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Time resolved Particle Image Velocimetry in confined Bluff-Body burner flames

D. Honoré, B. Lecordier, A. Susset, D. Jaffré, M. Perrin, J.M. Most, M. Trinité

Abstract Time resolved Particle Image Velocimetry has been applied to a non-premixed turbulent flame generated by a confined Bluff-Body burner. Original synchronisation of the experimental setup has allowed us to obtain sequences of consecutive instantaneous velocity fields. Experimental limitations of the application of PIV in industrial-like burner are pointed out, requiring the development of specific preprocessing of the particle images associated to an original iterative procedure for cross-correlation calculation. Temporal evolution of coherent structures in the recirculation zone generated by the wake effect of the Bluff-Body is visualized on sequences of consecutive velocity fields. Characterization of the temporal evolution of the stagnation points encountered in the recirculation zone reveals low frequency movements of their axial locations.

1 Introduction

Characterization of aerodynamic fields in turbulent flows is of great interest to the understanding and

modelisation of complex phenomena present in industrial natural gas flames. For the last few years, developments of imaging techniques has induced new advances in this research field. In previous experiments in an unconfined Bluff-Body model burner flame, we have observed the presence of a quasi-periodic ejection of coherent structures from the recirculation zone downstream from the burner exit, where gas / air mixing leads to the stabilization of the flame field (Susset *et al.*, 1998, Honoré *et al.*, 1998). In industrial boilers and furnaces, flame stability is enhanced by the high confinement of the flow due to the presence of a quarl, i.e. a refractory element between the burner and the combustion chamber. This configuration induces a more complex flow which can present on-axis stagnation points. Up to now, few experiments were devoted to such configurations. In the present study, a time resolved PIV technique was used in a confined Bluff-Body burner flame in order to characterize the effect of the confinement on the recirculation zone characteristics and flame stabilization processes.

2 The confined Bluff-Body model burner

Most industrial burners use some type of Bluff-Body to ensure flame stability. In addition, industrial burners are typically confined by a quarl, which also enhances flame stability. Basic phenomena responsible for flame stabilization were experimentally studied by use of several imaging techniques in Bluff-Body model burners, which are simplified industrial-like burners with axisymmetric geometry (Honoré *et al.*, 1998). Figure 1 shows a schematic of the confined Bluff-Body model burner.

D. Honoré, D. Jaffré, M. Perrin
Gaz de France, R&D Division
361 av. du Président Wilson
93211 Saint Denis La Plaine, France.

B. Lecordier, M. Trinité
CORIA
UMR CNRS 6614, Université de Rouen
76821 Mont-Saint-Aignan, France

A. Susset, J.M. Most
Laboratoire de Combustion et Détonique
UPR CNRS 9028, Université de Poitiers - ENSMA
BP 109, 86960 Futuroscope, France

Correspondence to : D. Honoré

It consists of a central methane jet with a bulk velocity of 21 m/s located at the center of a cylindrical Bluff-Body surrounding by an annular air jet with a bulk velocity of 15 m/s. Dimensions of the Bluff-Body corresponds to a large value of the blocage ratio parameter ($BR = 0.83$), defined as the ratio of the cross-sectional area of the Bluff-Body to the area of the air duct, and representative of the wake effect of the obstacle (Schefer *et al.*, 1996). Confinement of the flow induced by the quarl is reproduced by a cylindrical shape element placed on the nozzle of the burner, equipped with quartz windows to allow optical access to the flame (cf. 3.2). In this configuration, the wake effect of the Bluff-Body induces a recirculation zone downstream from the burner exit, characterized by interaction between centrifugal methane-driven vortex and centripetal air-driven vortex. This configuration corresponds to strongly recirculated flow with two axial stagnation points. A mean velocity field previously obtained by LDV measurements is shown in figure 2 (Imbach, 1995). For this experiment, typically 5000 measurements were recorded for a time duration of 2 minutes at each spatial location.

