Experimental study of gasoline direct injection spray using quantitative laser induced fluorescence in a firing SI engine.

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FARLIF (fuel-air-ratio by laser induced fluorescence) has been used to quantitatively investigate mixture process during injection in a firing direct-injection gasoline engine. Influence of operating conditions on fluorescence measurements has been especially studied to guaranty the validity of fuel-air ratio fields. Even though FARLIF method enables to get a fluorescence intensity proportional to fuel-air ratio, we demonstrate that controlling fuel-air ratio either by varying injected fuel quantity or by modifying air charge leads to two different rates of change in fluorescence signal. We therefore developed a specific calibration method taking into account those parameters and thus providing quantitative fuel-air ratio fields during injection.

1. Introduction

In order to enhance performance of future gasoline direct injection engines, it is necessary to precisely understand injection and mixture processes. Fuel distribution in the combustion chamber indeed strongly influences flame initiation, especially in stratified mixture [7,12].
Many works have been carried out to investigate injection into optical engines using planar laser induced fluorescence (PLIF) but a few propose quantitative results. As a matter of fact this technique is difficult to apply to engines studies because of high pressure and thermodynamic variations in the combustion chamber.
The FARLIF (fuel-air ratio by laser induced fluorescence) method, developed by Reboux et al [8,9,10] theoretically provides a linear evolution of fluorescence intensity versus fuel-air ratio, independently of pressure. However, applying this technique in a direct-injection spark-ignited engine requires particular precautions. We demonstrate in this paper how operating conditions have to be taken into account when quantitative results are needed

2. Theoretical background

FARLIF theoretical model is based on a two-levels model of fluorescence. The number of excited molecules depending on the time $N_2(t)$ can be deduced from the Einstein equation and written as follows [8] :

$$N_2(t) = \frac{N_0 U_\nu B_{12}}{(B_{12} + B_{21})U_\nu + A_{21} + Q_{21}} \left\{ 1 - e^{-\left[(B_{12} + B_{21})U_\nu + A_{21} + Q_{21}\right]t} \right\} \quad (1)$$

where A_{21}, B_{12}, B_{21}, Q_{21} are the Einstein coefficients for spontaneous emission, absorption,

stimulated emission and quenching respectively, N_0 is the initial population of tracer molecules (proportional to fuel concentration) and U_ν is the spectral energy density of the laser beam.
Considering a case of low excitation rate and a quenching rate higher than spontaneous emission equation (1) can be simplified as follow [8] :

$$N_2(t) = \frac{N_0 U_\nu B_{12}}{Q_{21}} \left\{ 1 - e^{-Q_{21} t} \right\} \tag{2}$$

The fluorescence signal measured is proportional to the time integrated population of excited molecules. When integrated between t=0 and t=∞, the former equation gives the fluorescence signal intensity Φ_{ft} as follows :

$$\Phi_{ft} = \frac{\Omega}{4\pi} A_{21} V \varepsilon h \nu U_\nu B_{12} T_1 \frac{N_0}{Q_{21}} \propto \frac{N_0}{Q_{21}} \propto \frac{[\text{fuel}]}{[O_2]} \propto \text{fuel} - \text{air ratio} \tag{3}$$

It now comes that the intensity is proportional to the ratio N_0/Q_{21}. As the tracer is added to the fuel and is chosen to be quenched only by oxygen, we can consider that N_0 is proportional to the fuel concentration and that Q_{21} is proportional to oxygen concentration. We can therefore conclude that fluorescence is linear with the fuel-air ratio.

3. Experimental setup

The engine used for this study is the same as the one used by Georjon et al in a previous work [3]. It is a single cylinder direct-injection spark-ignited four-valves engine equipped with an elongated piston which enables optical access through the piston head and through the cylinder head (fig. 1 and 2).

