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Simultaneous Development of Time Resolved Laser Tomography and PIV for Flames Propagation Studies

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***Abstract*:** An understanding of flame propagation needs the knowledge of the flame location and of the velocity field near the front. Time resolved laser Tomography coupled with high resolution cross correlation PIV has been developed. The method is based on the use of a copper vapor laser and a high-speed camera. The seeding level used for tomography provides an excellent resolution of the flame location and of the velocity vectors in the fresh gases. Experiment is conducted in a simulated engine where turbulence is controlled by means of a perforated grid. Interest is shown for the determination of laminar burning velocity and for the study of interaction between the flame front and the turbulent structures. Perspectives of stereoscopic PIV are also started on. It is shown that the existence of a normal component to the sheet plane of the velocity can lead to an erroneous flame velocity determination.

***Keywords*:** tomography, PIV, time resolved, stereoscopy, flame propagation.

1. Introduction

The first studies of Damköhler on turbulent premixed combustion have been focused on the velocity of propagation of the combustion zone, by looking at the similarities and differences with the classical laminar flame speed. The simple question concerning the direct links of these two quantities and the turbulence characteristics is not yet answered in a convenient way, fifty years after, although a large amount of knowledge has been accumulated.

One of the reasons why this (apparently) simple question has not been solved is that the flame displays several types of structures depending on the laminar flame characteristics compared with the turbulence characteristics. Another reason is that the flame itself, during its propagation, is able to modify the turbulence characteristics. This is mainly due to the heat release and volume expansion of burned gases.

One of the most important problems for flame propagation modeling is the difficulty to obtain simple and relevant experimental data, particularly in engines where large eddies are different from one cycle to another. An important step was reached in the 70s with the arrival of LDV (Laser Doppler Velocimetry). This non-intrusive method had provided many data concerning the velocity field in combustion chambers. However, the question is to know if the turbulent structures are only convected by burned gases expansion or if shear is generated by differential flame speed. The answer is probably a mixing of the two assumptions:

–Local flame speed is linked to front characteristics (curvature, length, and stretching).
–Front characteristics are influenced by local turbulence.
–Local turbulence can be affected by local flame speed.

We can say that a real progress is not possible in this way of the turbulence flame interaction knowledge if spatial and time resolved measurements are not performed.

An understanding of these problems has existed since laser sheet visualizations were used within combustion systems (Boyer, 1980) and various solutions have been proposed to overcome the limitations of using single sheet to 2D imaging (Lawes et al., 1998). The principle of laser Tomography is to illuminate fresh gases by means of small particles seeding in order to localize the reaction zone in the plane of the laser sheet.

In this domain of spatial measurements, a new way is now open with the recent development of Particle Image Velocimetry (PIV). The recent progress of PIV in the last years is essentially due to the exceptional evolution of computers and CCD cameras. One major point concerns the ability for these cameras to get two separated images within a short time (few microseconds) and to calculate velocity fields by using cross-correlation algorithms (Lecordier et al., 1994). Several advantages are linked to Cross-Correlation PIV compared to Auto-Correlation such as the sign of velocity vectors and the possibility to obtain very low particle displacement. The most important, for our purpose, is the possibility of using high concentration of particles providing good contrast pictures between the burned and the unburned region.

Unfortunately, the question of time resolution cannot be solved by using CCD camera (high speed CCD cameras have not solved this question of time resolution up to now). However, high speed laser Tomography resulting of the association of a copper vapor laser and a high-speed film camera can provide time resolved flame visualization and time resolved cross correlation PIV (Lecordier et al., 1994).

Now the problem of flames propagating in turbulent flows is widely dominated by the large structures that are essentially three-dimensional. The perspectives of stereoscopic PIV development (Prasad et al., 1993; Lecerf et al., 1998) is particularly interesting for turbulent flame applications.

The objective of this paper is to present the application to flame propagation of the high-speed Tomography associated to cross correlation PIV. For this purpose, high resolution PIV has been developed. Interest is shown for the determination of laminar burning velocities without the assumption of adiabatic temperature of the burned gases and for the study of interaction between the flame front and the turbulent structures. Stereoscopic PIV preliminary results show that it is a good tool to test if the displacement of the flame is within the laser sheet.

2. Development of the Method

2.1 PIV and Tomography

Nowadays, acquisition devices permit to acquire two or more successive images in high-speed flow with very short time delay (few microseconds). CCD cameras provide individual couples of images at the video rate and cannot be used for time resolved measurements. For this application high-speed film camera is required.

In the two cases, the existence of separated images allows the use cross-correlation PIV algorithm which affords significant advantages in comparison with auto-correlation. Keane and Adrian (1993) have made a presentation of this comparison. The most significant advantage of the cross-correlation is the measurement of a large range of velocities on the same flow that automatically includes zero and reverse velocities without having recourse to an external “image shifting.”

Because of the absence of central peak, cross-correlation compared to auto-correlation is particularly adapted for low particle displacements. Low displacements are to be considered with 3 dimensional flows to increase the probability presence of the same particle on the two exposures. In addition, it increases also the correlation peak level and consequently the detectability of velocity vectors.

