

EXPERIMENTAL STUDY OF FLAME-WALL INTERACTION BY PARTICLE IMAGING VELOCIMETRY TECHNIQUE

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ABSTRACT

In many industrial combustion chambers, the flame-wall interaction is still a relevant research subject owing to the fact that this complex phenomenon can induce high HC emissions. In the case of I.C. engines, it seems to be interesting to get new experimental data about flame quenching and local stretch rate effect on the flame. For that, we have decided to develop an experimental set-up which allows to be on head-on quenching configuration as in real case. By using Tomographic Particle Imaging Velocimetry and with the development of new algorithms, the determination of different quantities such as flame velocity, reactant one and flame speed versus different stretch cases is available. Therefore the aim of this paper is to criticise and to propose different methods to estimate as well as possible the local flame speed. For that, our method was firstly tested on simplified cases : spherical propagation or analytically generated flame front. Finally, it was applied on our configuration where the approach of the wall give rise to strong local curvatures and velocity gradients.

1. INTRODUCTION

Inside Internal Combustion engines, a great part of the combustion process itself develops near the wall, inducing strong heat transfer due to the flame – wall interaction. In fact main studies have been focused on measure quenching distance as function of stoichiometric ratio, fuels and wall temperature to estimate the maximum of heat transfer, and then to quantify the unburned gas emission caused by this unburned layer. In fact several studies show that flame-wall interaction is not responsible of HC emission in normal conditions ($\phi \approx 1$) (Bechtel and Blint, 1982, Safman, 1984, LoRusso et al., 1980). However, new engine combustion strategies appear and the knowledge of flame-wall interaction is not yet sufficient. Therefore, new studies were performed (Lu, 1990, Ezekoye, 1992) but, with the development of the Direct Numerical Simulation, new conclusions about flame stretch effects near the wall appear and need new experimental approach (Angelberger, 1997, Poinso et al., 1993, Wischmann and Bruneaux, 1995, Popp and Baum, 1997).

The global objective of our work is to contribute to correlate flame-wall quenching and instantaneous heat transfer, dependant on wall temperature, in the case of perpendicular flame propagation to the wall (head-on-quenching). This experimental set-up allows to evaluate the importance of curvature effects associated to local strain rate on the local flame quenching, as Bradley et al. (1996), have done numerically.

Sinibaldi and al, (1998) defined the total stretch, κ as :

$$\kappa = \kappa_s + \kappa_c \quad (1)$$

where κ_s is the aerodynamic strain and κ_c the curvature components. κ_s and κ_c are defined as follows:

$$\kappa_s = \nabla_r \cdot \vec{V}_r \cdot \vec{n} \quad (2)$$

and

$$\kappa_c = S_d / R \quad (3)$$

where R is the radius of the local curvature flame, S_d the displacement speed of the flame relative to the unburned flame, V_r the velocity of the reactive gas and \vec{n} is the unit normal of the flame boundary.

Poinso et al. (1992) defined the flame displacement speed as function of V_f , the velocity of the flame as :

$$S_d = \vec{V}_f \cdot \vec{n} - \vec{V}_r \cdot \vec{n} \quad (4)$$

In this paper, Tomographic Particle Imaging Velocimetry technique was applied to characterise the flame speed, flame curvature and aerodynamics strain rate at the vicinity of the wall. To quantify the stretch effect on the flame behaviour it needs to apply good algorithms on tomographic images, particularly when the flame curvature gradients are important. As suggested Lecordier (1997), PIV technique can provide fresh gases velocity field and local burning velocity with the use of adaptive grid.

The purpose of this paper is to explain how it is possible to get local data of flame displacement and behaviour in this complex experimental configuration and how resolve the relations above ((2), (3) and (4)) to quantify the effects of wall on the flame. Indeed, as it can be seen in Figure 3, fresh gases velocity can have very different order of magnitude near the wall and so needs appropriate algorithms. Moreover, the local displacement of the contour can not be predicted as in the case of spherical propagation and even for certain configurations, the displacement can be locally opposite (negative curvature). Lastly, the shear stress near the wall is important and induces important tangential components.