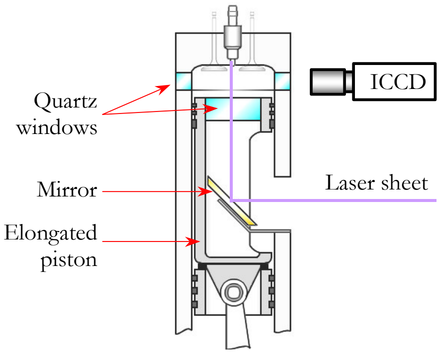

Fig. 1. Optical arrangement of the engine.

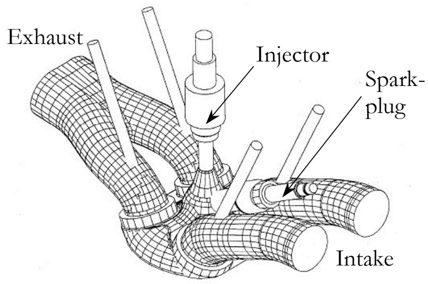

Fig. 2. Geometry of combustion chamber

In order to match the FARLIF hypotheses defined by Reboux et al [8], the fuel tracer is toluene added to iso-octane by 5% and the excitation laser wavelength is 248 nm provided by a KrF excimer laser. The fluorescence signal is filtered with a band-pass filter and recorded by an intensified charge coupled device (ICCD) Princeton Instruments PI-MAX camera.
All the calibration study has been carried out with an horizontal laser sheet passing through the cylinder head windows and a camera looking through the piston window via the mirror. The injection study has been then carried out with this configuration as well as with an inverted one (vertical laser sheet and looking through cylinder head window).
For each operating condition, a set of 50 images is recorded and averaged. The fluorescence intensity value presented in the further plots is taken as the mean grey level value in the visualization area.

4. Results and discussion

4.1. Fuel-air ratio dependence

According to Reboux et al [8,9,10], fluorescence intensity varies linearly with fuel-air ratio and does not depend on the pressure when it is higher than 3 bars. This can be verified by measuring fluorescence intensity and compare it to fuel-air ratio measured by a lambda sensor (fig. 3). We can notice a good linearity of fluorescence versus fuel-air ratio but we also remark a substantial difference in intensity depending on the visualization timing. This is due the temperature evolution during the compression stroke which modify the quenching rate of oxygen molecules [2]. Figure 4 shows the evolution of fluorescence during compression plotted against temperature calculated from pressure measurements using a polytropic hypothesis. A correction depending on temperature is therefore applied to images to balance this phenomenon.

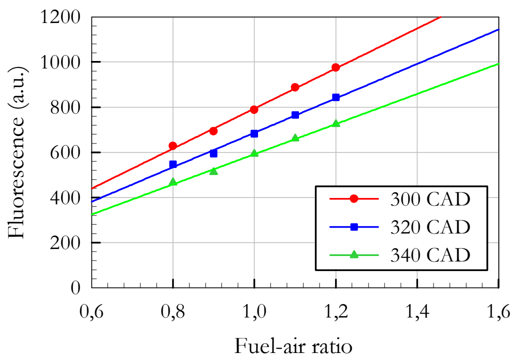

Fig. 3. Fluorescence intensity evolution plotted against fuel-air ratio when varying injection duration and keeping air charge constant

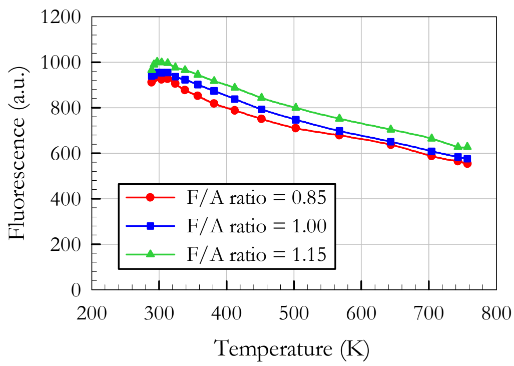

Fig. 4. Fluorescence intensity evolution during the compression stroke plotted against temperature.