Another major advantage concerns the maximum concentration of particles used for seeding. If the concentration is too important, it is not possible to extract the correlation peak position from the noise. The work of Rouland et al. (1994) and Rouland (1994) showed that with cross-correlation, the maximum concentration is higher compared to the level permit with auto-correlation. Figure 1 illustrates this property. The limit concentration limit C_L is defined when 50% of good vectors are statistically detected. C_L depends on particles displacement by mean of the normalized variable:

$$D_{\text{norm}} = \sqrt{X^2 + Y^2}$$

$$X, Y = \frac{x, y(\text{displacement in pixels})}{N_x N_y(\text{size of the windows in pixels})}$$

The concentration of particles is expressed as the percentage of pixels covered by image particles.

Values of C_L are significantly higher with cross-correlation. It is an important result because it shows that the seeding used for Tomography is suitable for PIV.

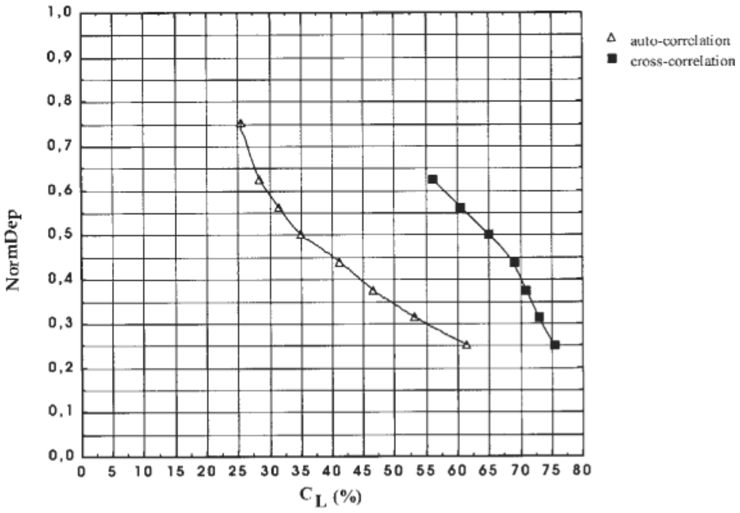


Fig. 1. Relation between the limit of particles concentration and the normalized displacement.

The flame Tomography is obtained by illumination of the particles by the laser sheet and by considering the change of concentration in the burned gases. If oil particles are used (silicon oil), the localization of the flame front is then obtained by thresholding. The resolution of the flame front position is directly linked to the concentration of particles, so the high level of concentration permits by the cross-correlation leads to good resolution of the flame front by Tomography.

Examples of flame Tomography and of a velocity field are given in Fig. 2. In this figure, the flame is spark ignited in a constant volume chamber (Lecordier, 1997). The level of particles concentration (silicon oil particles) gives an excellent resolution of the flame location and of the velocity vectors in the fresh gases.

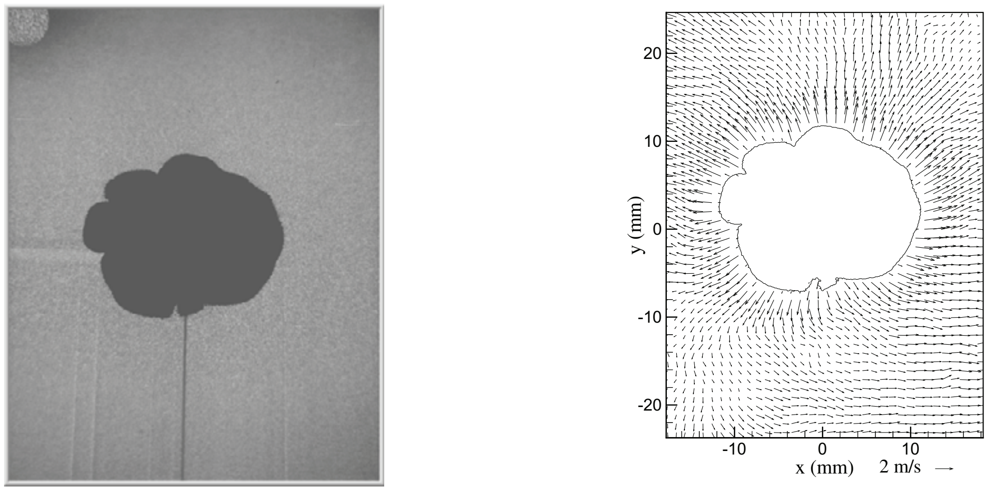


Fig. 2. Example of a flame Tomography and a cross-correlation velocity field obtained with a high concentration of particles.

2.2 High Resolution PIV

As it has been explained in Sec. 2.1, small displacement of particles is wished because only a few particles leave the interrogation areas from one image to the other and it increases the correlation level. For 3D flows (particularly in engines), particles can move in the laser sheet and no shift is possible to reduce the displacement value. In order to limit the loss of particles and consequently, the loss of information, the maximum displacement must not exceed the light sheet thickness. Otherwise, the sheet thickness should be increased (which would average the spatial field and lead to speckle risk) or the time between the two shots should be reduced. The main problem of the displacement reduction is the reduction of the velocity range.

