bits) was used, synchronized with a Nd:YAG laser firing at 10Hz. The laser sheet was placed horizontally and the camera was put at 45degrees from this plane. Due to optical distorsion, Scheimpflug setup was used to allow focusing in all part of the camera. This allowed recording without stringent concerns on heat release as in cases for which the camera would have been place perpendicular to the laser sheet, and therefore in burnt region. A developed algorithm allowed a transformation from pixels to physical dimension. This procedure is similar to procedures used in stereoscopic PIV experiments.

An important aspect of those visualizations is to reveal the structure of the swirling jets, especially as far as symmetry is concerned. Three main images obtained by averaging 200 images for each case. The mean images for three different conditions are shown in Fig.5.

One can notice on each image the outer part of the burner. One can see that an increase of swirl number leads to a more symmetrical distribution of the seeding particles. This has some important conclusions as far as LIPS measurements are concerned as one can see that even though the measurements and done along one diameter, they should be done also in another profile, positioned forty-five degrees with respect to the first one.

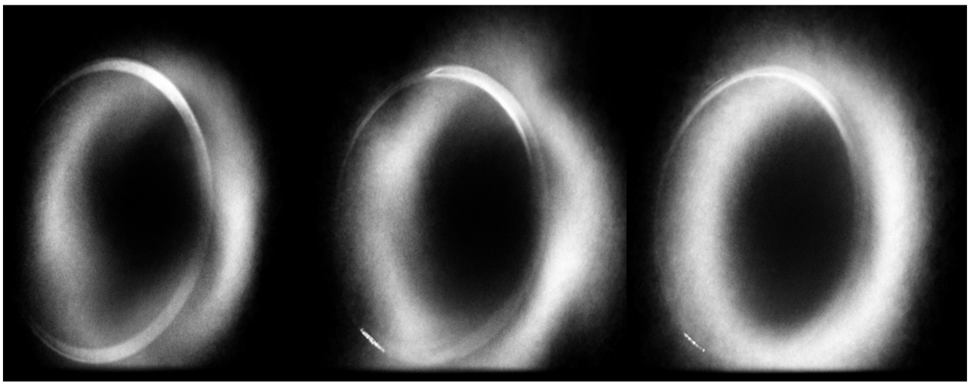

Figure 5. Visualization for S = 1.00, 1.40 and 1.80 (from left to right)

It is interesting to look closely at the case for which the swirl is equal to unity. One can clearly distinguish four different parts, each of them corresponding to one swirling jets. Each part is separated from the other by showing a sudden jump in the seeding density. This swirl number is too small to fully penetrate the inner jet and therefore its effets are limited to the outer part of the flame. On the other hand, the higher swirl number presents symmetrical results, suggesting that mixing is achieved between surrounding swirling air jets and main jet overall the radial component.

Those images are then transformed using the mapping function obtained previously and it is possible to have mean profiles along one radius (that was also used for LIPS measurements).

The results obtained are plotted in Fig.6 for five different swirls. In those non-reacting conditions, the PDF tend to increase with an increase of swirl number. The measurements reported last week were showing that particles were also detected in the center of the burner. Even if this tendency did not disappear, it seems to be relatively reduced when making the measurements out of the burner. Those measurements cannot be directly compared with LIPS as they were obtained in non-reacting conditions, where LIPS measurements are performed in reacting conditions.