So we have tested different available algorithms to estimate as well as possible the local flame speed. In following parts, we present the experimental set-up, the methods applied and the comparison between the different estimates obtained.

2. EXPERIMENTAL FACILITIES

Our experimental device is a steel tube 82x82x350 mm³: one end is free to make isobaric combustion, whereas the other end is the wall. Four windows, perpendicular to the surface, provide optical accesses. To ensure the good equivalence ratio value, the chamber is pumped at vacuum before fill it. The premixed mixture is prepared inside a tank and conducted to the combustion chamber via electrovalves. Ignition of the fresh gases is made by a spark from point-to-point electrodes at the centre of the vessel as it can be seen on the scheme in Figure 1.

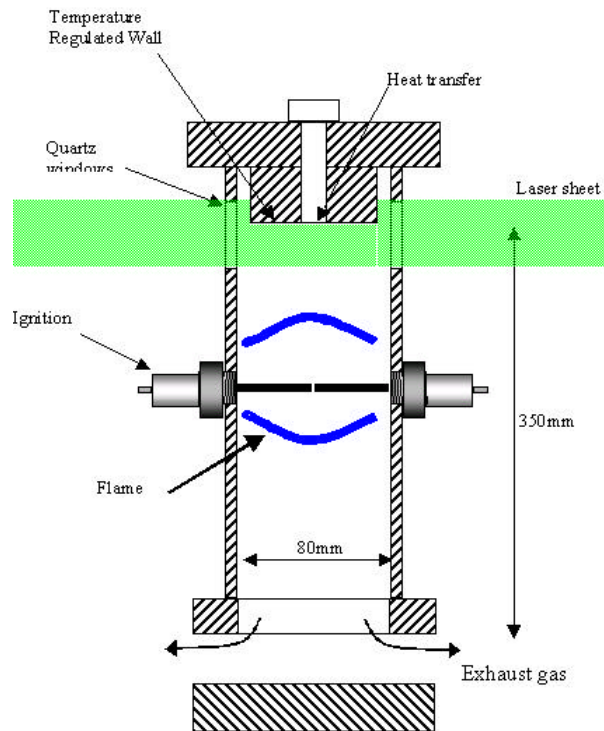


Figure 1 - Scheme of the Combustion chamber.

The methane-air flame is a quasi one-dimensional laminar isobaric one, freely developed inside a pipe. Different developments of flame can be obtained by changing the distance between the electrodes and the wall: a spherical propagation if this distance is less than half size of the tube (Fig 2a) or a unstable flame when the distance is greater than the half size (Fig 2b). All the sequence is controlled with a counter timer card. As the temperature wall can be regulated from 300 to 900 K and equivalence ratio can range from 0.6 to 1.2, results on understanding interaction processes will be directly useful for internal combustion engines.