4.2. Air charge effect

When applied to homogeneous mixture investigation, the calibration procedure described above is sufficient. But with the aim of studying stratified mixture, influence of air charge has to be taken into account. As a matter of fact, homogeneous operating mode is limited to partially-close-throttle loads to avoid damages on the windows of engine. An inlet pressure of 600 mbar has been defined as the limit for our engine when running in homogeneous mode. The measurements in stratified mode require a wide-opened throttle, that is to say an inlet pressure of about 1000 mbar. It means that calibration and experiment will not be carried out in the same conditions of pressure and oxygen concentration.

We therefore decided to study separately effect of air amount and fuel quantity. Air charge is controlled by a motorized throttle and quantified by the pressure in the inlet port. Fuel quantity is characterized by the injection duration. Those parameters are directly proportional to the mass flow rate of fuel and air.

As previously shown on figure 3, a variation of injection duration keeping air charge constant leads to linear evolution of fluorescence signal versus fuel-air ratio. Conversely, when varying air charge while keeping fuel quantity constant, we get an hyperbolic decrease which becomes linear when plotted against fuel-air ratio (fig. 5) because oxygen concentration appears in denominator of fuel-air ratio. However, we can notice that the slope is different whether the fuel-air ratio variation is achieved by a change of fuel quantity or air charge (respectively fig. 3 and 5).

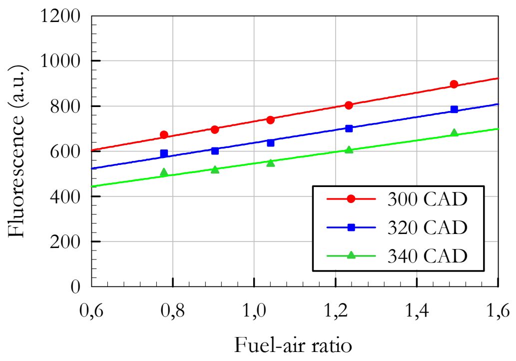

Fig. 5. Fluorescence intensity evolution when varying inlet pressure and keeping injection duration constant

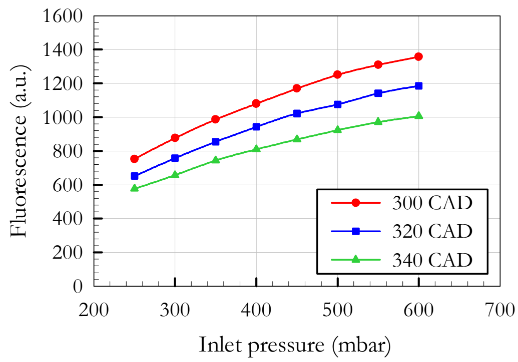

Fig. 6. Fluorescence intensity evolution when varying inlet pressure and keeping fuel-air ratio constant by adjusting injection duration.

It implies that fluorescence intensity varies with air charge even though the fuel-air ratio is constant. Figure 6 shows the result of an experiment where air charge has been changed and injection duration has been constantly adjusted to keep fuel-air ratio constant. It comes that fluorescence signal strongly rises when inlet pressure increases.
An explanation of this observation can be found by reformulating equation 3 of theoretical model by the following one, where A, B, C and D are constants :

$$\Phi_{ft} \propto \frac{A \times [\text{fuel}] + B}{C \times [O_2] + D} \tag{4}$$

This formulation is in agreement with the two different slopes observed when plotting fluorescence against fuel-air ratio by varying either fuel concentration or air charge. But this formula does not allow to consider that Φ_{ft} is directly proportional to fuel-air ratio. This could explains why fluorescence intensity varies when air charge changes even though fuel-air ratio is kept constant (fig. 6).

