3D Structures of Evaporating Fuel Droplets by means Stereoscopic PIV

by

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ABSTRACT

In the present work, Stereoscopic PIV has been applied for the analysis of the three-dimensional interaction between the spray droplets and the surrounding airflow in a gun-type burner, which is working under reacting conditions. In such a burner, the oil is pressure-atomized and mixed with air generating a recirculating, swirling flow. The full velocity vector map has been measured in several planes and then, it has been interpolated to the whole volume of the burner. Firstly, an estimate of the accuracy of the out-of-plane velocity component has been done, as the stereoscopic angle between the two CCD cameras axis was quite small (22º), due to the limitations imposed by the test rig. It has been found that the accuracy is only 3 times smaller than the accuracy for the in-plane components.

For the analysis of the interaction between the fuel droplets and the airflow, the rms of the three velocity components have been calculated in the whole volume of the burner. The analysis of the velocity fluctuations will provide some insight about the interaction between the airflow and the fuel droplets, the structure of the evaporation and the recirculation zones, and so on. It has been found that the minimum fluctuation is measured along the spray central axis, indicating that these droplets travel upwards, without interacting with the airflow. The maximum fluctuation has been measured in the shear flow region, in a conical region that covers from the baffle plate up to a height of approximately 40 mm. In this region the maximum values for the vorticity are measured as well. In the figure presented below, some of the three-dimensional iso-surfaces structures obtained for the rms of the three-velocity component are shown. In order to achieve the best visualization, the orientation has been set different for each case.

Fig.1. Three-dimensional rms structures obtained for the axial, radial and swirl velocity components in a gun-type-burner.
1. INTRODUCTION

In general, the study of multi-phase flows is difficult, as the different phases must be discriminated precisely. Point measurements, as Phase Doppler Anemometry, (Durst et al., (1981), Edwards, (1990)) can provide detailed information on particle diameter and velocity, but, unfortunately, can’t say much about the spatial structures present in the flow field. On the other hand, planar measurement techniques, as Particle Image Velocimetry, (Raffel et al., (1998), Grant, (1997)) are based on the recording of a fluid plane, and allow the measurement of two-dimensional spatial structures. However, PIV alone does not provide information about size and velocity simultaneously, and, therefore, has to be combined with other techniques (Palero and Arroyo, (1998), Ikeda et al., (2000), Maeda et al., (2000)), when it is applied for the diagnosis of multi-phase flows.

The present work is dedicated to the analysis of the spatial structures formed in a gun-type burner, with the purpose of increasing the understanding of the spray dynamics and its interaction with a combusting, turbulent airflow. The gun-type burner is a widely used oil burner for industrial and domestic applications. The oil is pressure-atomized and mixed with air, generating a recirculating, swirling flow. This is a two-phase flow, being the disperse phase the unburned spray droplets and the continuous phase, the surrounding airflow.

Before starting, a brief summary of the steps followed previously is needed, in order to make clear the current status of this research. Initial experiments in this burner were done by PDA (Ikeda et al., (1995)), and droplet behavior was described by size-classified PDA measurements (Kawahara et al., (1996)). It was found that the small droplets (under 30 µm in diameter) entrained the recirculation region near the baffle plate, while larger droplets (bigger than 50 µm) penetrated the airflow due to their large momentum.

As the spatial interaction between the airflow and the fuel droplets is essential for understanding the turbulent mixing mechanism, PIV was applied for the measurement of the two-dimensional, two-component velocity vector map in reacting and non-reacting conditions (Ikeda et al., (1999)). For reacting conditions it was possible to obtain good measurements of the axial and radial velocity components in a fluid plane, in spite of the adverse measurement conditions mainly due to the presence of evaporating droplets and soot.