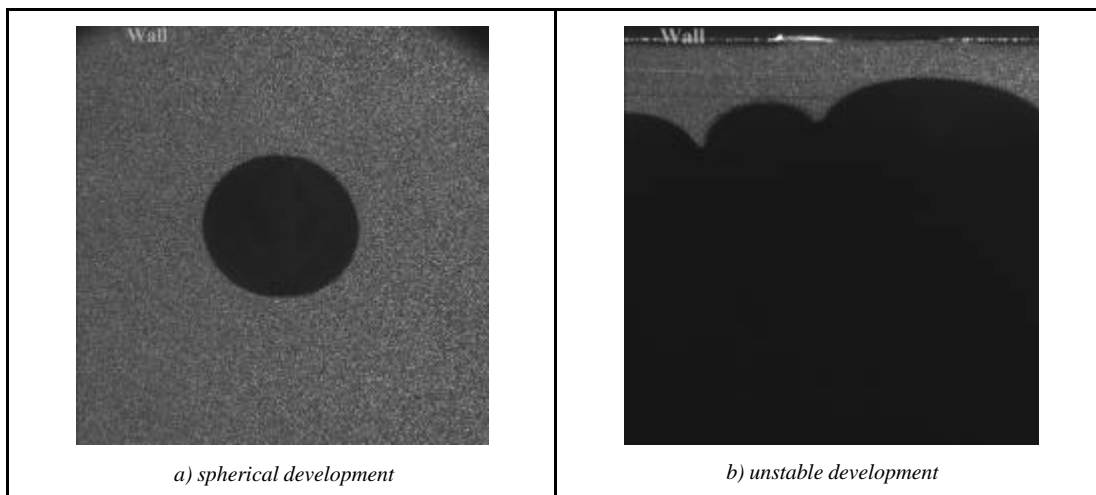


Figure 2 - Example of laser tomography images.

A double cavities pulsed Spectra Physics Nd:Yag laser is used to provide two laser sheets (about 500 μm thickness and 40 mm height with 100 mJ per pulse). The frequency of the pulse is 10 Hz and the time between each pulse, Δt is 200 μs . The images of light scattered by silicon oil droplets (typically 5 μm diameter) were recorded on a double

frames Kodak PIV camera (1008x1016 pixels). One pair of images is obtained at each flame propagation. The CCD resolution with adequate magnification was 39 $\mu\text{m}/\text{pixel}$. To be ensuring that no spontaneous flame emission disturbs the images, an interferential filter, centered at 532 nm, is placed front of the CCD camera CCD. A TSI synchronizer controls the PIV system.

3. IMAGES ANALYSIS

Due to the fact that oil droplets burn inside the flame front, the boundary between products (dark zone) and reactants (white zone) is relatively clear. To estimate this boundary, image analysis process was done under Matlab environment: before using threshold procedure, a 3*3 median filter is used. So individual images can be used to study flame behaviour at the vicinity of the wall and to determine boundaries between the flame and the wall.

In other hand, the pair of images allows instantaneous flow fields estimate by Particle Imaging Velocimetry. The computation of velocity field is firstly obtained by the cross correlation algorithm developed by TSI (Insight software). An example of a velocity field associated with flame fronts is presented in Figure 3. For this example, the interrogation grid was 32x32 pixels² with an overlapping of 75%.

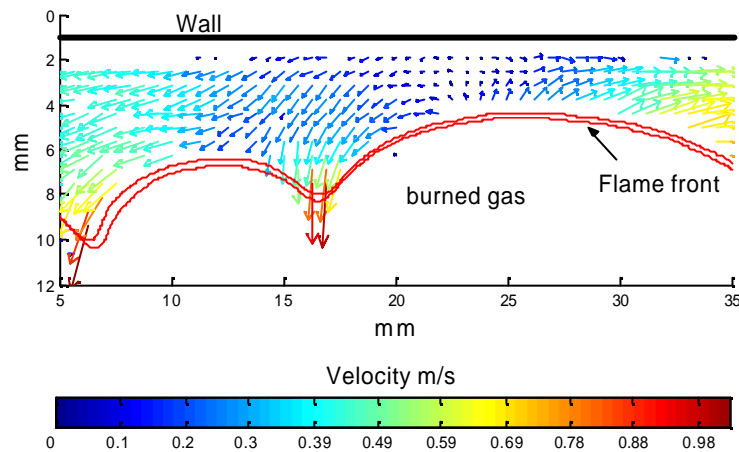


Figure 3 – Flow field at the vicinity of the wall, with flame front propagation

To study local flame characteristics, the contour of flame front is calculated from binary images. The classical method consists of a polynomial or a spline interpolation to filter the edge. But with this method, the cut-off frequency level is not controlled. To avoid this drawback, Lecordier (1997) used a Fourier decomposition to remove high frequency noise. We have chosen to use a low pass Hamming Finite Impulse Response filter, calculated on 21 pixels (Pajot (2000)). The low-pass cutting frequency f_c defined from the Nyquist frequency is 0.5 pixel^{-1} . All points of the contour are separated of 1 pixel, we multiply this period by twice to obtain our Nyquist frequency. We filter all structures greater than 10 pixels (0.39 mm) and the new contour has a constant sampling step.