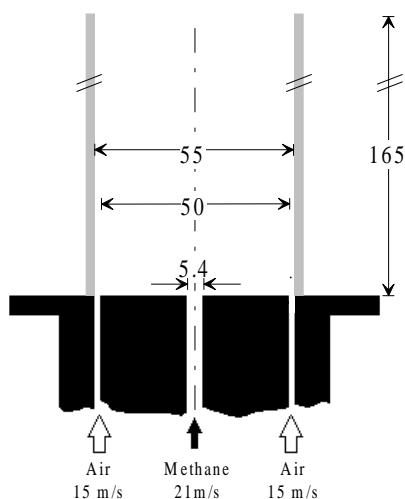


Fig. 1. Schematic of the confined Bluff-Body model burner.

Large Bluff-Body blocage ratio and high air velocities induce the closing of the recirculation zone on the axis, which is characterized by a rear stagnation point. Upstream from this location, recirculated air flow impinging on the methane jet induces a forward stagnation point. Methane flow is then forced in the radial direction in the recirculation zone. This increases the fuel / air mixing and explains the enhancement of the flame stability. In the present operating conditions, the flame is detached : combustion occurs away from the burner nozzle in the vicinity of the air vortex (Schefer *et al.*, 1996).

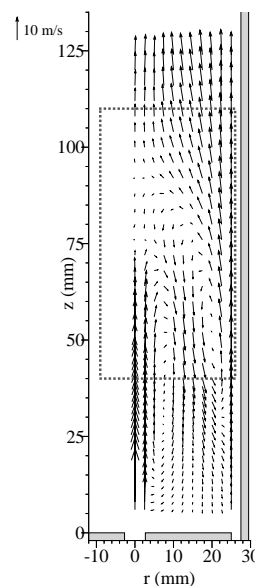


Fig. 2. Mean velocity field obtained by LDV. (dotted region = field of view of present time resolved PIV measurements)

3 The time resolved PIV technique

3.1 Time resolved PIV setup

The main principles and the description of the time resolved PIV system are presented in details elsewhere (Lecordier *et al.* 1999a). The following section focuses on its application on the confined Bluff-Body burner flame. The time resolved PIV setup consists mainly of a drum camera (CORDIN 447/351) synchronised with a 45 W copper vapor laser (Oxford Laser ACL 45). This laser is pulsed with an adjustable repetition rate up to 10 kHz in the normal working conditions. Mean pulse energies are 6.5 mJ at wavelengths of 510.6 nm and 578.2 nm and their durations lies between 10 ns and 60 ns with a time jitter between successive pulses less than 2 ns. The laser sheet (150 mm x 1 mm) generated by a set of cylindrical lenses crosses vertically the flow over the confinement tube specially designed for laser diagnostics (cf. 3.2). Both methane and air flows are seeded with zirconium oxide particles (nominal diameter $\approx 1 \mu\text{m}$).

The high speed photographic camera, viewing perpendicular to the laser sheet records images of particles on a 35 mm B&W film of 860 mm length loaded thanks to a special film cassette into a film track which lines the inside cylinder of rotating drum.

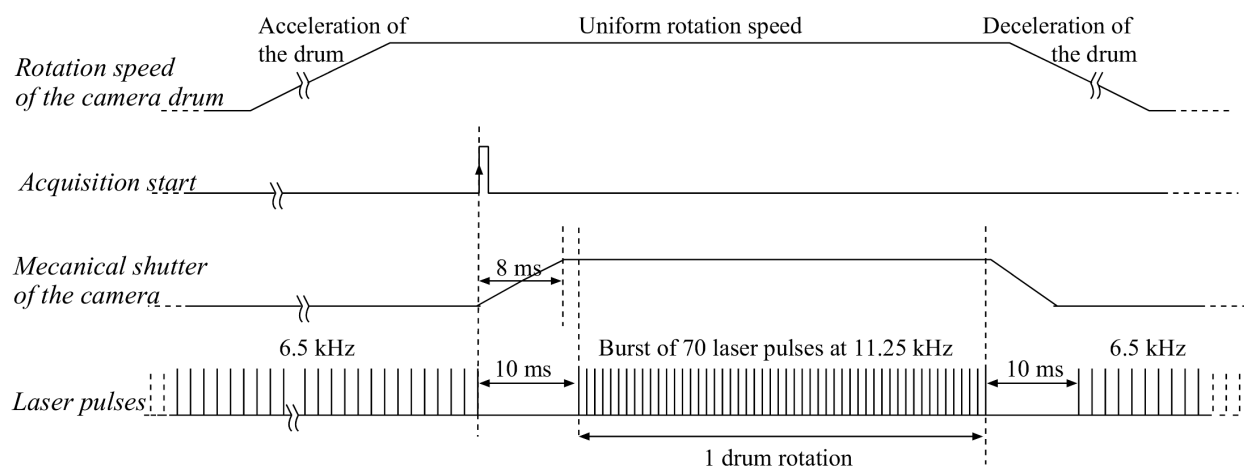


Fig. 3. Synchronisation diagram of the experimental setup.