Since the flow field in a gun-type burner is three-dimensional, it is essential to know the three-velocity components simultaneously. Then, the next step was to apply Stereoscopic PIV. This technique is an extension of the classical PIV, in which a fluid plane is visualized from two directions simultaneously. The differences between these two projections permit us to extract the out-of-plane component. Stereoscopic PIV has been successfully applied to air (Arroyo and Greatard (1991), Willert, (1997)) and liquid flows (Prasad and Adrian, (1993), Prasad and Jensen, (1995)), and also in reacting conditions for the study of a lifted flame (Han et al, (2000)). This technique was applied to the analysis of the velocity field in the central plane of the gun type burner in reacting (Palero and Ikeda, (2001)) and non-reacting conditions (Palero et al., (2000)). The results were compared with PDA data, showing that Stereoscopic PIV is a technique with a great potential for the analysis of complex flows.

A step more has been done and, in order to establish the behaviour of different droplet sizes in the flow field, Multi-Intensity-Layer PIV was also used (Palero and Ikeda (2002)). This technique allows the measurement of the velocity of droplets belonging to different size classes by accounting for differences in the scattered light intensity. The data obtained with Multi-Intensity-Layer PIV were compared again with size-classified PDA showing good agreement for all the size classes.

2. EXPERIMENTAL SET-UP

2.1 Gun-type burner

The gun-type burner (Fig. 2) is an oil burner available commercially for rather small (0.1 MW class) industrial furnaces and boilers. The burner specifications are listed in Table 1, and a detailed description of the burner characteristics is given in Ikeda et al (1995). Heavy oil (type A, Japanese Industrial Standard) is pressurized up to 0.7 MPa and a hollow cone spray is produced with a 60º included angle. A baffle plate acts as a flame holder and aids in reducing soot formation. The swirling flow enhances the turbulent mixing of fuel and air and the swirl-induced recirculation stabilizes the flame. The airflow was not seeded as only the disperse phase was analyzed.
2.2 Imaging system

The experimental set-up used for the current investigation is presented in Fig. 3. A plane is illuminated with a dual-cavity Nd:YAG laser (Spectra-Physics PIV-400, 400 mJ pulse, 532 nm). The time $\Delta T$ between the two laser pulses was kept at 25 $\mu$s. Commercial DANTEC optics was used to form a laser sheet 1 mm thick. The laser sheet was illuminating the XY plane, that is the plane recorded with the CCD cameras.

Two CCD cameras (TSI PIVCAM 10-30, 8 bit, cross-correlation, 1008(H)x1018(V) pixels, Kodak ES1.0) were used with a 60 mm focal length Micro Nikkor lenses at f# = 11. Two filters were attached to each camera. A neutral filter (Kenko, ND8) and an interferential filter (High Technology, center $\lambda = 532$ nm, half bandwidth: 2.76 nm), designed for selecting the light scattered by the droplets corresponding to the laser wavelength.

Stereoscopic PIV can be applied in two different optical configurations: the translational and angular displacement methods. In the translational method, the optical axes of the cameras are parallel to each other and perpendicular to the fluid plane while in the angular method the camera axes form a certain angle with the fluid plane’s normal, called, stereoscopic angle. In this work the angular set-up has been chosen. In that way the common field of view is maximized and the aberrations can be kept small, since the lenses are working in an on-axis configuration. The stereoscopic angle was set at 11º (22º between the camera axis), as the test rig does not allow wider angles.

When the angular configuration is used, the image plane is not parallel to the object plane and the Scheimpflug condition has to be applied in order to have the image plane in focus. It means that the object plane, the lens

<table>
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<th>Table 1: Burner specifications</th>
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<td><strong>Fuel consumption</strong></td>
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plane and the image plane have to intersect along a common line. This is accomplished by rotating the lens to a certain angle. However, the Scheimpflug camera arrangement introduces perspective distortion to the images, causing a rectangle in the light-sheet plane to be projected as a trapezoid on the image sensor. Since the image magnification is not uniform, a complex mapping function is required to map points from the fluid to the image planes correctly. Normally, a set of polynomial equations is used (Sollof et al., 1997). A calibration procedure is required to measure and correct the perspective distortion (Bjorkquist, 1998). The viewed area was 90x84 mm² (spatial resolution of 11.3 pixels/mm in the radial, and 12 pixels/mm in the axial direction). In order to measure the whole volume, the burner was displaced perpendicularly to the laser sheet. Seventeen planes were recorded from \(z = -40 \text{ mm}\) to \(z = 40 \text{ mm}\) every 5 mm. 450 image pairs were recorded on each plane.