With the co-ordinates of the contour, we can calculate the geometrical characteristics as the unit normal direction and the local curvature.

4. CALCULATION AND COMPARISON BETWEEN DIFFERENT ESTIMATES OF FLAME SPEED.

We have chosen two examples of flame propagation at the vicinity of the wall: the first case corresponds to a quasi-spherical propagation (Fig 2a), so with low shear stress and the second one to a case with strong gradient of fresh gas velocity (Fig 2b). The local instantaneous propagation velocity of the flame (S_d) can be calculated using equ. 4. Therefore, it needs to have, in fact, at each point of the flame front, the flame velocity (V_f) and the reactant one (V_r).

4.1. FRESH GAS VELOCITY MEASUREMENT:

To estimate the reactant flame, (V_r), some authors use classical regular mesh grid PIV and interpolate locally the velocity or take the velocity value nearest the local flame front location as it presented in Figure 4. But with this estimate, where the curvature is important, we can take a velocity value estimated as far as 3 mm far from the contour location.

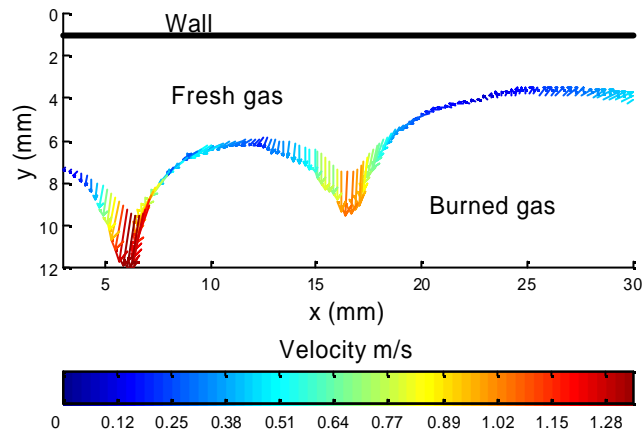


Figure 4 – Reactant velocity field at the flame front

Therefore, we have chosen to apply the adaptive grid method developed by Lecordier (1997) along the flame boundary. For that, we use the Matpiv algorithm (Sveen, 2000, Raffel, 1998) under Matlab environment. The windows of analyses are oriented with the normal direction of the first flame front and are tangential of each flame front (Fig 5). The grid rotation is calculated with a bilinear interpolation of the original local image. Bicubic interpolation has been tested, but any benefits in terms of image quality are observed. We calculate the correlation of both windows contained fresh gases and interpolate the correlation peak with a 3*3 gaussian function to obtain a subpixel precision. Validation of the vector is made by taking a Signal-Noise ratio (SNR) greater than 1.4. The interrogation windows size limits the minimum eddy size measurement as it can be seen in Figure 5. In our configuration, this size is about 0.6 mm using a 16 X 16 correlation grid size. An example of fresh gas velocity obtained is presented in Fig 6. Unhappily, even if the value of the velocity is certainly more “real”, some vectors were not validated with a $SNR > 1.4$, as at the location of the strongest curvature, because an important part of the calculation grid contains products gases and so no oil droplets.

