Three-Dimensional Characterization of Strong Recirculating Flow by Stereoscopic PIV

Yuji Ikeda, Virginia Palero, Kei Sato and Tsuyoshi Nakajima
Department of Mechanical Engineering
Kobe University
JAPAN

ABSTRACT

Spray characteristics in the swirling flow were investigated by Stereoscopic PIV. Spatial spray structures were measured by PIV as well as PDA in order to understand stable flame stabilization. The feasibility study of Stereoscopic PIV in spray flame was also demonstrated. The size and location of recirculation flow were measured. The stereoscopic PIV could provide 3-D flow fluctuation that cannot be measured by convectional measurement systems.

Keywords : spray, stereoscopic PIV, three-dimensional swirl flow, recirculating flow

INTRODUCTION

Currently, spray formation, drop breakup and the corresponding turbulent two-phase flow represent some of the challenging problems in fluid mechanics [1]. Definite experiments are difficult because a number of different measurement tasks are required to characterize the various components of the process. Diagnostics designed for spray and fluid mechanics measurement are limited in specific areas so there are gaps in our information on key phenomena such as the internal flow field of atomizers, the breakup region and very dense spray regions. Drop evaporation, collisions, oscillations, deformation and breakup are difficult phenomena to measure and have escaped completely successful characterization. Therefore, many important problems remain and the current state of the technology is far from satisfactory.

In these last years diagnostics have developed quickly as a result of the improvement of the computers, laser, CCD arrays and related electronics and software. Non-intrusive optical diagnostics have been proved the most suitable measurement system for three-dimensional non-steady spray, in which the drops may be deformed easily and the spray and flow field are easily disturbed. Among the optical methods the most commonly used are Laser Doppler Velocimetry (LDV) or Phase Doppler Anemometry (PDA) as point measurement techniques and Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) as planar techniques.

Laser Doppler Velocimetry and Phase Doppler Anemometry, describe turbulent characteristics and droplet dynamics at very high data rates, but it is hard to gain insight about spatial structures in the flow. PDA has been successfully applied in sprays [2] and some recent extension of the technique has even increased its performance with the development of the size-classified PDA [3]. With this method it is possible to classify droplets by their sizes and measure the velocity of drops that belong to a determined range of sizes.

Planar imaging techniques (PIV, PTV) have a significant advantage as they are not normally affected by the material of the particles and allow identification of particle shapes such as ligament fragments and deformed droplets. These methods can record a suitable volume of the spray so that structures, ligaments, breakup mechanics, spatial distribution of the drops and other general qualitative features of the spray can be studied along with the size distribution. They present also some limitations as time series data, turbulent spectrum analysis or small spatial resolution. PIV is a well-known velocity measurement technique that can measure the two-dimensional or three-dimensional (when extended to Stereoscopic PIV) velocity field in a whole fluid plane [4, 5]. The recent improvements of this technique have lead to its application for the study of complex flows (spray, combustion, turbulence) even though the special characteristics of such flows (presence of particles with different sizes in the same measurement plane, large velocity gradients). PIV application to non-combusting and combusting spray was examined and good agreement with PDA data was found [6]. But even if PIV has shown great performance in its application to these flows, much more optimization of the technique has to be done in order to overcome the drawbacks still present for PIV application to complex flows.

In that sense, many authors are concentrating their efforts in investigating more accurate techniques for the analysis of PIV images. Some authors [7-9] have suggested different improvements for the cross-correlation PIV. The main advantage of such approaches is to extend the dynamic velocity range and enhance the accuracy of the technique without dramatically increasing the computation time. Hart [10] has developed a Super-Resolution algorithm based in recursive correlation. That algorithm allows the calculation of the velocity vector using an interrogation area that can be as small as the dimensions of individual particle images. Then, the spatial resolution will be greatly increased. That is very important in flows where there are regions with large velocity gradients, as it will help to have a more detailed knowledge of the velocity field.

We have been investigating the spray characteristics and droplet dynamics in a practical burner by means of the application of several optical techniques: PDA [2], size-classified PDA [3], PIV [6] and Stereoscopic PIV [11, 12]. Our purpose is to understand the flame holding mechanism, that is, the recirculation flow region, where strong shear and droplet followability becomes a critical issue. We are also interested in describing the recirculating flow in the swirl movement. Therefore, Stereoscopic PIV was applied as that technique will provide the full three-dimensional velocity vector map in a whole fluid plane.