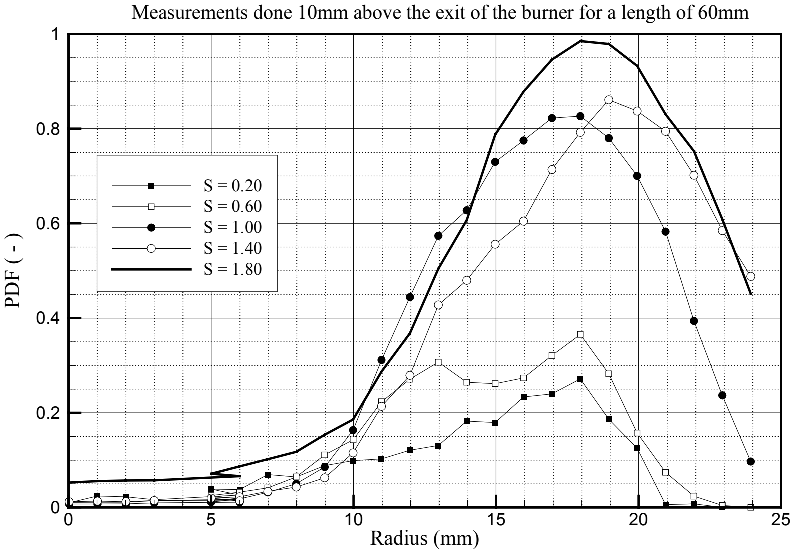

Figure 6. PDF of particles as function of swirl

To be able to provide some data that could be helpful for LIPS measurements, similar experiments were conducted but in reacting conditions. For burning cases, 200 images are also averaged in order to produce the mean image (see Fig.7). The threshold used is slightly smaller than the one used in non-reacting conditions, due to a change in the aperture. This however leads to a relatively low value for the PDF (as shown in Fig.8). However, the shape of the PDF is not changed when using a smaller threshold, only the value of the PDF. The present value has some arbitrary units, as its purpose is mainly to show qualitatively what is expected when making quantitative measurements of equivalence ratio.

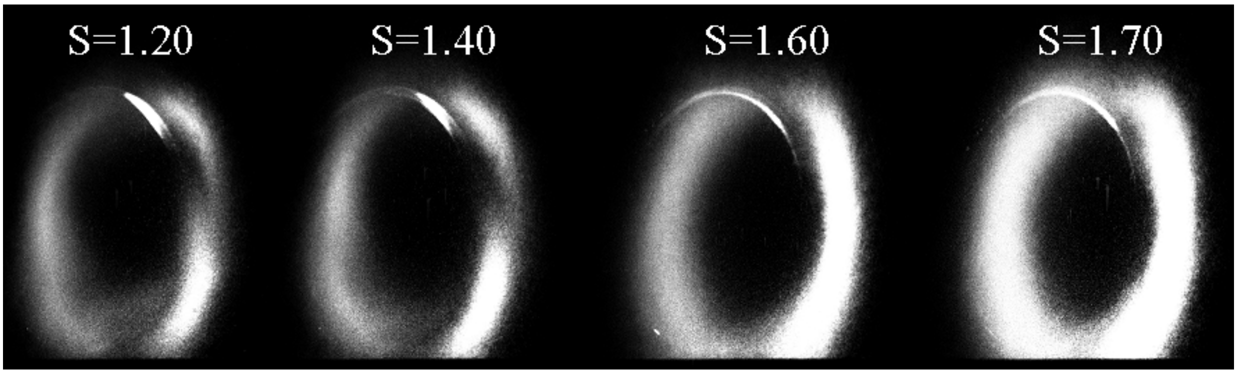

Figure 7. Visualization in reacting conditions

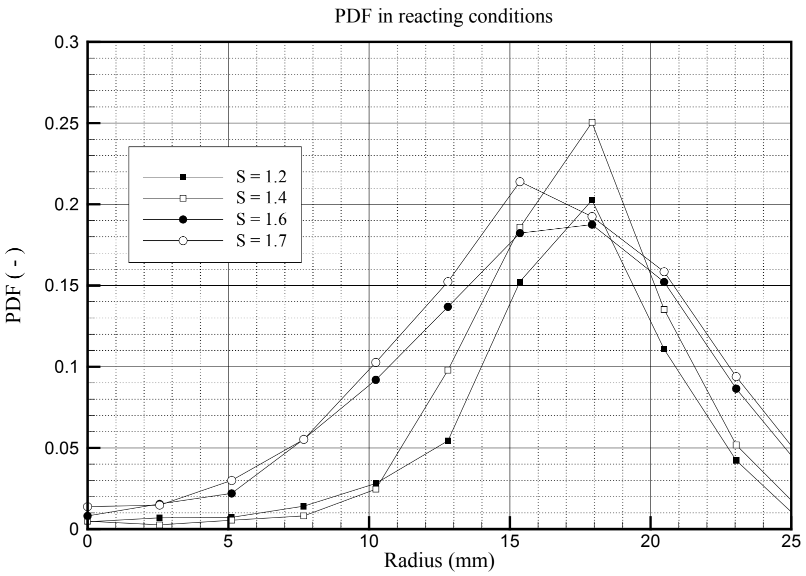

Figure 8. PDF in reacting conditions

Local equivalence ratio measurements

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 431nm±10nm, typically used to monitor CH* emission) to attenuate the emission and the smaller 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.