The film is exposed thanks to a fixed mirror reflecting the light emerging from the camera lens. The drum is powered by an electric motor, controlled by an electronic control unit. The maximum film speed is 0.134 mm/ μ s which corresponds to 9400 rpm.

A synchronisation cycle of the camera and the copper vapor laser is given in figure 3. When the camera drum has reached the chosen speed, the acquisition cycle is started manually by pressing a button. At the same time, the laser is switched off and a trigger is sent to the shutter command. Delay time from trigger to shutter release is approximately 8 milliseconds. During the opening and closing stages of the mechanical shutter, the laser is switched off to avoid the film exposure. 10 ms after the start of the cycle, a burst of 70 laser pulses at 11.25 kHz exposes the whole photographic film. This duration of recording (6.22 ms) is fixed by the drum speed which is set to avoid images overlapping on the film. In the present study, the high acquisition rate (88.8 μ s between frame) has been chosen to make PIV measurements from two consecutive images possible. The field of view was focused on a region containing at least the top of the recirculation zone as well as the two stagnation points. Figure 2 shows the chosen field of view associated with the LDV mean velocity field.

After film developing, the tomographic images were digitized with a scanner at 2000 dpi resolution (Kodak RFS 2035+). The latter corresponds to an image format of 1900 x 950 pixel² which gives a magnification factor of 0.037 mm/pixel. Instantaneous velocity field can then be obtained from cross-correlation calculation of each two consecutive

particle images of the sequence. The main principles of this approach are similar in many ways with those based on a CCD camera to record images of particle. Nevertheless, precautions peculiar to film support and scanning stage have to be taken into account. A detailed description of these precautions are presented in reference (Lecordier et al., 1999a). The measurement accuracy of our PIV system has been evaluated from images of a stationary seeded flow. In such a situation, assuming that the particle movement is nearly equal to zero considering the high rate of image acquisition, the smallest detectable and reliable measurement of particle displacement corresponds to the measurement accuracy, which has been determined to be less than 0.1 pixel. In the present work, this accuracy corresponds to a velocity of 0.05 m/s (Lecordier et al. 1999a).

3.2 Limitations of PIV in confined Bluff-Body burner flame

The time resolved PIV technique was applied on the confined Bluff-Body burner with a specific confinement tube (figure 4). It consists of two half cylindrical quartz windows for light collection truncated and assembled with two thin flat windows for laser sheet crossing. The windows 2 mm thickness did not cause any image distortion as confirmed by imaging ruled targets. To further minimize background reflections, rear cylindrical window was coated with a high temperature black paint.

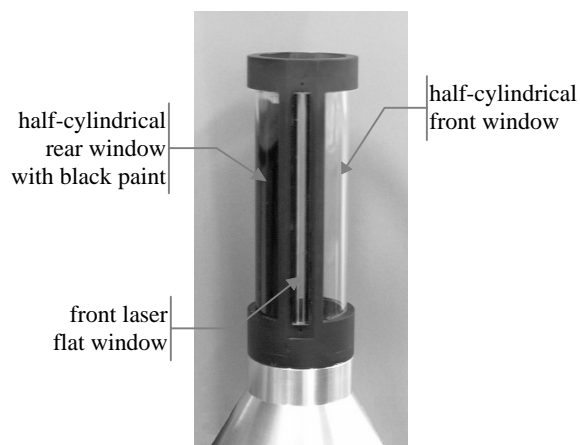


Fig. 4. Photography of the specific confinement tube. (Side view of the Bluff-Body burner nozzle).