In order to increase the precision and the velocity range for short displacements a new method has been developed by Lecordier (1997). A constant accuracy on the velocity measurement is obtained whatever the displacement values (Fig. 3). This method consists in iteratively translating and orientating the interrogation area (of a pixel fraction) until the cross-correlation peak is centered on zero displacement. In so doing, the bias on the position of cross-correlation maximum is lowered to 0.02 pixel, (Westerweel et al., 1997). The signal noise ratio (SNR) is then constant for large and sub-pixel displacements and the RMS for a constant velocity is significantly reduced. In addition, interrogation areas can be reduced after each iteration and it increases spatial resolution.

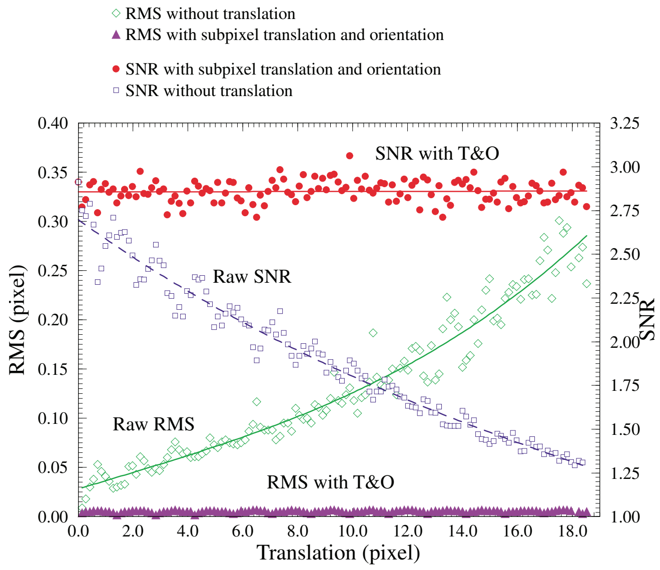


Fig. 3. Representation of the effect of the iterative process with translation and orientation of the interrogation areas (Lecordier, 1997).

This method is particularly interesting for stereoscopic PIV where the resolution for the velocity component normal to the sheet is linked to the capacity to detect very small displacement variations.

Another problem is the spatial resolution of the velocity field close to the flame front. The flame pictures exhibit an important difference of intensity between the burned and the unburned region. When a window of analyze contains this threshold, the correlation is disrupted and thus the velocity vector cannot be obtained. To resolve the velocity field close to the flame front, an adaptive grid has been constructed as explained in Fig. 4. Each window of analyze is placed on the two successive flame fronts and are oriented with the normal direction. With this procedure, they are shifted with the flame front displacement. This method will be very useful to determine the laminar burning velocity.

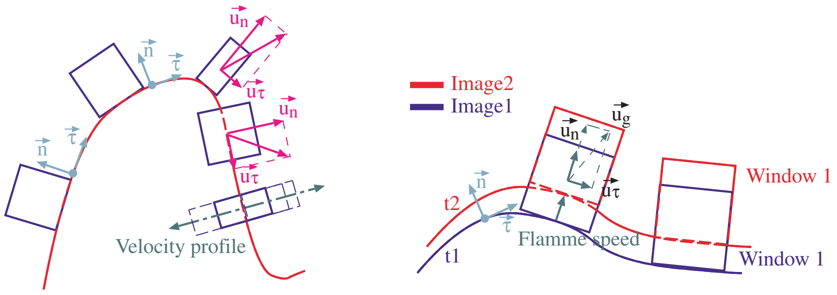


Fig. 4. Principle of the adaptive grid close to the flame front.

2.3 Stereoscopic Arrangement

Two methods exist for the stereoscopic configuration:

- –The translation method used by Prasad and Adrian (1993), where the two frames of each system (lens and camera) are parallel to the sheet and where each camera is shifted in its plane as explained in Fig. 5.
- –The angular method, where the two planes of each system make a fixed angle with the sheet.

The set up of the angular approach allows to work near the optical axis, limiting off-axis aberrations. But this method requires tilting the image plane to maintain the focus. In so doing, distortion effects due to varying magnification, (Hinsch, 1995) must be corrected with a numerical or an optical process.

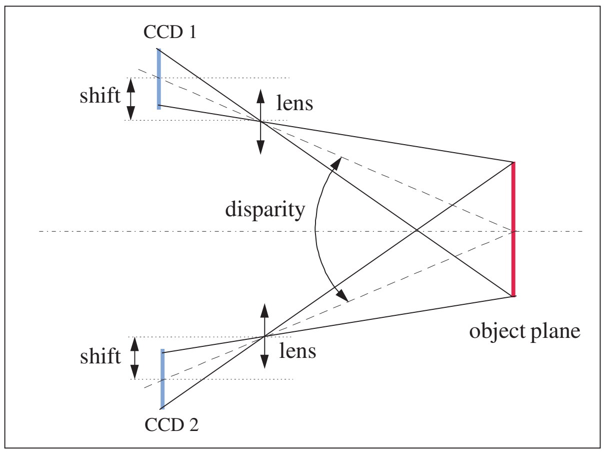


Fig. 5. Schematic diagram of the translation method for Stereoscopic PIV.