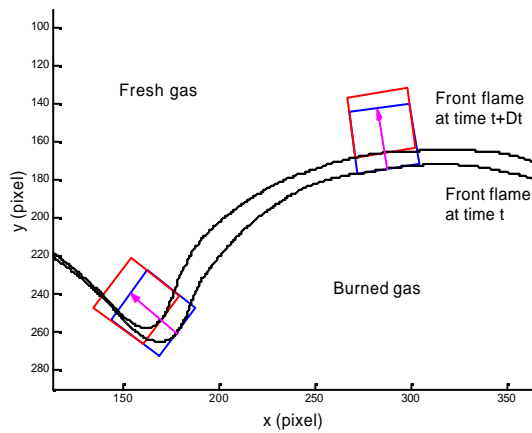


Figure 5 – Definition of the adaptive grid

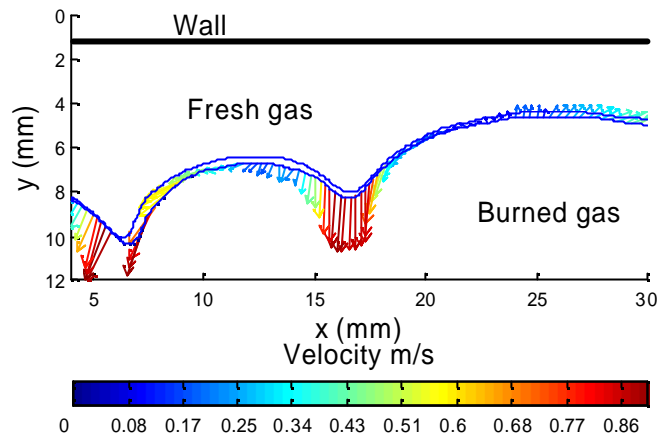


Figure 6 –Determination of the fresh gases velocity via adaptive grid method

4.2. FLAME SPEED VELOCITY

Flame speed velocity is usually measured along the flame front by dividing the distance dx along the normal line at each point by the time between images Δt . This method has been used by many authors (Lecordier 1997, Renou 1999) for spherical laminar and turbulent flames. However two limitations occur :

- First, one is due to the error introduced by the displacement between two contours. For example, if the flame displacement is $V_f = 2.5 \text{ ms}^{-1}$ and $\Delta t = 200 \text{ ms}$, the distance dx is equal to 0.5 mm (or 12.8 pixels) whereas the precision is only one pixel, involving an error of 7.8%. Therefore, it would be necessary to increase Δt to increase dx .
- Secondly, the combining effects of stretch and convection can not help to predict the flame displacement. Figure 7 illustrates this bias problem : the normal direction converges to the same point, i.e. the centre of the first flame front local curvature, but does not predict the flame front translation. Therefore, the solution is to reduce Δt between two images but limits the spatial resolution.

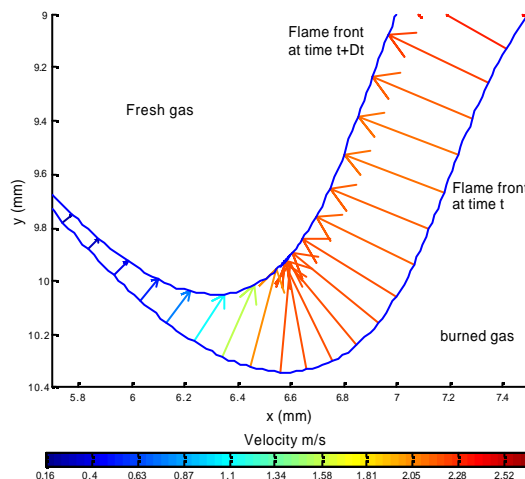


Figure 7 - Displacement of the flame front by classical method

Therefore, we have chosen to develop a method to improve this estimate of the flame displacement speed. This technique consists of recognising locally the geometrical form of the boundary flame with the standard cross-correlation calculation used in PIV, similarly to Optical Character Recognising softwares. We tested this algorithm with spherical flame where any bias is made using classical distance method.