Despite these efforts, laser reflections on cylindrical windows were still observed on particle images. An example of a particle image taken in the middle of a time resolved PIV sequence is shown in figure 5.a. One clearly sees the increase of the laser reflection intensity in the right region of the image, corresponding to the vicinity of the curved window. Figure 5.b shows the mean tomographic image calculated over all the instantaneous particles images of the same sequence. The random distribution of particles on instantaneous images induces their disappearance on the mean image, whereas laser reflections, always present on each instantaneous image, are found again on the mean image. Then, subtraction of the mean image from instantaneous images allows elimination of almost all laser reflections (figure 5.c). This simple image processing, performed on each instantaneous image of the sequences before PIV calculation avoided optical bias due to laser reflections.

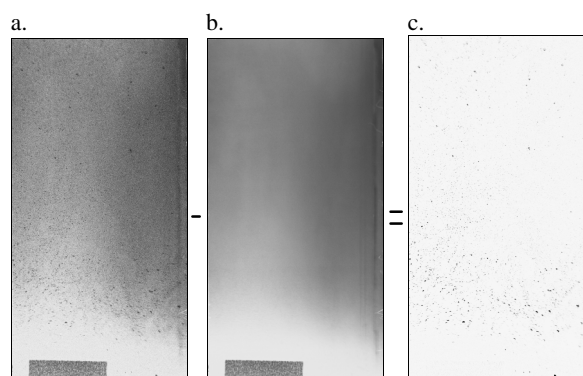


Fig. 5. Illustration of elimination of laser reflections on particle image by subtraction of mean image (all images in negative). a : instantaneous image, b : mean image, c : instantaneous image after subtraction.

Agglomeration of zirconium oxide particles was observed on the quartz window. This phenomenon is due to thermophoresis effects. It mainly appears on the top of the confinement tube where the flame is fully developed, i.e. in a region out the field of view of the present PIV measurements. Nevertheless, this effect forced to disassemble the burner and clean the confinement tube after each sequence acquisition, limiting the number of acquisition achievable.

The high velocities encountered in the Bluff-Body burner flame require large dimension of interrogation window to ensure validity of the correlation calculation. However, in our complex flow, these large interrogation windows may induce tremendous decrease in spatial resolution which then would prohibit quantitative characterization of low velocity structures of the flow (stagnation points, vortices, recirculation zone,...). This effect can be avoided by the use of a window shifting procedure (Westerweel *et al.*, 1997, Lecordier *et al.*, 1999b), allowing small dimensions of the interrogation windows without loss of high velocity particles.

Biases induced by large velocity gradients on velocity measurements by PIV were previously described in an unconfined Bluff-Body burner flame (Susset *et al.*, 1998). These biases can be minimized by reducing the size of the interrogation window to the velocity gradient direction (Huang *et al.*, 1993). In our flow, since the velocity gradients are stronger in the radial direction, the width of the interrogation windows have been reduced as much as possible.

3.3 Specific PIV processing

Optical and aerodynamic limitations of PIV in confined flame have lead us to develop an original PIV processing including two successive stages. The first one consists to estimate the mean velocity field of each individual sequence. In order to perform this first stage, one velocity field from each individual couple of particle images was computed with large rectangular interrogation window : 256 pixels in the axis direction and 64 pixels in the radial direction. Next, each velocity field is validated by 3 different methods : one based on the minimum signal noise ratio of correlation signal, an other on the maximum value of the vector magnitude and the last one is a comparison of neighboring vectors with a median filtering. The results of the validation was used to obtain the first estimation of the mean velocity field of the sequence.

During the next stage, the velocity fields were computed a second time, but the mean velocity field was used to shift the interrogation windows of the local mean velocity. This local translation allows us to reduce the out-of-focus effects and then to decrease the axial size of the interrogation window to 128 pixels. Next, the velocity fields are validated by the same way as in the first stage and the spurious vectors are replaced thanks to a 2D Gaussian fit using neighboring vectors.

In conclusion, the particle image processing by mean image subtraction as well as the optimized size interrogation window associated with an original window shifting procedure allow us to measure instantaneous velocity in the complex turbulent flow generated by a confined Bluff-Body burner.

4 Results

4.1 Mean velocity field

In order to validate the complete processings developed for the application of the time resolved PIV technique on confined Bluff-Body burner flame, a mean velocity field was calculated over 4 sequences, i.e. a total of 271 instantaneous velocity fields. Figure 6 compares the averaged velocity field obtained by PIV with the corresponding region of the mean velocity field previously obtained by LDV (Imbach, 1995). For sake of clarity, one eighth of the PIV measurements is shown.