In this work we will apply the Hart Super-resolution (HSR) algorithm [10] for the analysis of the flow images recorded using a Stereoscopic PIV (SPIV) angular system in a gun-type burner (no-reacting condition). Our main objective is to increase the measurement accuracy in a strong shear flow and acquire more knowledge about droplet dynamics in the recirculation region. Results will be validated with PDA and will show how the application of the HSR algorithm improves the spray characterization.

EXPERIMENTAL SET-UP

Figure 1 shows the gun-type burner used in these studies. This type of oil burner is commercially available for rather small (0.1 MW class) industrial furnaces and boilers. The baffle plate serves as a flame holder and aids in reducing soot formation. The heavy oil (type A, Japanese Industrial Standard) was pressurized up to 0.7 MPa and a hollow cone spray was produced with a 60° included angle.

Figure 2 shows the experimental set-up used in this work. A dual-cavity Nd:YAG laser (SP PIV-400, 400 mJ a pulse, 532 nm) formed a sheet 2 mm thick for illumination. Two CCD cameras (TSI PIVCAM 10-30, cross-correlation, 1000×1016 pixels, Kodak ES1.0) were used with a 60 mm focal length Micro Nikkor lenses and were working at f#2.8. The stereoscopic angle was 22.5° (45° between both camera axes) and the pulse separation, $\Delta T = 25\mu s$. The viewed area was 90×84 mm^2 (spatial resolution of 11.1 pixels/mm in the radial (OY) direction and 12.1 pixels/mm in the axial (OX) direction). Figure 3 shows a typical stereoscopic image pair obtained with this system when a pressure injection of 0.7 MPa is applied.

The analysis of each stereoscopic image pair was done using the Hart Super-Resolution algorithm [10] that is based on a recursive correlation. The principle of the recursive correlation is the same as the traditional correlation processing. That is, a subregion is selected, the region is correlated and the peak correlation is determined. But, unlike traditional correlation, the resulting value is stored and the subregion is broken into smaller regions that are, in turn, correlated to yield the velocity over a reduced region of determination. The previous correlation is used as an estimate to limit the search for the current correlation.

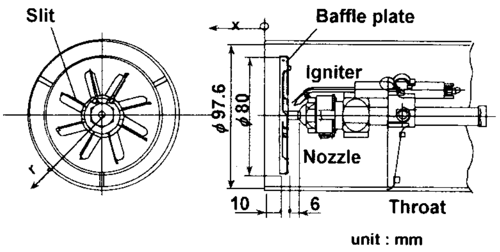


Fig. 1 Gun-type burner

In this way, the probability of locking onto the correct displacement is maintained at a high level despite the small data sets. Then, the correlation window size will be progressively diminishing, increasing the spatial resolution of the analysis.

In this case, the primary correlation window for each image of every stereoscopic pair was 32×32 pixels (2.88×2.68mm^2) and the smallest final subregion suitable for our particular case was 16×16 pixels (1.44×1.34 mm^2). Three-dimensional vector maps are computed by interpolating these two two-dimensional vector fields in a new grid created to define the locations where the three-dimensional velocity is desired. The final grid spacing was 2 mm (45×45velocity vectors).

For the PDA measurements a Dantec Phase Doppler Velocimeter was used. The dual beam system comprises a 5W (nominal power) Ar^+ laser and a conventional fiber optic PDA transmitter with a 40 MHz Bragg cell for frequency shifting and a 500 mm focal length front lens. The diameter of the geometrical probe volume was 0.1 mm and its length 1 mm. A Dantec PDA processor, with 1 μs time resolution, was used for data acquisition. PDA data were taken every 2 mm grid close to spray nozzle and 3 mm grid in the downstream in the rest (50.000 samples on each point).