In this development, the translation method has been chosen (Lecerf et al., 1999). Coupled with the high resolution PIV method of Lecordier in an optimal configuration limiting off-axis aberrations, a good accuracy on 2D and therefore 3D measurements has been reached. The method has been validated on different experimental situations such as calibrated test images and isotropic grid turbulence.

2.4 Experimental Set up

The schematic of the experimental set up is in Fig. 6. To illuminate the flow field, an Oxford copper vapor laser (45 Watts) is used. It delivers 6.5 mJ per pulse with 100 ns pulse width at adjustable repetition rates up to 10,000 Hz. The laser can also operate in the burst mode down to single pulse operation.

The laser beam is focused with spherical and cylindrical lenses and directed to produce a 0.6 mm thick laser light sheet across the mid plane of the combustion chamber.

To obtain a time following of the flame propagation, a high-speed Cordin camera model 351, able to take up to 35,000 frames per second has been used. The film used to record the LST is Ilford HP5 Plus (400 ASA).

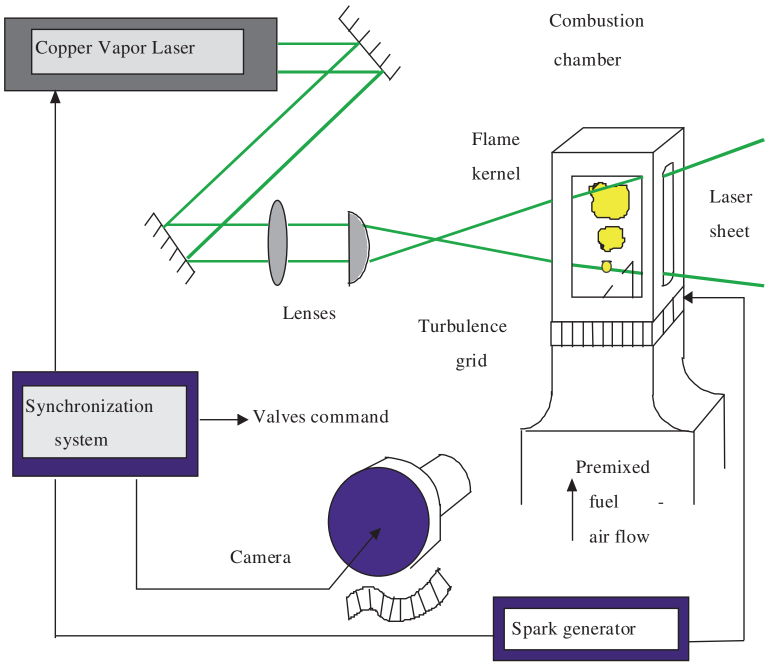


Fig. 6. Schematic of the experimental set up.

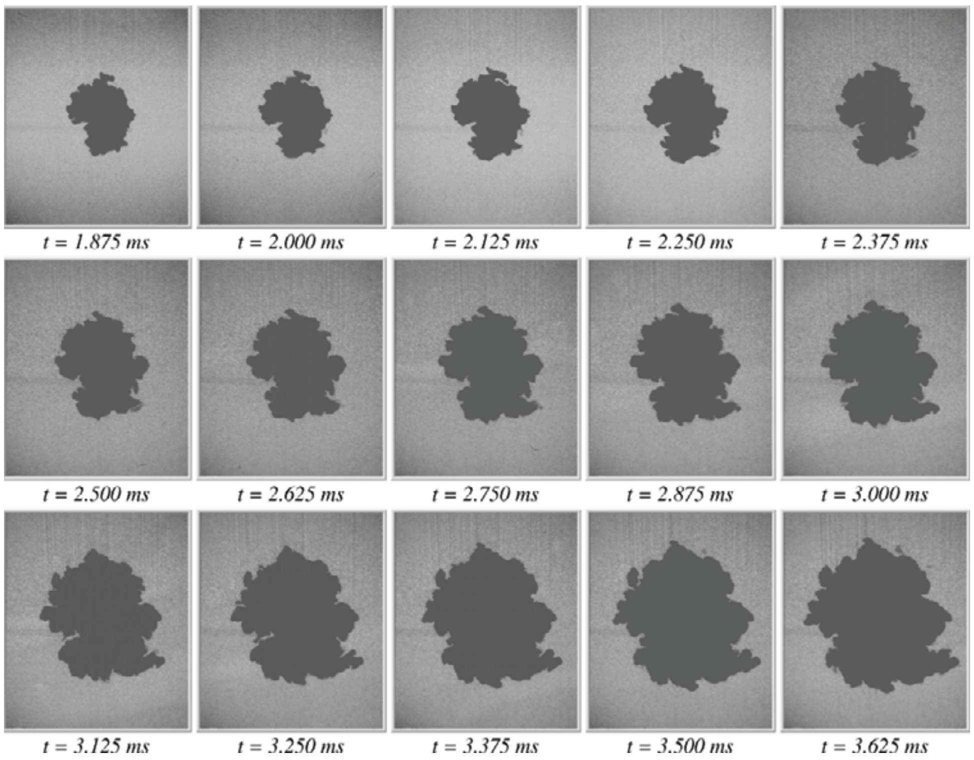


Fig. 7. Part of a typical photographic record of a propagating flame.