A direct picture of the flame produced by the burner is shown in Fig. 4. It is possible to distinguish three main regions. These regions are, from top to bottom: the main combustion region containing much soot luminescence; below, it is found a transparent region, where the fuel droplets are evaporating; the last one is the flame-holding region, near the baffle plate.

![Fig. 4. Direct image of the flame](image1.png) ![Fig. 5. Stereoscopic PIV image pair](image2.png)

An example of a typical stereoscopic image pair recorded in these experiments is shown in Fig. 5. Light was propagating from left to right. It is important to point out that the area imaged in Fig. 4 is bigger than the area shown in Fig. 5, where only a small portion of the upper combustion area is visualized.

The smallest droplets will follow the airflow, while droplets bigger than 50 \(\mu\text{m}\) will penetrate the airflow. As the droplets move inside the flame, their sizes will be reduced due to the evaporation. In general, it is possible to have good measurements of the unburned droplets’ velocity, as the fuel droplets are easily imaged. The unburned droplets can be observed in the center of the imaged plane. They present stronger intensity on the right image, as forward scattering is stronger than backward scattering (Van der Hulst, 1957). However, on the image sides and the recirculation zones, it is not possible to distinguish clearly the image of the fuel droplets. Instead, a strong luminescence is recorded. This luminescence is coming mainly from the smallest droplets and soot particles. Here, the soot is playing an important role. Due to their small size (in the order of the nm) the soot particles are acting as ‘tracers’, following the airflow, and, therefore, providing information about its velocity. As the soot is not uniformly distributed, spurious vectors will be obtained at the points with a lack of information either from soot or droplets. It has been mentioned before that PIV alone does not allow the measurement of the particle size and velocity. Then, applying only PIV it is not possible to distinguish whether a measured velocity vector comes from soot particles (airflow velocity) or fuel droplets. PIV has to be combined with another technique that allows size discrimination such as Multi-Intensity PIV (Palero and Ikeda, 2002).

2.3 **Image analysis**
A PC with two frame-grabbers captured and processed the images that were analyzed using the cross-correlated sub-regions of frame-straddled images (Insight software, version 3.00, TSI Inc). 3D vector maps were computed by interpolating the two 2D vector fields in a new grid created to define the locations where the 3D velocity was desired (Insight manual). The 3D-grid spacing was 2 mm, some 45x45 vectors were interpolated from 60x60 measured vectors on each stereoscopic image (interrogation area: 32x32 pixels, 50% overlap).

Several factors have to be considered for the elimination of the spurious vectors. Since the software used in the present work does not allow setting local validation criteria, and the velocity ranges from 0 to 25 m/s, these have to be quite general in order to avoid the elimination of correctly measured vectors. On the other hand, as the turbulent interaction between the spray droplets and the airflow is being studied, we refused to use smoothing or any other algorithm that would improve the appearance of the instantaneous velocity vector maps, but somehow would mask the real velocity.

In particular, two validation criteria were applied: first, a range filter (the vector can not exceed reasonable limits in the displacement) and, second, the vector value has to be similar to the mean value of the nearest neighboring vectors (Keane and Adrian (1990)). Every vector was compared with the mean vector obtained after averaging the 3x3 surrounding vectors. After all the validation criteria were applied, less than 8% of the measured vectors were eliminated.