As shown by the visualization results, the swirling air jets influence may not be symmetric for small swirl and therefore measurements should be performed along two different lines. The definition of the two lines is given in Fig.9 where d_{00} and d_{45} represent the two lines, at 45° from each other. The four swirling air jets are also represented in this figure. Each time a profile will be given, the line along which it has been taken will be referred as being either d_{00} or d_{45}.

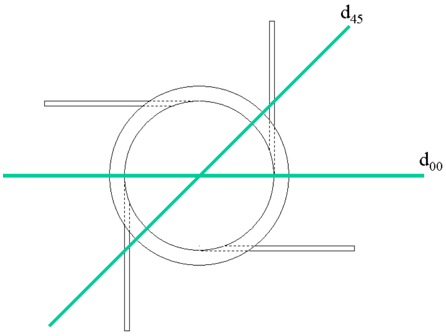

Figure 9. Schematic representation of the measurement line

The swirl number was varied from 1.00 to 1.70, as for the visualization technique. For clarity reasons, only three swirl numbers are represented in Fig.10. Those profiles are averaged profiles over 4mm in space and correspond to the mean values obtained at a radial point (both form left and right side) and were taken along d_{00} line.

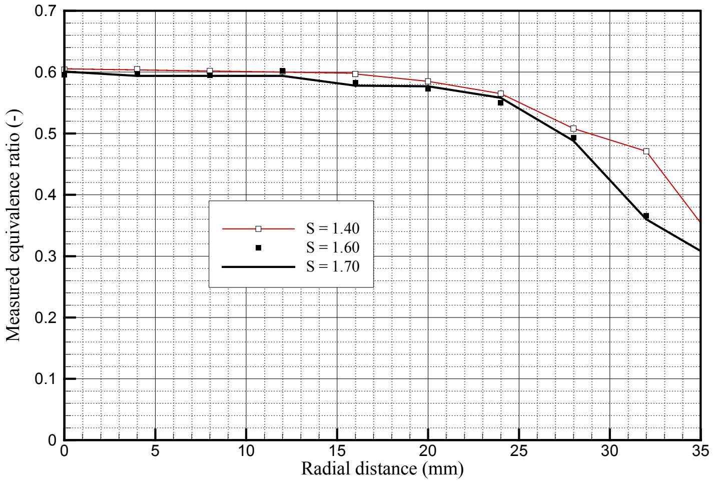

Figure 10. Evolution of local equivalence ratio with swirl

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). When looking along a different direction (referred as d45 in Fig.9), one obtains a similar trend for the three previously shown swirl numbers. The results are given in Fig.11.