Two kinds of combustion chamber were used. In the first, the combustion is ignited behind a grid of a vertical wind tunnel, (Renou et al., 1998). The different gas/air mixtures are convected to the tunnel exit and pass through the grid, then the expanding flame propagates downstream in a decaying isotropic turbulence. The second consist on a constant volume chamber where initial turbulence is produced by a piston movement pushing the fresh gases through a perforated plate (Lecordier, 1997).

Fresh gases are seeded by means of fine silicon oil particles. A typical photographic record of a propagating flame is shown in Fig. 7 in the case of the constant volume chamber. To extract quantitative information of photographic records, a high-resolution film acquisition device has been used. A film scanner, Kodak RFS 2035, connect with Macintosh computer (Quadra 950) digitizes each film picture. Its area array sensor provides six millions pixels per scan. Each frames (24mm × 36mm format) is digitized in a 3072 × 2048 pixels on 24 bit (16 millions of colors) or 8 bit (256 gray scales).

This device is able to conserve the high photographic film resolution and thus provides a powerful digitalization film process to perform cross-correlation PIV algorithm from two successive images. In order to conserve subpixel precision for the coincidence of the two images, several tricks have been developed (Lecordier, 1997).

3. Results on Combustion Applications

This method is intensively used in our laboratory particularly for studying propagation of flame ignited by a spark like in engine. The results presented here are fully detailed in the thesis of Lecordier. In order to give an idea of the precision of the method, some results are given concerning the laminar flame speed determination. Other results showing the flame front turbulence interaction are also presented.

3.1 Determination of the Laminar Flame Velocity

Figure 8 shows an example of a laminar flame propagation of a propane/air mixture at stoichiometry, spark ignited in the constant volume chamber. Before the ignition, the mixture is without velocity and the expansion of burned gases provides progressively velocity to fresh gases in the direction normal to the front. This increasing velocity is linked to the flame speed and to the combustion speed.

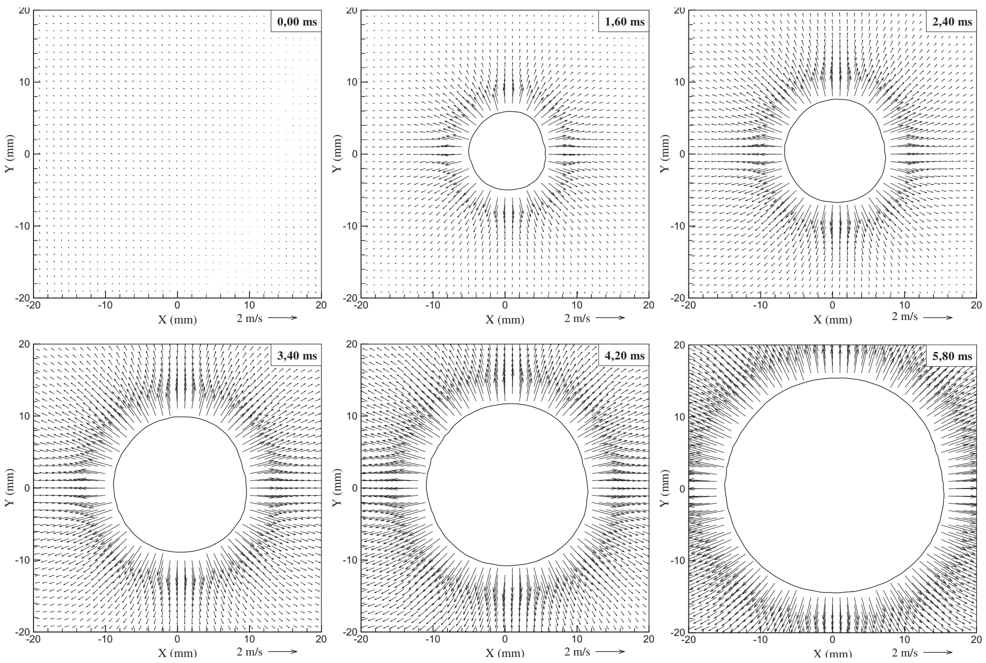


Fig. 8. Time evolution of fresh gases velocity for a laminar flame ignited in a propane/air stoichiometric mixture.

In addition, it shows that the flame geometry remained spherical for the duration of the investigation and that the influence of the wall on the propagation is small.