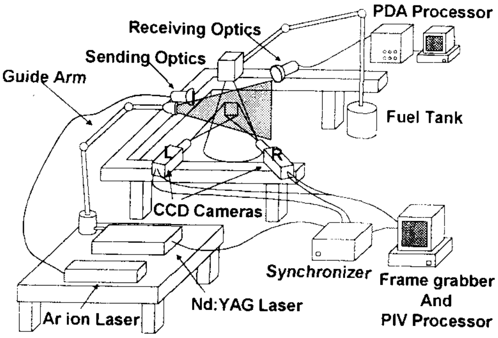
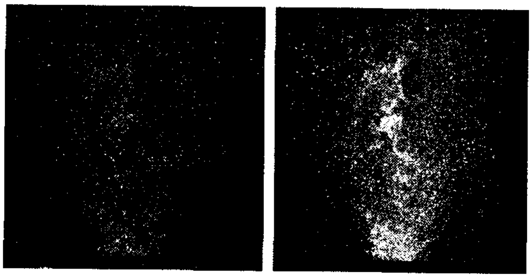


Fig. 2 Experimental set-up



(a) (b)

Fig. 3 Stereoscopic image pair; a) left image; b) right image

RESULTS AND DISCUSSION

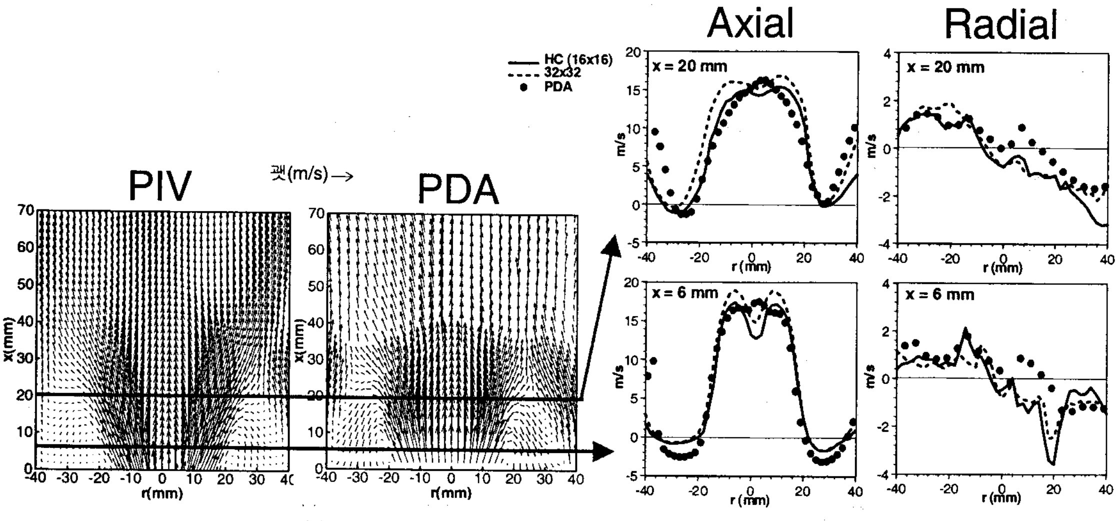
In figure 4 (a), the two-dimensional velocity vector maps measured with SPIV and PDA are shown. The SPIV velocity vector map has been calculated as the average of 450 three-dimensional instantaneous velocity vector maps obtained after the application of the HSR algorithm.

In these vector maps, it is possible to see the spray cone structure, clearer for the SPIV data. High velocities happen near the baffle plate and droplets have strong penetration. There is a strong shear flow region, due to the interaction between the spray droplets and the airflow, and it is also possible to distinguish two recirculation areas placed symmetrically related to the spray central axis. Size and position of the recirculation areas measured with both techniques are practically the same as well as the structure of the reversing flows inside these areas. There are two reversing flows: the inner flow produced by the air coming from the slits in the baffle plate and the outer reversing flow, produced by the interaction of the spray droplets with the air flow coming through the burner throat.

In figure 4 (b) comparison between the axial and swirl velocity components measured with PDA (black dots), HSR (continues line) and regular cross-correlation algorithm (32x32 window size, dashed line) in two locations along the spray axis ($x = 6$ and 20 mm) is shown. These locations correspond to a line inside the recirculation zone and in its tail.