Before analyzing the results obtained, let us clarify the notation. Two coordinate systems are being used in the present work: rectangular and cylindrical coordinates. The CCD cameras are recording XY planes (Z = constant). Thus, the measured in-plane velocity components are \( (V_x, V_y) \) and \( V_z \) is the out-of-plane component extracted from the two stereoscopic views. However, the burner has cylindrical symmetry and, therefore, it seems logical to work with cylindrical instead of rectangular coordinates. So, the velocity vector in cylindrical coordinates, \( (V_r, V_\theta, V_z) \), can be calculated from the velocity vector expressed in rectangular coordinates in the usual way:

\[
\begin{align*}
V_r &= \cos \theta \cdot V_x + \sin \theta \cdot V_y \\
V_\theta &= -\sin \theta \cdot V_x + \cos \theta \cdot V_z \\
V_z &= V_z
\end{align*}
\]

where the angle \( \theta \) is obtained from \( \tan(\theta) = \frac{z}{x} \).

3. RESULTS AND DISCUSSION

3.1. Accuracy of the velocity measurement

The accuracy of the in-plane components is given by the minimum displacement that can be measured. In general, algorithms used in PIV can achieve an accuracy of 0.1 pixels. Many authors are currently working in new algorithms for the analysis of the PIV images, which improve the accuracy and the spatial resolution, without dramatically increasing the calculation time (Hart, (1999), Lecordier et al, (1999), Scarano and Riethmüller, (1999), among others). Here a standard PIV cross-correlation algorithm has been used. Then, for an average spatial resolution of 85.5 \( \mu \)m/pixel, the minimum displacement detected is 8.55 \( \mu \)m. As the time between exposures was kept at 25 \( \mu \)s, the minimum in-plane velocity measured would be 0.34 m/s, assuming uniform velocity through the window.

The accuracy of the out-of-plane (swirl) component can be calculated from Lawson and Wu (1997 a). These authors defined the theoretical error ratio as \( \varepsilon_r = \frac{\delta(\Delta z)}{\delta(\Delta x)} \), where \( \Delta z \) and \( \Delta x \) are the displacements in the out and in-plane directions respectively. As the stereoscopic angle was set at 11º, due to the limitation imposed by the test rig, the expected error ratio would have been \( \varepsilon_r = 5 \). Then, the accuracy on the measured swirl component will be \( \approx 1.7 \) m/s, clearly too large for ensuring a good characterization of the velocity flow field.

On the other hand, the same authors also defined the experimental error ratio as \( \varepsilon_r = \frac{\hat{\delta}_m(\Delta z)}{\hat{\delta}_m(\Delta x)} \) (Lawson and Wu, 1997 (b)), where \( \hat{\delta}_m(\Delta z) \) and \( \hat{\delta}_m(\Delta x) \) are the RMS of the displacement in the out and in-plane directions.
respectively. Then, as a way of evaluating the accuracy of our experimental data, the error ratio has been calculated all over the central plane of the burner (Fig. 6). In average, $e_r \sim 2-3$. The error ratio increases on the image sides, due to the lack of droplets and soot particles, as it can be seen in the images shown in the Fig. 4. Then, we can conclude that, in general, the experimental error ratio is smaller than the theoretical error predicted by Lawson and Wu (1997, b). This smaller error ratio can be owed to the application of the Scheimpflug condition, so that sharp focused images are achieved. Besides, the f# could be reduced, so that the working conditions were similar to the measuring conditions in classical PIV.

**Fig. 6. Error ratio**

3.2. Velocity measurements

For the visualisation of the 3D structures in the spray, the iso-surfaces of the three velocity components have been calculated. On every measured plane, 450 instantaneous velocity vector maps have been averaged. The average maps have been interpolated into a cylindrical volume and the iso-component surfaces have been extracted, using some features available in the commercial software Tecplot ver. 7.5. In order to have the best visualization of the structures in the flow, the spatial orientation has been set different for each case.

The detailed description of the three-dimensional velocity structures and the phenomena that happen in the burner is given in Palero et Ikeda (2002). Nevertheless, these results will be briefly summarised here. In Fig. 7, an example of the iso-surface components obtained for each velocity component is shown. The iso-component surfaces for different values of the three-velocity components are concentric, centred in the nozzle exit. However, some asymmetry is found and more penetration of the droplets is measured on one side of the burner, probably because of a misalignment between the nozzle and the burner plate.