The laminar velocity is a major parameter for reacting flows studies. It plays an important part in flame sheet models because it is involved in the determination of the local mass rate of formation of products per volume unit. For an unstreched premixed flame, a universal definition of the laminar burning velocity u_L^0 is the velocity, relative to unburned gas, with which a plane flame front travels along the normal to its surface (Andrews and Bradley, 1972).

$$u_L^0 = S_u^0 - u_g^0$$

For a stretched flame, such a unique definition of the laminar burning velocity is more tricky and different approaches can be envisaged. The most natural starting point is to define the stretched laminar velocity in the same way as that of an unstretched flame, i.e. :

$$u_n = S_u - u_g$$

where S_u and u_g are stretch-dependent.

In a spherical configuration, the speed u_n can be linked to the mass of unburned gas with a density ρ_u. In the case of a laminar unstretched burning velocity u_L^0 is linked to S_u^0 by the following expression

$$u_L^0 = \left[\frac{\rho_u}{\rho_b}\right] S_u^0$$

where ρ_u and ρ_b are respectively the density of the unburned and burned gases.

This last expression was habitually used for laminar burning velocity with an assumption of adiabatic temperature for ρ_b and the evolution of S_u^0 deduced from the time evolution of the radius r_u of the spherical flame:

$$S_u^0 = \frac{dr_u}{dt}.$$

By considering the detailed velocity profiles ahead of the spherical flame front (Fig. 9), it is now possible to determinate exact and precise gas velocity u_g without adiabatic temperature assumption. In addition, effect of curvature and stretch can be introduced as a dependence with the Markstein number (Lecordier et al., 1998) can be evaluated.

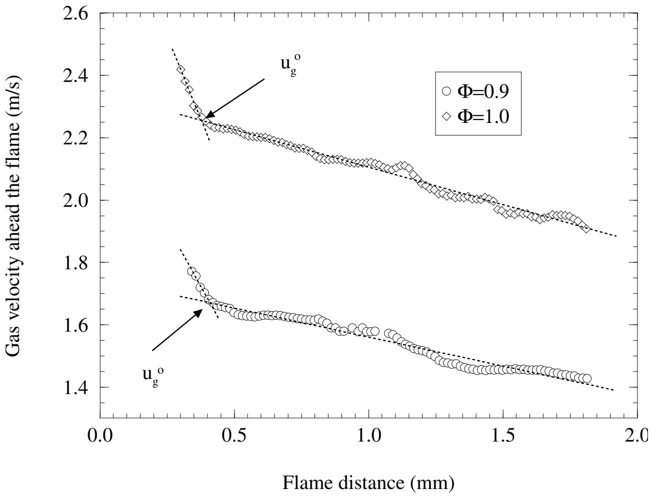


Fig. 9. Velocity profiles ahead the spherical laminar flame front for two values of the equivalent ratio.

3.2 Flame Turbulence Interaction

Figure 10 shows an example of turbulent flame propagation in the constant volume chamber. Color levels indicate the vorticity. Because of the velocity induced ahead the flame front by the expansion of burned gases, spatial averaging for determination of $\overline{u'^2}$ and $\overline{v'^2}$ (the turbulence intensity) is not significant in presence of flame.

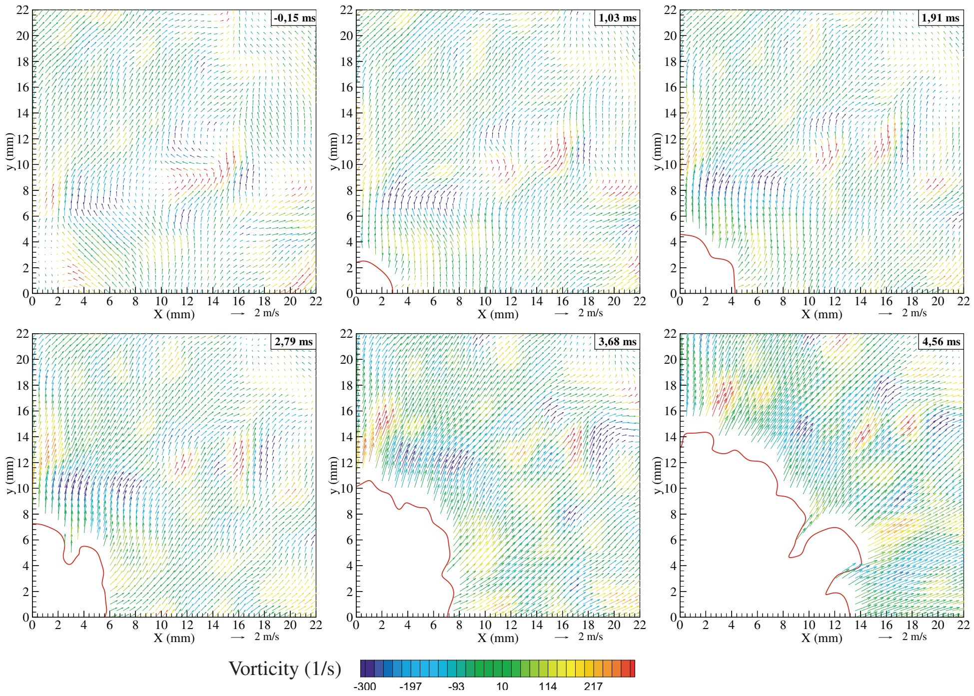


Fig. 10. Time evolution of a turbulent flame propagation in an homogeneous turbulence.

