SUITABILITY OF VOLUMETRIC 3-COMPONENT VELOCIMETRY METHOD FOR MEASUREMENT OF PRESSURE SWIRL SPRAYS

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Abstract

A spray generated by two types of pressure swirl atomizers (PSAs) (i.e. spill-return and simplex atomizers) was examined by means of a volumetric 3-component velocimetry (V3V) measurement system (V3V-Flex©, TSI Inc.). The experimental setup is first described in this paper, and the image processing steps are outlined later. The 3D3C measurements of instantaneous droplet velocities were provided for several operating regimes, and the suitability of the V3V-Flex© method for the description of the 3D complex spray flow is depicted.

Keywords: V3V-Flex©, pressure swirl atomizer, volumetric 3-component velocimetry, particle image velocimetry, flow field

1 Introduction

PSAs are widely used in combustion and especially in combustion turbines. So far only, non–intrusive methods such point wise (LDA/PDA) and planar (2D2C or 2D3C PIV) methods or high-speed imagining were used to investigate this type of spray flow in terms of droplet velocity, droplet/particle diameter, cone angle, etc. For further details on LDA/PDA/PIV, we refer to [1]. Very few studies proposed a full 3D3C description of the spray flow. Volumetric methods needed for validation and phenomena visualization in fluid mechanics are more attainable nowadays. There are different volumetric techniques as mentioned by Boomsma et al. [2], 1) Holographic PIV, this technique has a very good spatial resolution, but the field of view is very small (several mm). 2) Tomographic PIV, four cameras setup is often used. Field of view is in most cases about 10 mm. 3) Volumetric particle tracking velocimetry (PTV), experimental setup usually uses three cameras, thought more cameras could be used. This method uses “triangulation” to extract the position of a particle in 3D space. Volumetric particle tracking velocimetry (PTV) is the principle of V3V-Flex© technique introduced in 2016 by TSI Inc. and considered in this study. It associates a velocity vector to each individual seeding particle detected in the volume of measurement. It offers much less ghost particles than Tomographic PIV with higher accuracy for detecting of high velocity gradients in the flow [3]. Higher is the seeding, and higher would be the density of the velocity vectors measured. The size of the volume of measurement would be proportional mainly to the size of the seeding particles and the energy of the laser involved. A configuration of three or four cameras can be considered with a totally free positioning of the cameras. In this study, the water droplets generated by the spray are used as a natural seeding, and no additional seeding particles were added to the flow. Spray that the PSA produces is three dimensional and very complex. The V3V-Flex© system has the potential to significantly advance our understanding of 3D complex spray flows.

2 Experimental setup

The experiments were conducted at TSI GmbH fluid Mechanics Laboratory in Aachen, Germany. The V3V-Flex© system was composed of four PowerView 8 MP CCD cameras equipped with 135 mm Samyang lenses, a Nd:YAG pulsed laser with 200 mJ/pulse at a maximum frequency of 15 Hz, mirrors to back illuminate the volume of measurement, because of the different light intensity across the volume of measurement, nozzle housing, calibration system for V3V-Flex© including a back illuminated target and traverse for moving the target through the volume of measurement. The full system was controlled externally from the software Insight4GV3V©. The cameras and laser were synchronized by synchronizer.
(Model 610036) with 200 ps resolution. Two cylindrical lenses were used to expand the laser beam to the size of the measurement volume.

The housing for the nozzle is composed of tubing, control valves and pressure gauges measuring up to 16 bar with an accuracy of 0.256 bar mounted at the inlet and outlet tubing. The experimental setup is shown in Fig. 1, where 1 is Computer, 2–Synchronizer, 3–Mounting system for the cameras, 4–Cameras, 5–Laser, 6–Pressure sensors, 7–Control valves, 8–Hollow cone spray, 9–Mirror for the laser deflection, 10–Vessel collecting discharged water, 11–Water cooling system for the laser, 12–Working table. The maximum pressure considered in this study was 4.5 bar and water was used as a working fluid. Note that water has slightly different properties than Jet-A1 fuel (kerosene) which is normally used in other experiments with PSAs, see Tab. 1.

Table 1: Properties of water and kerosene, temperature 25 °C

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Kerosene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface tension [kg/s²]</td>
<td>0.072</td>
<td>0.029</td>
</tr>
<tr>
<td>Dynamic viscosity [kg/m · s]</td>
<td>0.00089</td>
<td>0.0016</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>997</td>
<td>795</td>
</tr>
</tbody>
</table>

Two PSAs, shown in Fig. 2, were tested on five regimes. The operating conditions are reported in Tab. 2. (SL = spill line, $P_{in}$ = inlet over pressure). The V3V-Flex© was set to capture 70 pair of images for each of the four cameras used and at a frequency of 3.75 Hz, this leads to a total acquisition time of 18.6 seconds. The time separation between successive images of the same pair was set to 15 µs which lead to a particle displacement of approximately 6 pixels.

Table 2: Test conditions

<table>
<thead>
<tr>
<th></th>
<th>Spill-return PSA</th>
<th>Simplex PSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$P_{in} = 4.5$ bar, SL = closed</td>
<td>$P_{in} = 4.5$ bar</td>
</tr>
<tr>
<td>2</td>
<td>$P_{in} = 4.5$ bar, SL = open</td>
<td>$P_{in} = 3.5$ bar</td>
</tr>
<tr>
<td>3</td>
<td>$P_{in} = 3.5$ bar, SL = closed</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 1: Experimental setup

Figure 2: PSAs a) Spill-return; b) simplex
One of the main differences between the two Pressure Swirl Atomizers tested in this study is that the “spill-return” atomizer contains a bypass (spill-line) in the rear back of the swirl chamber. Fluid in the swirl chamber, which is injected via the tangential ports, is separated into two streams. One stream goes to the spill line and the other goes through the discharge orifice. The amount of fluid in the spill line was controlled by a control valve (position 7 in Fig. 1) [4].