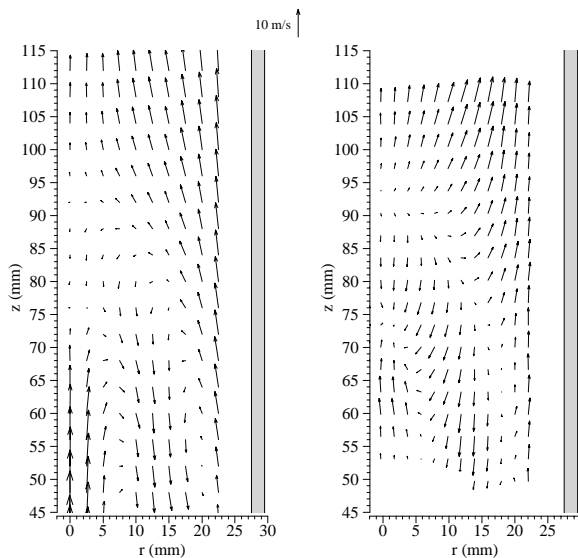


Fig. 6. Comparison of mean velocity fields obtained by LDV (left) and PIV (right).

The overall structure of the mean velocity field is quite similar for the two measurement techniques. Indeed, difference of locations of the rear stagnation point (observed at $z = 92$ mm by LDV) is less than 1 mm, whereas it does not exceed 2 mm for the forward stagnation point (observed at $z = 76$ mm by LDV). Main difference comes from the methane jet in the low part of the field, which is underestimated by PIV. Note that the flow in this region presents the highest velocity. Despite the chosen processing procedure, high velocity axial component may induce a loss of high velocity particles favoring slowest particles in the correlation calculation. Figure 6 shows also that the radial component of velocity in the region ($r = 15$ mm; $z = 100$ mm) is of opposite sign between PIV and LDV. Centrifugal aspect of the mean flow in this region observed in PIV can be explained by the non convergence of the average calculation due to the low number of independent sequences. It may also come from spots on particles images coming from laser reflections which were not totally eliminated by the mean image subtraction processing.

4.2 Visualization of temporal evolution of the recirculation zone

Figure 7 presents 14 instantaneous velocity fields extracted from a 6 ms sequence of 70 consecutive PIV measurements. Here, only one fourth of the PIV measurements is shown for sake of clarity.

Instantaneous fields point out the effects of the optical and aerodynamic limitations discussed above. Indeed, non-continuity of the flow is observed in the velocity fields in the region around the ($r = 10$ mm ; $z = 95$ mm) location. As previously mentioned, the presence of laser reflections spots on the particle images despite the subtraction procedure affects the correlation calculation in this region, and therefore induces local underestimation of velocity.

Nevertheless, one can observe the temporal evolution of coherent structures which reveals the complexity of the instantaneous flow in the recirculation zone. From the beginning of the sequence, one distinguishes the existence of a vortex at the border of the air jet ($r = 21$ mm ; $z = 60$ mm). This vortex is not convecting downstream from the flow, and induces a continuous local injection of air in the recirculation zone. 2.5 ms after the beginning of the sequence, a strong recirculation of the flow coming from the top of the recirculation zone is observed around ($r = 10$ mm ; $z = 70$ mm). This structure is then convected upstream in the recirculation zone. From $\tau = 4$ ms, it encounters the air vortex. To the end of

the sequence, their interaction induces a local acceleration of the recirculated air flow.

This result shows the ability of the time resolved PIV technique to point out temporal evolution of turbulent coherent structures. However, further analysis of the PIV for quantitative characterization of the flow requires development of specific post-processing procedures.

4.3

Temporal evolution of the stagnation points

Complex flow generated by the confined Bluff-Body burner is mainly characterized by the presence of two stagnation points. In order to point out their behavior in the recirculation zone, post-processing of the consecutive instantaneous velocity fields have been focused on the temporal following of their location. Figure 8 presents an axial profile of the axial component of the velocity extracted from an instantaneous field.