The question is to know how the flame front "absorbs" the vorticity which is pushed in the normal direction to the flame surface by the flame propagation. One can observe that the vorticity is convected and progressively reached by the flame. Different turbulent levels have been studied and a spatial scale of flame-turbulence interaction can be defined. It is much larger than the conventional turbulent integral scale. Another important parameter can be examined with these results: It is the turbulent flame propagation velocity S_T, but measurements of non-stabilized outwardly propagating flame fronts are further complicated by flame development. Movement of the flame kernel in the early stages of flame growth can result in a flame displacement well away from the laser sheet. With a single illuminating laser sheet it is often impossible to determine whether the sheet is "slicing" through the center of the flame kernel. If it is not, the measured flame speed will be higher than actuality because of the expansion of the flame normal to the sheet, this may be neglected if the sheet bisects the flame.

3.3 Interest of Stereoscopy for Combustion Application

If the sheet cannot be considered as bisecting the flame, the use of Tomography is not possible to deduce the flame velocity. Stereoscopic PIV can be an interesting help to check this assumption. The existence of a normal component to the sheet plane can be used to determinate if the flame is propagating in the plane of the sheet or not.

In Fig. 11, a 3D view of the velocity field is represented when a spherical laminar flame is approaching under the plane of the laser sheet. This experiment is performed to validate 3D results. The spherical propagation of the flame induces spherical properties of the velocity field as it is shown in the figure. One can verify that the velocity vector module is constant at a constant distance from the ignition center.

In Fig. 12, the third component is represented along an axial profile: For the flame 1, the velocity value is negligible, it indicates that the sheet is bisecting the flame. It is not the case for the flame 2 where the third component reaches a maximum value symmetrically.

In the turbulent case, the question is to know if the propagation is spherical in terms of mean front location. Figure 13 shows a 3D field ahead of the wrinkle flame front. The negative value of the third component near the front reveals a propagation that is not parallel to the laser sheet and the local values of the velocity angle could be used to evaluate the local angle of propagation.

Up to now stereoscopy is performed with two CCD cameras (Sony XC 8500) and cannot be extended to time resolved results, however prompt progress can be expected with the CCD cameras evolution.

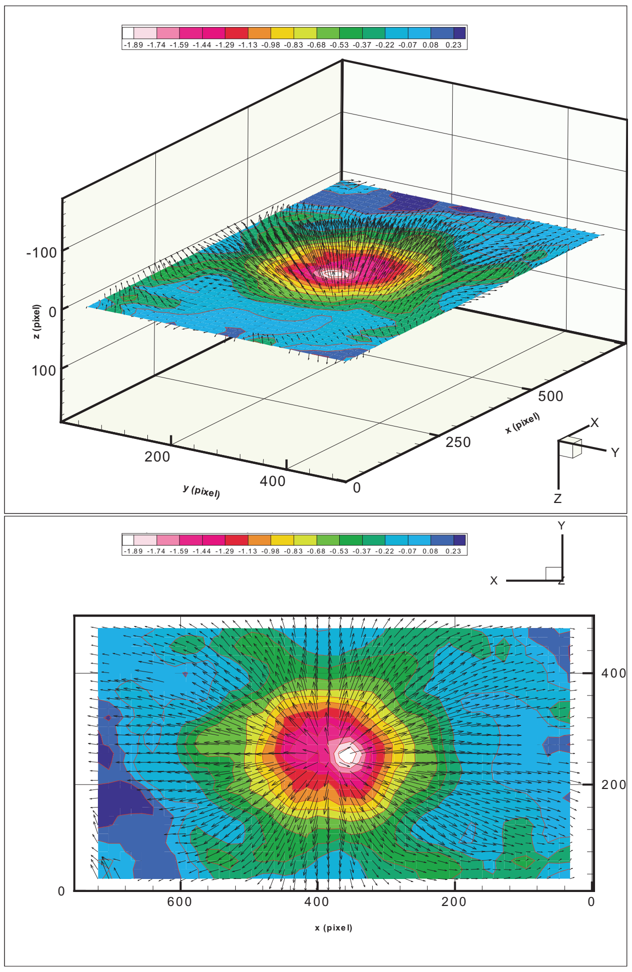
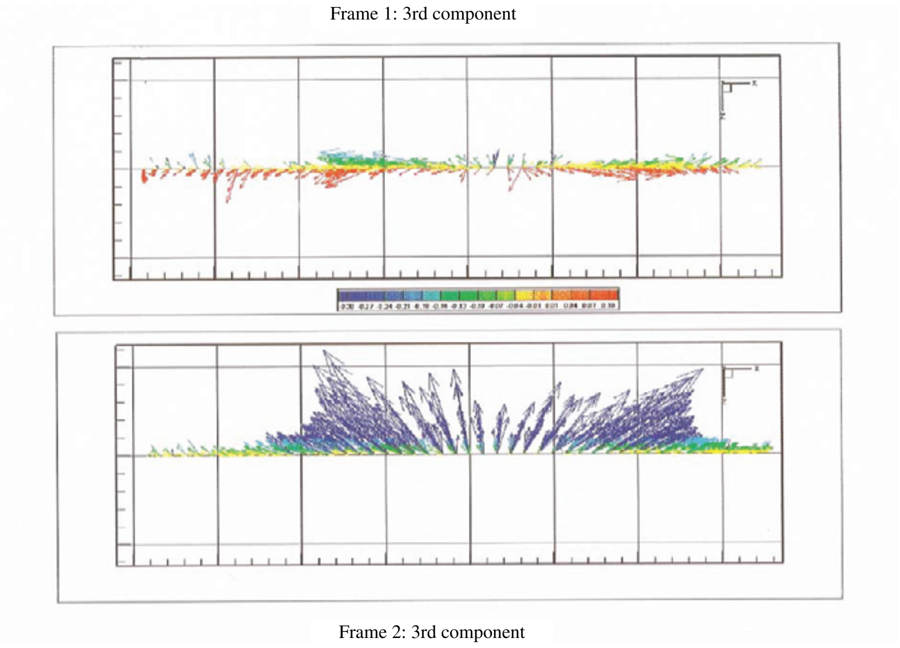