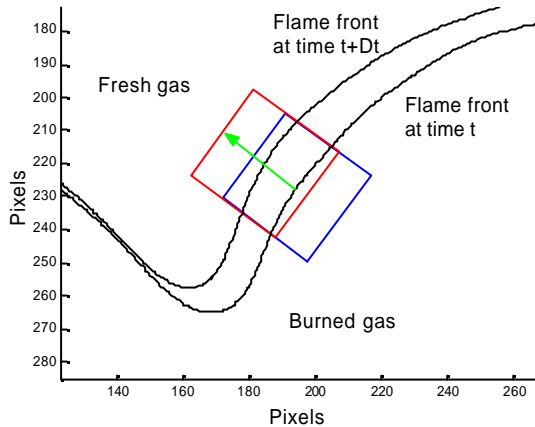


Figure 8- Interrogation windows

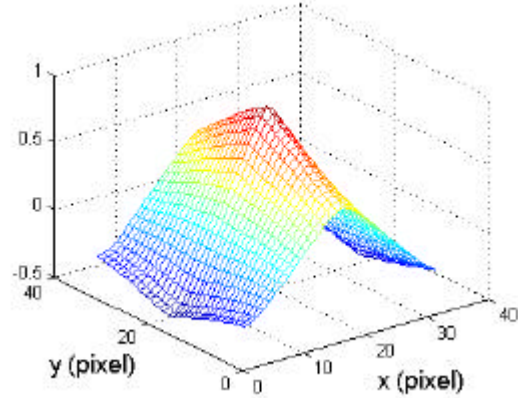


Figure 9- Example of correlation function

The different steps of this algorithm are:

1. Binarisation of the images.
2. Flame front determination, filter and calculation of the unit normal direction.
3. Rotation and translation of windows centred on the flame front as shows Figure 8.
4. Calculation of the cross-correlation function, interpolation of the peak and fit it with a 2D Gaussian function to find the displacement (Figure 9)
5. Validation of the displacement using the height of the correlation peak.

In Figure 10, we have reported the results obtained with three ways of estimate :

- The classical method, i.e. the estimate of the displacement of the flame front by normal direction prolongation
- Our method (called F.F.R.), described above, applied on raw images
- Our method but applied on binarised images (FFRB).

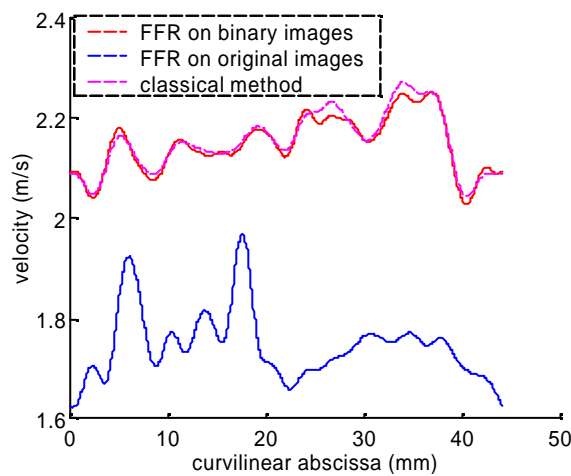


Figure 10 – Comparison of different estimates of the flame front displacement

Due to the spherical configuration, the classical method is well known to give good estimate of the flame propagation speed. Therefore, the Front Flame Recognition method, using binarised images provides good results. Indeed, the error between the classical estimate and the FFRB is lower than 1 %. On the contrary, the FFR applied on original images gives more error. In fact when we observe the correlation repartition, fresh and burned gases do not contribute in the same part of the correlation as proves Figure 11.

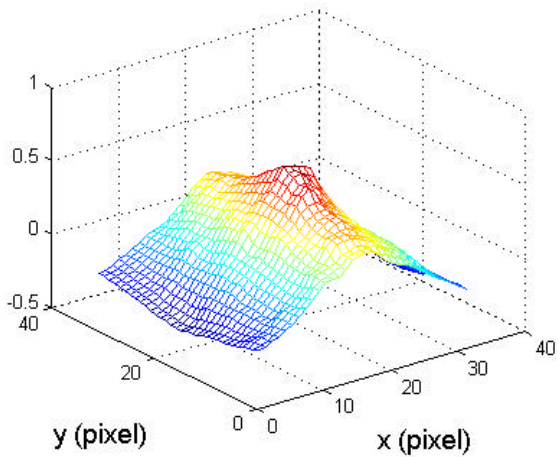


Figure 11 – Effect of reactants and products contribution on the correlation function shape.