The recirculation zones play an essential role in the flame stabilization as the airflow is entering and mixing with the evaporating droplets. There, turbulent activity can be observed as well as the formation of vortices (see Palero and Ikeda, 2001). It was found that the recirculation zone is forming an annular structure of radius half of the burner’s radius (Fig 7a). Thus, it seems that the dimensions and geometry of the burner are directly related with the size and shape of recirculation zone. Although the measurement in these zones is difficult, as there is a mixture of soot and small (evaporating) droplets, good measurements can be obtained as the soot particles are acting as ‘tracers’, following the airflow, and, therefore, providing information about its velocity.

Concerning to the axial component (Fig 7a), it can be seen that the maximum axial component goes from ~20 m/s in the shear flow region, down to, approximately, 15 m/s in the central flow region. Droplets will decelerate quickly, and therefore, a large velocity gradient is observed, as a consequence of the interaction with the airflow coming from the burner throat.

The results obtained for the swirl component are shown in Fig. (7 c), where the iso-surfaces for a swirl of 3 m/s are represented. Two differentiated structures can be distinguished in the centre of the burner. These correspond to
the spray droplets that are entering from the nozzle and have a strong swirl. The maximum swirl is measured in a very small region, close to the baffle plate and has a value of 4 m/s. Then, the swirl decreases quickly as droplets move upwards. The swirl component also presents asymmetric structures. However, lower swirl values are obtained in the regions were the axial and radial component show higher penetration. On the burner’s sides the movement corresponding to the soot and small droplets, that are following the airflow, is measured as well.

![Fig. 7. Iso-surfaces for the three velocity components](image)

From the measurements of the fuel droplet’s velocity it was also possible to locate the evaporation area. The typical scale for combustion is of the order of a few milliseconds for fuel droplets, assuming a $d^2$ law for evaporation, where $d$ is the droplet’s diameter. Droplets with an initial velocity smaller than 15 m/s will be almost completely evaporated after travelling some 40 mm in the flame. Droplets with higher initial velocity will cross the evaporation region, losing part of their mass and reducing their velocity. Then, it is not possible to measure any velocity smaller than 10 m/s there, because all the slow droplets will be evaporated by then. From these measurements it can be seen that the evaporating region covers approximately from $y \approx 45$ mm up to $y \approx 85$ mm.

### 3.3. Calculation of the rms for the three-velocity components

In order to improve our knowledge of the flow field characteristics, it is important to know the fluctuation of the velocity components as well. The analysis of these velocity fluctuations might provide some insight about the interaction between the airflow and the fuel droplets, the structure of the evaporation and the recirculation zones, and so on. With the purpose of obtaining some of this information, the rms ($\sigma_v$) for each velocity component has been calculated at every point of the space as:

$$\sigma_v = \sqrt{\frac{\sum_{i=1}^{n} (v_i - \bar{v})^2}{n(n-1)}}$$

(1)

Where, $\bar{v}$ is the average velocity component at that point, and $v_i$ is the instantaneous velocity value.

Let us start analyzing the rms obtained for the axial component. In the figure 8, all the values obtained have been plotted. The smallest fluctuation is measured in the central spray axis. Then, the droplets moving along this direction do not interact with the surrounding airflow. The rms remains constant along the central axis and is independent of the droplet velocity. The region with the maximum velocity fluctuation, and therefore, maximum turbulence intensity, is located precisely in the shear flow regions. It can be seen that it is a hollow, conical structure, which smaller radius is about 10 mm, biggest radius is about 25 mm and height is 35 mm, except for the area where more penetration is measured, where is reaching a height of 45 mm. This is the region where the main
interaction airflow-fuel droplet takes place. Finally, most of the volume shows values for the rms of the axial component between 3-4 m/s.

The rms obtained for the radial component (Fig. 8), reaches its minimum value in the central plane (Z=0). The rms increases as the distance to the OZ axis increases, and forms parallel, vertical structures at both sides of the plane of minimum rms. Something similar occurs with the rms for the swirl component. The minimum value for the rms is obtained in the plane X=0 and increases as the coordinate X increases.