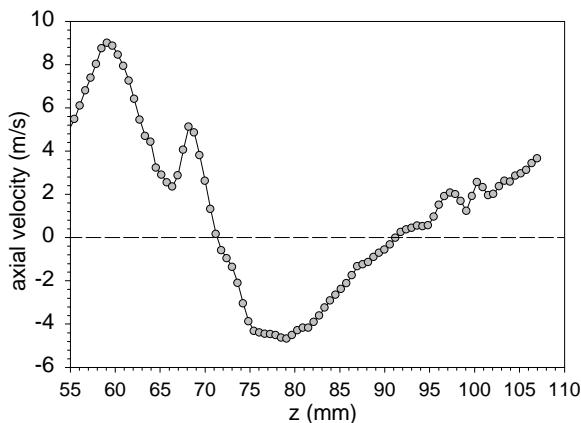


Fig. 8. Example of instantaneous axial profile of axial component of velocity extracted from a time resolved PIV velocity field.

One clearly sees that the two stagnation points exist also in the instantaneous flow. Figure 9 shows three temporal evolutions of the axial location of the stagnation points deduced from different 6 ms sequences.

One can observe low variations of the stagnation points during each sequence. Stagnation points seem not be affected by the strong flow interactions observed in the turbulent recirculation zone. However, one can notice that the mean locations of the stagnation points are different for each sequence. This seems to indicate that stagnation points may have axial movements characterized by a low frequency. Unfortunately this eventual low frequency can not be

resolved in the present study because of the limitation of the PIV sequence duration. Further investigations on low frequency phenomena would be certainly obtained by using "pseudo" real time synchronisation (Lecordier et al. 1999a).

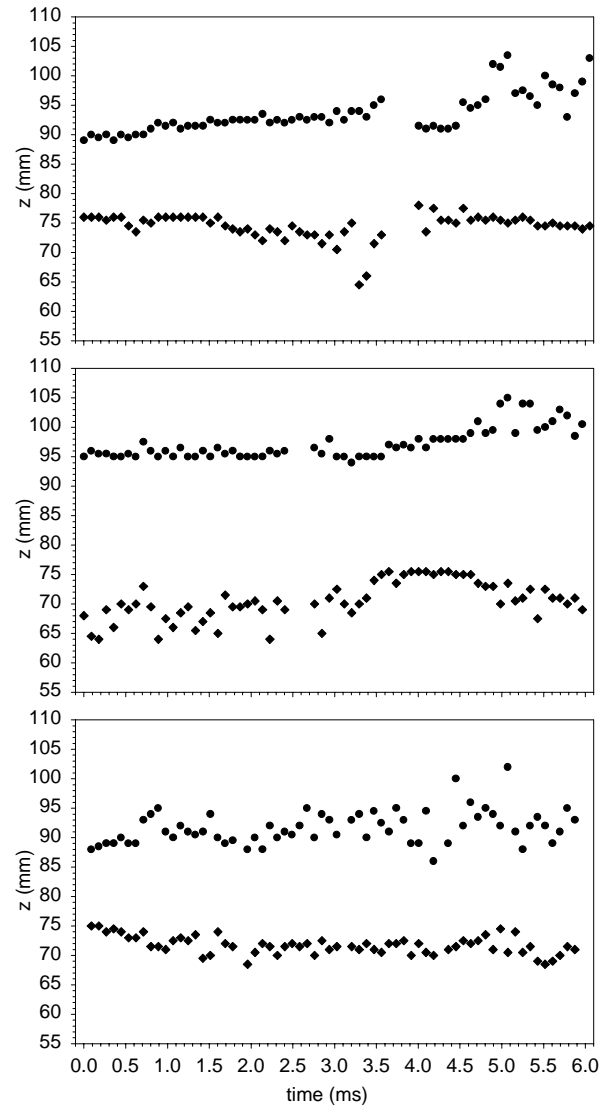


Fig. 9. Temporal evolutions of locations of rear stagnation point (circle) and forward stagnation point (diamond).

5 Conclusion

A time resolved PIV technique was applied on a confined Bluff-Body burner flame. Optical and aerodynamic limitations due to the high level of confinement of the flow as well as the high velocity gradients encountered in the recirculation zone were observed. These experimental biases have lead to develop a specific procedure of image and correlation calculation processings. Time resolved PIV technique

has revealed its ability to qualitatively characterize temporal evolution of turbulent coherent structures. Post-processing of the successive instantaneous velocity fields was performed to quantitatively characterize temporally evolution of the two stagnation points. Contrary to highly turbulent structures in the recirculation zone, these stagnation points seem to have low frequency movements. Further developments of post-processing procedures will allow to go into a better understanding of unsteady phenomena found in turbulent flow leading to the flame stabilization.