To improve better the FFR Binarised method (FFRB), we have generated a flame 2D surface (512 by 512 pixels²) with strong stretch, as it can be seen in Figure 12. This surface is subjected to a fixed growth, simulating flame front displacement. With this testing case, we firstly estimate the displacement by the classical method and we can see (Figure 13 a) that where the stretch is important, the velocity vectors are not well determined. In other hand, with FFRB method, the propagation of flame front seems to be better estimated (Figure 13b).

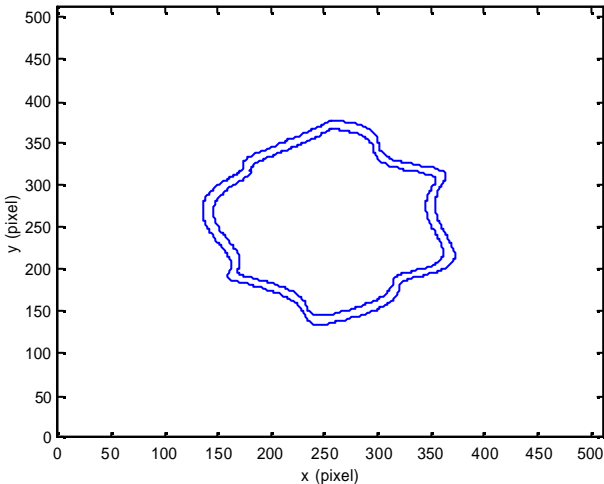


Figure 12– Flame front displacement generated analytically

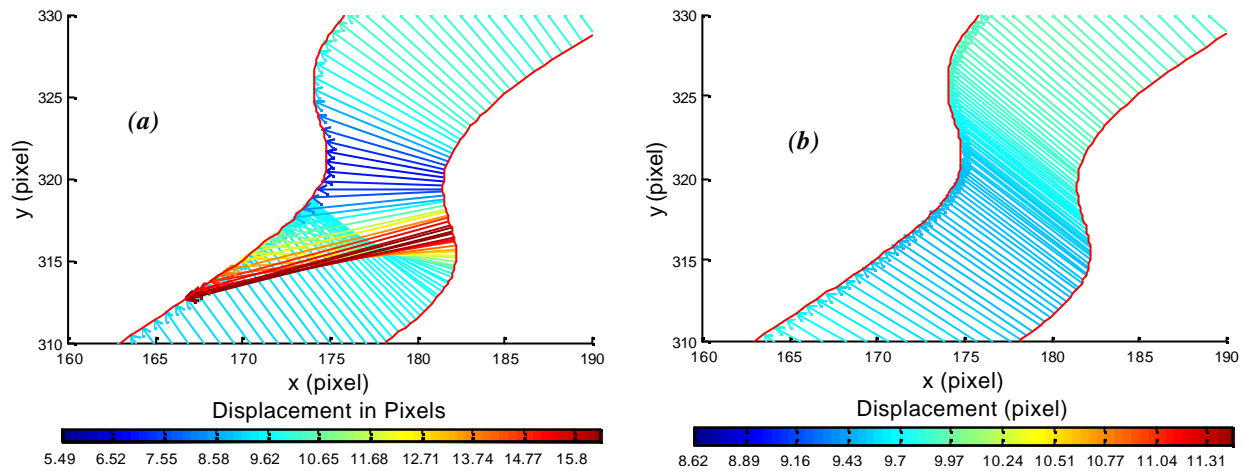


Figure 13 – Flame velocity determined by both methods

But, we must keep in mind that with classical determination, the velocity obtained is this one normal to the flame front and with FFRB, it is not the case. This feature can be clearly observed in Figure 13. So, if one wants to compare these methods, it is necessary to estimate the normal component of the velocity obtained analytically with FFRB method. Therefore, with our generated flames surfaces, we can compare the displacement applied with the one estimated by FFRB. A good agreement is obtained (Figure 14a). So, if we take the normal component of this velocity and compare with the classical determination, the error can be very important as high as 100%, especially where high curvatures are encountered (Figure 14b).