4.3. Calibration procedure

In order to get the calibration curve giving the relationship between fluorescence intensity and fuel-air ratio at 1000 mbar, we will have to extrapolate the curves obtained within the range of 200 and 600 mbar.
Without any fuel injected we know that the fuel-air ratio is equal to zero. The fluorescence intensity measured is therefore equal to the noise due to environment. It gives us a reference point of the calibration curve.
Then, we extrapolate the curves obtained when varying air charge and keeping injection duration constant. We know that the decrease of fuel-air ratio when increasing the inlet pressure is hyperbolic because oxygen concentration appears at the denominator of fuel-air ratio. We can therefore determine theoretical fuel-air ratio at 1000 mbar using those injection durations (fig. 7). The same type of extrapolation is applied on fluorescence curves against inlet pressure to get the theoretical fluorescence intensity corresponding to the fuel-air ratios previously determined (fig. 8).

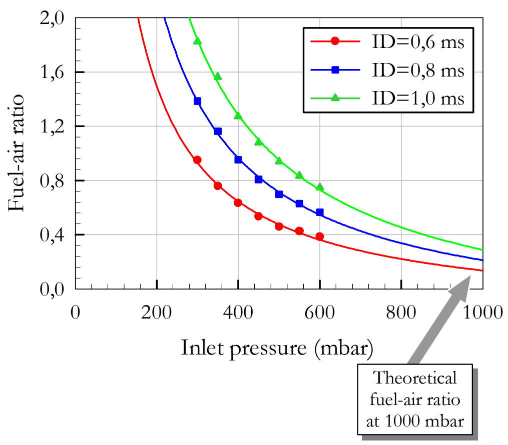

Fig. 7. Obtaining of theoretical fuel-air ratio at 1000 mbar by extrapolating fuel-air ratio evolution when varying inlet pressure and keeping injection duration (ID) constant.

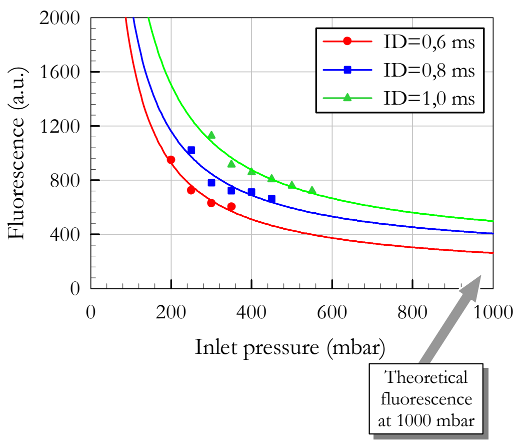

Fig. 8. Obtaining of theoretical fluorescence at 1000 mbar by extrapolating fluorescence evolution when varying inlet pressure and keeping injection duration (ID) constant.

Finally, we also extrapolate curves obtained by varying air charge and keeping fuel-air ratio constant in order to get a more precise calibration curve. The equation used to fit this curve is a rational one with 3 parameters a, b and c of type :

$$y = \frac{1 + ax}{b + cx} \tag{5}$$

Figure 9 shows the result of this regression and provides new couples of values of theoretical fluorescence intensity and fuel-air ratio.

Gathering those theoretical couples of values and fitting them with a linear regression, we can obtain the relationship between fluorescence and fuel-air ratio (fig. 10). Images recorded in wide-opened throttle conditions can therefore be translated into quantitative fuel-air ratio fields.

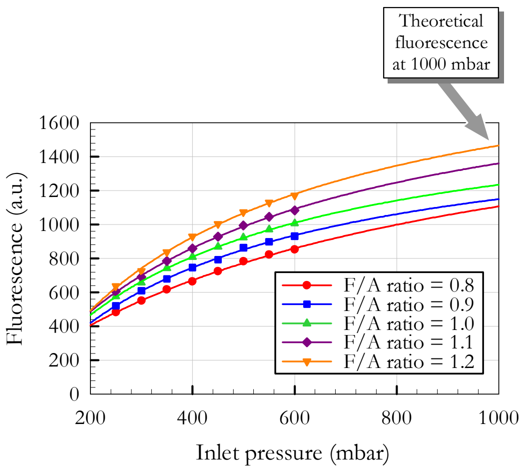

Fig. 9. Obtaining of theoretical fluorescence at 1000 mbar by extrapolating fluorescence evolution when varying inlet pressure and keeping fuel-air ratio constant.