Fig. 11. 3D-velocity field above a propagating spherical laminar flame.


Frame 1: 3rd component

Frame 2: 3rd component

Fig. 12. Axial profile of the third component for the laminar flame propagation : Flame 1 perfect bisecting laser sheet ; Flame 2 non perfect bisecting laser sheet.

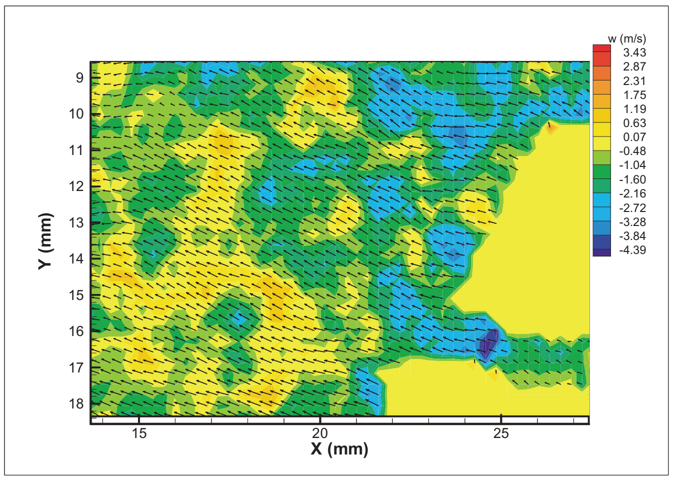


Fig. 13. 3D-velocity field near a turbulent propagating flame (the velocity component normal to the plan sheet is represented in colors levels).

4. Conclusion

The ideal optical diagnostic suitable for a complete knowledge of flame/turbulence interaction would be the determination, in any point of space and at any time, of the position of the front and of the three components of the velocity. Time resolved high-speed Tomography coupled with high resolution PIV is a first step in this direction.

In this paper, it is shown that high density of seeding can provide a good accuracy of the front location and of the velocity field by using high resolution cross-correlation PIV.

The ability of the method has been demonstrated to determine the laminar burning speed with a high precision.

Concerning the turbulent flames, it has been shown that the interaction of the flame front with turbulent structures can be visualized and studied in terms of spatial scales and turbulence characteristics modification.

Concerning turbulent combustion speed, 2D measurements in a plane are not sufficient. 3D stereoscopic measurements for velocity have been demonstrated to be a promising way.

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Bertrand Lecordier : He received a Master's in physic from Rouen University in 1991, a post-graduate diploma in 1992 and a Ph.D. in energetic in 1997 from the same University. In 1998, he joined CNRS (Centre National de la Recherche Scientifique) as Research Scientist and he currently works at CORIA laboratory (Rouen University). His current research interests are in the field of reacting flows, particularly the study of interaction between an unsteady premixed flame and a turbulent flow field as well as the development of advanced laser diagnostics techniques for reacting flows.

Arnaud Lecerf : He received a Master's in physic from Rouen University in 1994 and a post-graduate diploma in 1995. He is preparing a Ph.D. from 1995 supported by the local government (Haute Normandie). His Ph.D. research is centered on Stereoscopic PIV developed in the context of a CEC Program (Euro PIV). He works on applications of stereoscopic PIV to turbulent flows and flames studies. He develops also software to drive CCD cameras and Yag laser for specific PIV applications