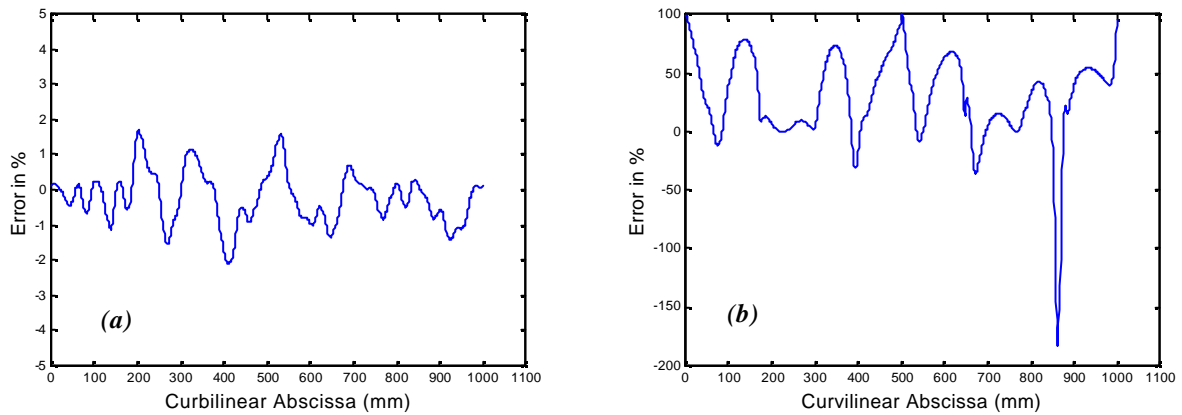


Figure 14– Errors between different estimates.

So finally, if we apply this method, i.e. the Flame Front Recognition On Binarised Tomographic Images, on the same case previously used (Figure 7), we can conclude that the determination of the flame velocity is better with this method and is relevant for flame front with strong curvatures as we can see on Figure 15.

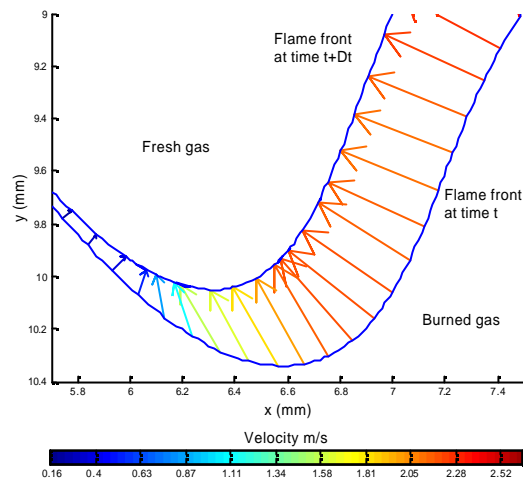


Figure 15 – Flame Velocity estimated by FFRB method.

5. CONCLUSION AND PERSPECTIVES

In this presentation, we have shown that with appropriated algorithms applied on Particle Imaging Velocimetry images, the flame speed can be better estimated. In fact, the difference between classical algorithm and the Flame Front Recognition method applied on Binarised Tomographic flames can be negligible in the case of classical spherical propagation. But in the case of flame propagation at the vicinity of a wall, interesting configuration for a better understanding of the flame-wall interaction in the S.I. engine combustion chamber, the strong level of curvature and velocity gradients make that this method can give relevant results.

This method was only applied in the case of classical Particle Imaging Velocimetry technique to validate it. In fact, new experimental data will be get to follow flame structure behaviour at the approach of the wall and for that the use of high speed Tomographic Piv technique will be great appropriate.

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