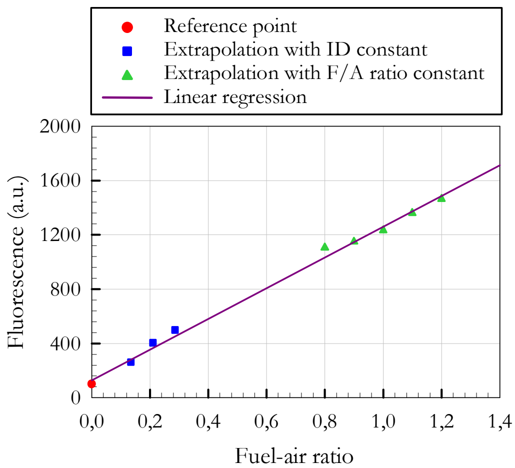

Fig. 10. Principle of obtaining the theoretical calibration curve at 1000 mbar.

4.4. Spray visualization

Once the calibration procedure carried out, we have measured fuel-air ratio fields during the injection process of our engine running in stratified mixture configuration. Mean evolution of the spay viewed through the cylinder head window is presented on figure 11. It is compared with liquid phase visualization obtained by Mie scattering just by removing the filter. Both are obtained by averaging 50 individual non consecutive pictures.

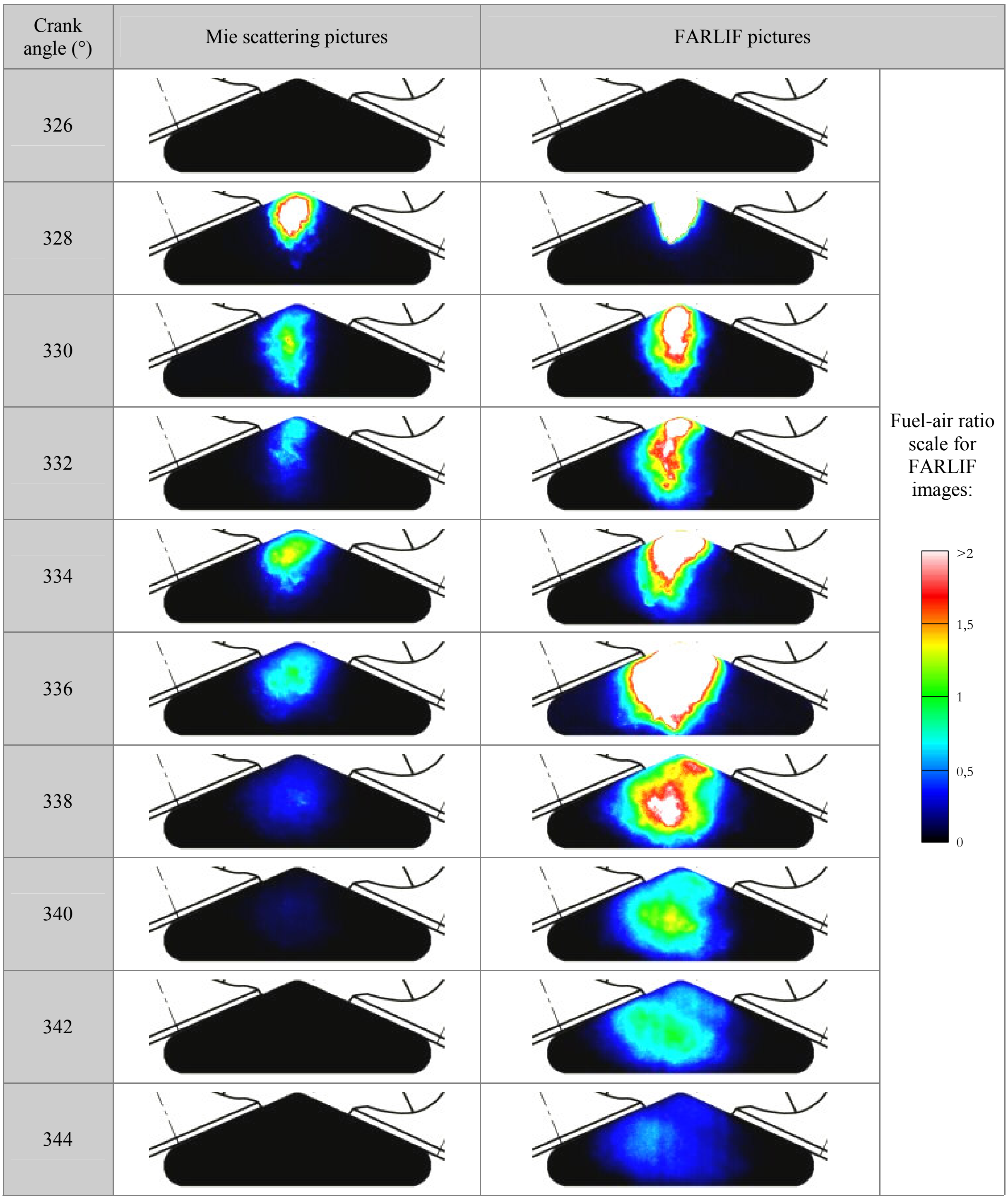

Fig. 11. Averaged images of spray development by Mie scattering and FARLIF in stratified conditions (Start of injection : 318 CAD - Ignition command : 333 CAD)

The fuel-air ratio scale for FARLIF images has been intentionally saturated beyond a value of 2. It is an arbitrary choice but we can consider that combustion can not exist beyond this value. For example, Sacadura et al [11] have chosen a limit value of 4 whereas Donghee et al [1] have chosen 1.5. Since we are especially interested in values around stoichiometry, the choice of scale limit is not essential.
In fact, areas where fuel-air ratio is superior to 2 correspond to non-vaporised fuel, as shown by the Mie scattering pictures. We can see a good agreement between liquid presence and high fuel-air ratio areas. Liquid phase pictures are useful because fluorescence does not enable to distinguish liquid and vapor phases.
We can notice on this evolution a first step of injection corresponding to the "sac volume" of injector (from 328 to 332 CAD) [12]. This first fuel quantity begins to vaporize before the main spray appears (at 334 CAD), first under liquid phase and then vaporizes progressively. Subsequently, flame reaches visualization area and consumes the fuel until fuel-air ratio appears to be zero.
A comparison between fuel-air ratio fields obtained by the two different optical accesses has also been achieved. A separated calibration following the procedure described previously has been carried out for each optical configuration. Taking into account the position of each measurement plane, we can see a good concordance between the two types of pictures, which let us think that our calibration method is viable (fig. 12).