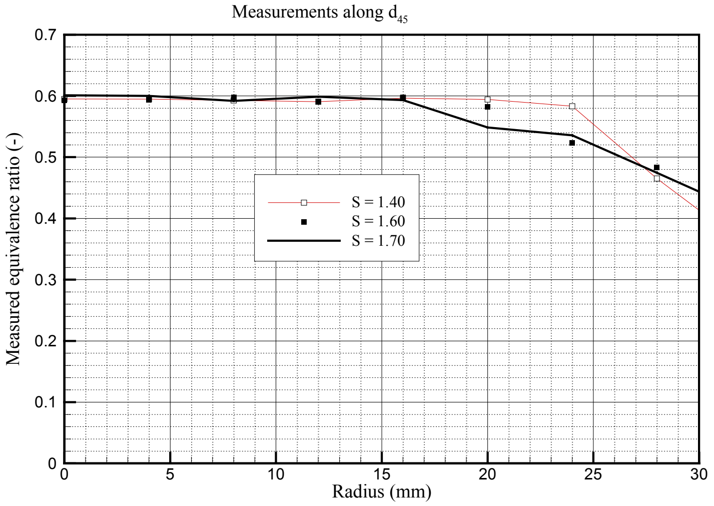

Figure 11. Evolution of local equivalence ratio with swirl along d45 line

One can find similar trends as already seen in profiles taken along d00. An increase of swirl tends to diminish the region for which the equivalence ratio is the one of the main mixture. From those two plots, one may say that for fundamental measurements of premixed turbulent combustion, one should limit the measurements to a region of 12mm for high swirls and to 16mm for lower swirls. After those radii, the actual equivalence ratio would be different from the one imposed, due to mixing with surrounding air jets. Even tough an increase of swirling jets tends to create wider jets; the momentum of those jets is high enough to penetrate into the jet, therefore creating locally leaner mixtures.
Based upon the LIPS results, it is possible to derive a two-dimensional map using d_{00} and d_{45} measurements, assuming quarter symmetry. The results are displayed in Fig.12 for three different swirl numbers.

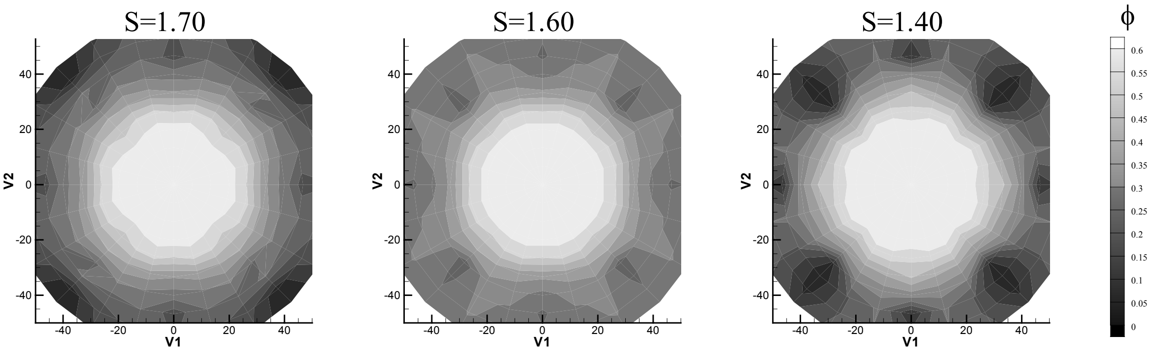

Figure 12. Pseudo-visualization of the contours of stoichiometry

Conclusions

Laser Induced Plasma Spectroscopy (LIPS) has been investigated as being a technique enable to get local equivalence ratio measurements. The hydrogen emission is used to characterize the methane presence whereas oxygen and nitrogen are used for the oxidizers monitoring. Ratio of either of those quantities could yield quantitative measurements of equivalence ratio. Calibration obtained in a jet showed consistent results. To emphasize the possibilities given by LIPS, different region of the spectrum have been chosen and for each typical calibration could be obtained between atomic emission ratio and imposed stoichiometry. The practical application of the lips has shown that Low-Swirl Burner flame does exhibit gradients in their open flame configuration and that those gradients will be enhanced by imposed swirl. This has clearly impacts on fundamental measurements done in this kind of geometry. Further considerations will address measurements inside the nozzle to provide detailed boundary conditions for simulation purpose.

References

Chan, C. K., Lau, K. S., Chin, W. K. and Cheng, R. K.: Freely Propagating Open Premixed Turbulent Flames Stabilized by Swirl, 24th Symposium (International) on Combustion, Combustion Inst., 1992, pp. 511-518.

Phuoc, T.X., and White, F.P.: Laser-Induced spark for measurements of the fuel-air ratio of a combustible mixture, Fuel 181, 2002, pp1761-1765.

Schulz, C. and Sick, V., Tracer-LIF diagnostics: quantitative measurement of fuel concentration, temperature and fuel/air ratio in practical combustion systems, Progress in Energy and Combustion Science, Volume 31, Issue 1, 2005, Pages 75-121.

Schmieder, R.W., Combustion applications of laser-induced breakdown spectroscopy, Sandia National Laboratories, Sand81-8886, 1982.

Tachibana, S., Zimmer, L., and Suzuki, K., Study on turbulent premixed flames of a low-swirl burner, Journal of the Combustion Society of Japan, 46(137), 2004, pp17-23.

Zimmer, L., Tachibana, S. and Suzuki, K.: Local equivalence ratio measurements using Laser Induced Plasma Spectroscopy, 2005 Asian Joint Conference on Propulsion and Power, 2005