3 Volumetric velocity system

3.1 Calibration

A calibration of the V3V-Flex system was required before starting the measurement. The calibration aims to correct the optical distortions of the cameras, find the camera orientation, and provide the magnification function that will help in the step of matching the particles between the different apertures and getting the position the particles in the 3D volume of measurement. A calibration target of 200×200 mm with dots spaced uniformly in x–y direction of 5×5 mm was used. The distance between calibration planes was 2 mm in z-direction. The results of the calibration process show a maximum mean dewarping error of 24 pixels (see Fig. 3). The cameras were aligned with the centre of the calibration target where three dots are missing. The missing dots were used to find the orientation of each of the apertures. The final size of the measurement volume obtained was A×B×C mm³ = 40×50×20 mm³. The measurement volume was positioned under the nozzle discharge orifice (see Fig. 3).

3.2 Image processing

The image processing done with the software Insight 4G-V3V© aims to extract information about the position and velocity of the droplets in the spray flow. An example of the raw images captured in time t₀ is shown in Fig. 4. A large number of individual droplets were captured in the images and the different region of a spray flow could be identified.

There are six individual steps in the image processing as shown in Fig. 5. The first step is the image capturing. Each camera captures an image at time t₀ and then at time t₀+c (c = 15 µs is time separation between successive images). A set of four images, for time t₀ and t₀+c, is obtained (top left, top right, bottom left, bottom right). Pre-processing can be applied to improve contrast between the particle and the background. Gaussian filter is applied to the raw images to improve the shape of the pixelated droplets. Afterwards, particles in each image are identified based on their peak of intensity and a threshold value defined by the user. The identified particles are then matched between the different apertures to reconstruct a 3D positions of particles in measurement volume using the information obtained from the calibration. The matched particle are then tracked on time using a robust matching algorithm and a velocity vectors is associated to each particle detected in the flow. 3D randomly spaced vectors are then obtained in the volume of measurement which can be interpolated to obtain a regular grid of vectors.
Figure 4: Raw images as seen by the different apertures

Figure 5: Computational process
4 Results

As it was mentioned before, five measurements were made using the two PSAs. In each experiment, more than 30,000 particles were recognized. The system was able to measure more than 12,000 random velocity vectors for the matched particles. The number of velocity vectors raised almost four times when the velocity interpolation was used.

4.1 Particle positions in 3D

In Fig. 6 a–e position of particles in the volume of measurement is shown. Each blue dot corresponds to a droplet at a time \( t_0 \). In Fig. 6c and 6d an influence of the spill line opening on the spray behaviour is shown when the spill line is opened (Fig. 6d) the spray is wider (approximately 24 degrees). The spray cone angle can be derived from particle positions or can be also determined from analysis of raw images shown in Fig. 4.

![Images of particle positions in 3D](image)

Figure 6: Particle in the volumetric domain

We can also see if some denser area is produced within the spray. An example is given in Fig. 6f showing a histogram of particle positions in \( Y-Z \) plane. The spray is more dense around spray cone and also near the nozzle tip in primary breakup region, where the spray forms liquid film (more particles are recognized and matched).
4.2 Velocity vectors in 3D

Figure 7: Instantaneous velocity vectors in the volume of measurement
Fig. 7 shows instantaneous velocity vectors randomly spaced in the flow (i.e. before interpolation) coloured by the velocity magnitude levels. It also shows how particle lose their kinetic energy (momentum) in the streamwise direction of the flow from the discharge orifice. This loss of kinetic energy is caused by a drag of surrounding gas acting on the surface of the droplets. In Fig. 7d we can also see how the spill-line opening influences the velocities in the spray. It is also clear that the velocity magnitude increases when the pressure is increased. Fig. 7f shows that the span of the axial velocity is ranging from 30 m/s to \(-30\) m/s. It can be caused by false vectors that were created during image processing especially in area of the flow where individual droplets couldn’t be identified properly (i.e. near the output of the nozzle).

Fig. 8 below shows the data obtained without filtering the velocities; spurious vectors with high amplitude are highlighted by the red circle. The false vectors could be created during the processing due to the presence of some matched ghost particles. A proper filtering of the velocity vectors based on a local comparison might be applied to get rid of these vectors.

5 Conclusion
The present study showed the ability of V3V-Flex\(^\text{©}\) to measure the velocity of the droplets of a spray flow generated by a PS atomizer. The influence of the pressure of the liquid and the geometry of the nozzle on the development of the spray is also depicted. A volume of \(50\times40\times20\) mm\(^3\) could be achieved. However, the spray generated by a PSA is much larger than the measured volume. A larger volume of measurement could not be set due to a limitation in terms of the energy of the light source (i.e. laser) available to illuminate the small droplets in the flow used as seeding. Studying the interaction of the spray with surrounding flow is also of interest and can be achieved by considering a proper seeding of the surrounding flow using soap bubbles for example. For combustion application, the velocity information of the droplet is important but also the size distribution. The size information cannot be derived directly from the images obtained with V3V-Flex due to the small size of the droplets involved. In fact, the Mie scattering of the laser light emitted by the droplets covers few pixels on the raw images recorded by the cameras and might be different from the real size of the droplets. So for a full description of the flow (droplet size/velocity) V3V- Flex\(^\text{©}\) can be combined with other measurement technique more accurate for sizing the droplets such as PDPA.

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