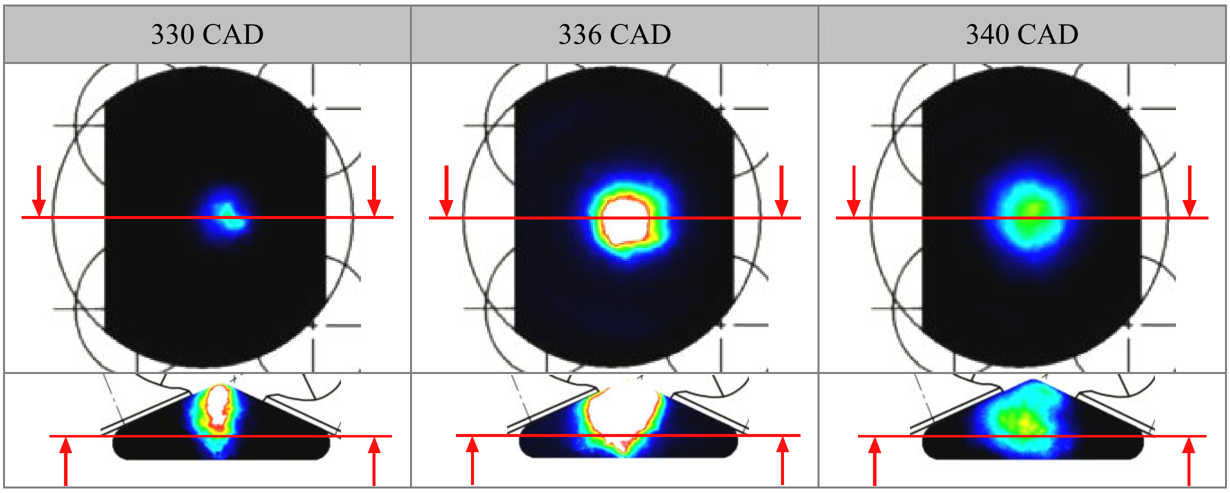

Fig. 12. Comparison of fuel-air ration fields obtained by the two different optical accesses

One possible problem of this method appears in high density liquid areas. As a matter of fact, when the laser sheet encounters dense liquid area, Mie scattering can be powerful enough to lighten molecules located outside the laser sheet and generate extra fluorescence leading to an overestimation of fuel-air ratio [4]. This bias is hard to quantify but the comparison of the results obtained by the two measure planes is a good way to note that pictures do not seem to be affected by this phenomenon.

Another experiment has been carried out to evaluate cycle to cycle dispersion. For example, fig. 13 shows individual pictures recorded just before the ignition command. We can observe very important spatial dispersion between the different pictures. Unfortunately, the spark-plug is not visible through the window and therefore, we can not measure the dispersion directly at ignition point. However, we can expect a very high dispersion of fuel-air ratio around the spark-plug which explain why it is difficult to obtain a good stability of combustion in stratified mode.

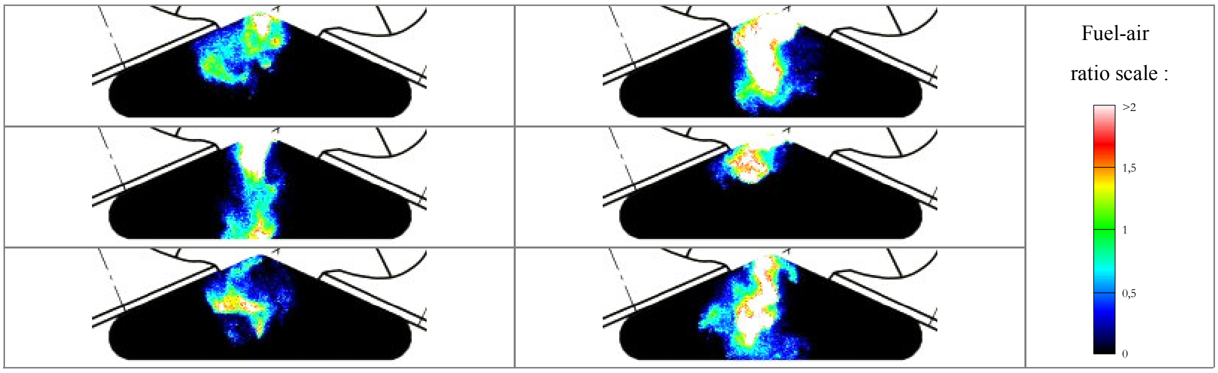

Fig. 13. Individual fuel-air ratio fields at ignition timing.

5. Conclusion and prospects

Quantitative fuel-air ratio fields during injection in stratified mode have been obtained thanks to FARLIF method.

However, we have focused the influence of operating conditions which can modify intensity of fluorescence. In particular, we have demonstrated that controlling fuel air-ratio either by varying injected fuel quantity or by modifying air charge leads to two different rates of change of the fluorescence signal.

An accurate calibration taking into account those parameters as well as temperature has therefore been carried out to enable quantitative fuel-air ratio measurements during injection in stratified air-fuel mixture.

Afterwards, we will apply FARLIF to a new geometry of combustion chamber to study influence of different parameters (such as injection pressure, injector geometry, injector implementation) on mixing process and cycle to cycle stability.

6. References

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