These characteristics are related with the way in which the rms of the axial, radial and swirl components are related with the rms of the velocity expressed in rectangular coordinates:

\[
\begin{align*}
\sigma_{V_y}^2 &= \sigma_{V_y}^2 \\
\sigma_{V_r}^2 &= (\cos^2 \theta) \sigma_{V_x}^2 + (\sin^2 \theta) \sigma_{V_z}^2 \\
\sigma_{V_\theta}^2 &= (\sin^2 \theta) \sigma_{V_x}^2 + (\cos^2 \theta) \sigma_{V_z}^2
\end{align*}
\]

For each recorded plane, the directly measured in-plane components (Vx and Vy), have the smallest rms. The out-of-plane component is always measured with bigger rms for, as the accuracy of its measurement is lower. Then, the rms for the axial component will be directly the rms obtained for the in-plane component Vy. On the other hand, the radial and swirl rms components are obtained as a combination of the rms of the rms of the Vx and Vz components. In that way, for \( \theta = 0, \pi \sigma_{V_r} = \sigma_{V_x} \), while for \( \theta = \pi/2, 3\pi/2 \sigma_{V_\theta} = \sigma_{V_z} \). Then, the minimum rms will be measured at these locations. The rms in any other location will be bigger as there will be contribution of the rms coming from the swirl component.
Fig. 8. Three-dimensional rms structures for the axial component
Fig. 9. Three-dimensional rms structures for the radial and swirl components

The vorticity has also been calculated. The process followed for obtaining a three-dimensional representation of the vorticity is similar to the process followed for the velocity components and their rms. Only one component has been calculated, as the distance between the planes is too large, and, therefore, it is not possible to calculate the other vorticity components. The vorticity has been normalized, and the results are shown in fig 10 and 11. In the figure 10 a two-dimensional representation of the vorticity in the central plane of the burner is shown. Several structures can be identified there. In the center, there is a small vortex, rotating clockwise. The maximum value of the vorticity there is \( \sim 0.25 \). This vortex is produced by the air coming next to it, there is a much stronger vortex, rotating anti-clockwise. This vortex is located in the same region where the maximum fluctuation is measured, and shows some asymmetry as well, as it can be seen that the branches on the left side extend to \( y = 50 \) mm. In the recirculation zone it can be seen that the vorticity has opposite direction on each side. Also two small structures can be visualized at the far end. These correspond to the vorticity induced by the airflow coming from the burner throat. In the figure 11, a three-dimensional representation of the two vortices is shown. The same vorticity value has been plotted (0.20).
Fig. 10. 2-D vorticity

Fig. 11. 3-D vorticity. The two vortices can be seen: a small vortex in the center and a bigger one, covering the shear flow region

4. CONCLUSIONS

Stereoscopic PIV has been applied for the analysis of the three-dimensional structures that appear in the interaction between the continuous phase (airflow) and the disperse phase (fuel droplets) in a gun-type burner, which is working under reacting conditions. Firstly, an estimate of the accuracy of the out-of-plane component has been done, founding that the accuracy is about three times smaller than the accuracy of the in-plane components. This is smaller than the accuracy expected theoretically.

The three velocity components present concentric structures, which centre is located in the nozzle exit. Using the information from the velocity components, it is possible to locate the evaporation region (from \( y \approx 45 \text{ mm} \) up to \( y \approx 85 \text{ mm} \)). From the rms three-dimensional structures it is possible to know the position and shape of the region where the interaction between the spray droplets and the airflow takes place: it is the shear flow region. The minimum interaction droplets-airflow is found in the central spray axis.

The vorticity has been calculated and several vortices have been found. A small vortex is located in the centre of
the burner, rotating clockwise and a bigger vortex, rotating anticlockwise, located in the shear flow region, that is in the region where the maximum interaction between the fuel droplets and the airflow is found.

References