For the axial component we can see the same flow features that described previously. That is, high velocity in the central region, strong shear flow and recirculating flow (areas with negative axial component). Although the size and position of these areas is the same, velocities measured with PDA present bigger absolute values than when measured with SPIV.

Between the center and the recirculation areas there are the shear flow regions, resulting from the gas flow-droplet interaction. These

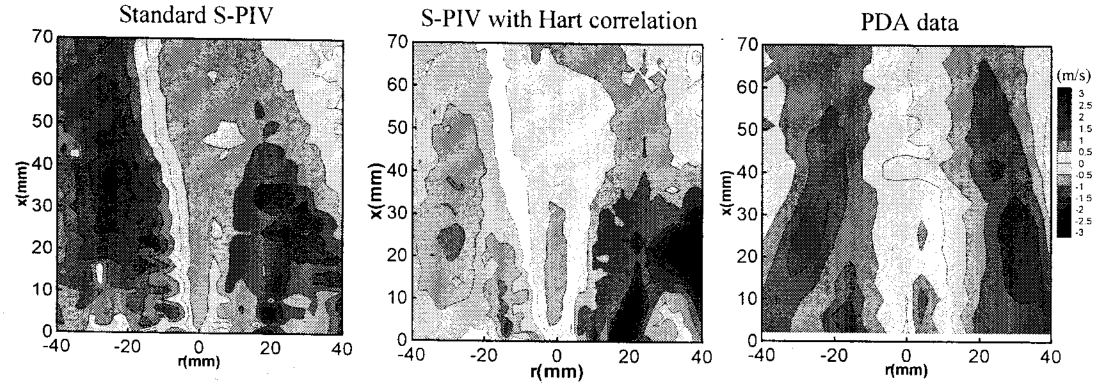


(a) (b)

Fig. 4 a)SPIV(Hart Super-resolution algorithm) vs. PDA : b)comparison between the velocity obtained when Hart Super-resolution Algorithm is applied, regular cross-correlation(32x32 pixels) and PDA

regions are difficultto describe with PIV as there are large velocity gradient. In these areas is very important to increase the spatial resolution in order to obtain a more detailed understanding the mechanism of the air-droplet interaction. It is clear that the application of the HSR algorithm provides very good match between SPIV and PDA in the shear flow regions (x= 6 and 20 mm) and not only there but also near the spray central axis (x= 6 mm).

For the swirl component, we can notice that the flow is axisymmetrical and swirling. This swirling flow is produced by the slit airflow coming through the slits on the baffle plate. The agreement between SPIV and PDA is clear, mainly in the region with positive swirl. This agreement can be seen also in figure 5 where the swirl component measured by SPIV



(a) (b) (c)

Fig. 5 Comparison of the swirl component obtained with (a) SPIV regular cross-correlation (interrogation area : 32x32 pixels), (b) SPIV(Hart Super-resolution) and (c) PDA ((a) traditional correlation algorithm, (b) Hart Super-resolution algorithm) and PDA (figure 5 c) in the whole fluid plane are shown. In these contour graphs the swirl velocity component reaches its maximum value at about 25 mm down stream from baffle plate than at the other parts. Comparing with the PDA data, the traditional correlation algorithm tends to over estimate the swirl component on the region of the spray where the swirl is positive. When the Hart Super Resolution algorithm is applied, the agreement between SPIV and PDA is almost perfect in that area. Not only the component values are very similar but also the contour structure. The agreement in the region with negative swirl is not as perfect as in the other case, probably due to some lack of droplet images there.

CONCLUSIONS

In this paper the Hart Super-resolution algorithm, based on a recursive correlation, has been applied together with Stereoscopic PIV for the analysis of a strong recirculating flow, generated by a gun-type burner. The comparison with PDA shows how the HSR algorithm provides a better description of the flow characteristics. For the axial velocity component, the central flow region, with high velocity value, and the shear flow region, with strong velocity gradient, are now described more accurately (better agreement between PDA and HSR than when the regular cross-correlation is applied).

For the swirl component HSR provides the same features obtained with PDA, specially in the region with positive swirl velocity. The traditional correlation algorithm is over estimating the positive values of the swirl component and can not describe completely all the features of that component, as it is shown when the comparison with PDA is done.

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