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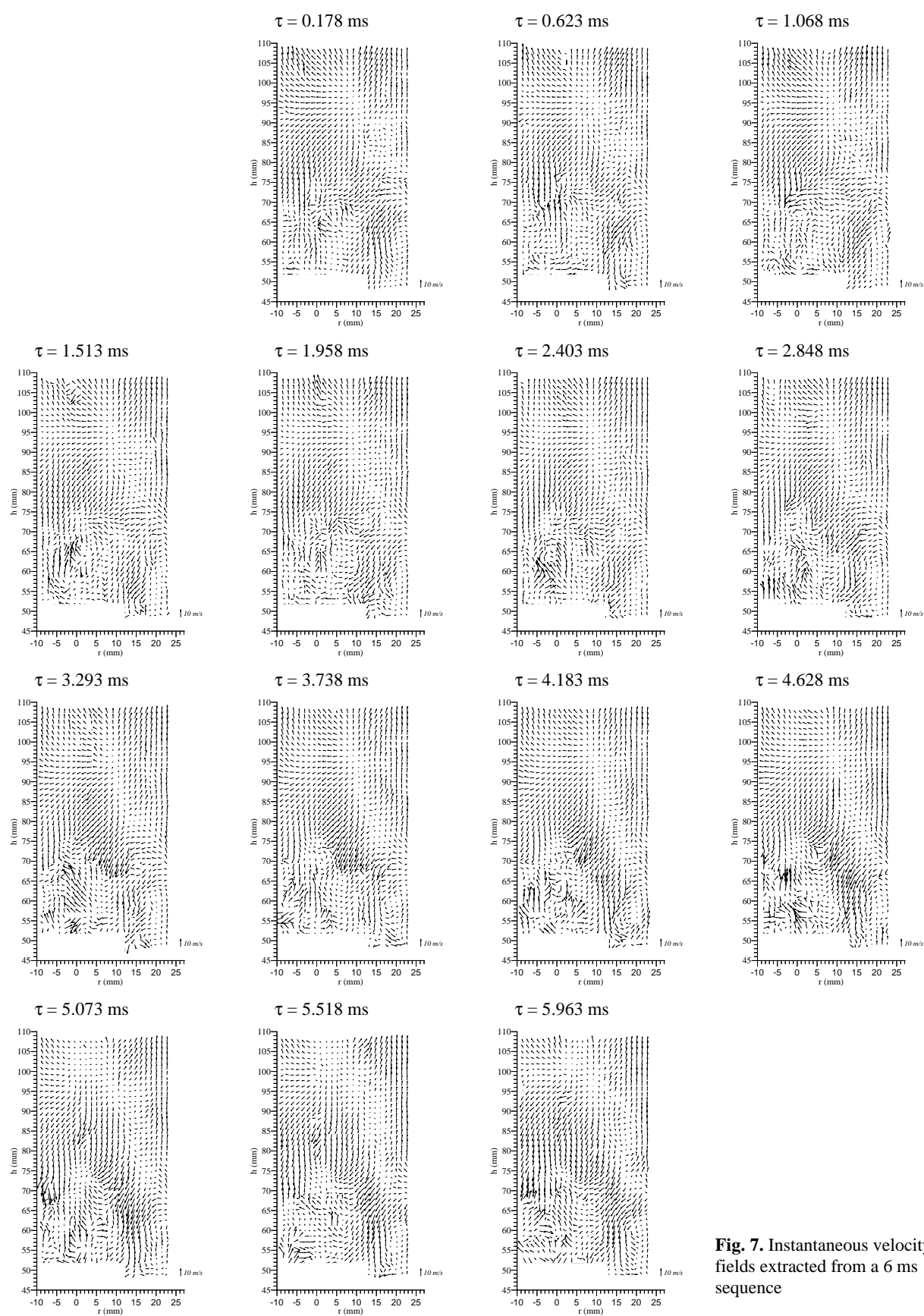


Fig. 7. Instantaneous velocity fields extracted from a 6 ms sequence