Measurement of droplet size and velocity distributions in sprays using Interferometric Particle Imaging (IPI) and Particle Tracking Velocimetry (PTV)

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Abstract

This paper presents droplet size measurements in a spray using Interferometric Particle Imaging (IPI). IPI is a technique for measuring the size of transparent, spherical droplets in the whole field. The velocity of each droplet is determined using particle tracking techniques (PTV). Measurements were carried out on a Danfoss oil pressure-swirl atomizer operated with water, and results were compared to phase-Doppler (PDA) measurements. In shape the data acquired with IPI and PDA are very similar, however due to different sampling methods employed by the two measuring techniques, IPI yields consistently smaller mean diameters than PDA.

1. Introduction

Sprays are widely used in several applications, e.g. spray combustion, spray-painting, crop spraying and many other applications. For the different applications a wide range of spray devices have been developed and they are generally designated as atomizers or nozzles. For combustion in domestic heating burners the pressure-swirl or simplex atomizer has been found to be the most reliable type of atomizer.

The process of atomization with a pressure-swirl atomizer is a process where a liquid sheet is broken up by the kinetic energy of the liquid. The liquid sheet is formed by the pressure-swirl atomizer as a result of a swirling motion and the formation of an air-core within the atomizer. As the liquid moves away from the atomizer fragments of the sheet are broken off and these subsequently disintegrate into droplets and the spray is formed. The droplet size and velocity distribution in the spray are important, because they govern the combustion in the burner or the results in other applications. Therefore accurate information about these spray properties is desirable.

There are various methods employed in drop size and velocity measurements. Phase Doppler anemometry (PDA) is widely used in research laboratories and in the industry for spray measurements, e.g. [1]. PDA employs temporal sampling, and because of its limited measurement volume, it is weak when used to measure flux and concentration.

Interferometric Particle Imaging (IPI) is a relatively new technique for determining the diameter of transparent spherical particles from out-of-focus images, though its origins can be traced to a number of sources [2-3]. The strength of the IPI technique lies in its ability to measure the instantaneous size and velocity of spatially distributed droplets.

2. Interferometric Particle Imaging (IPI)

In the focused field the incident light scattered by a transparent spherical particle produces two glare points (as seen from the receiver) on the particle's surface. According to geometric optics, one glare point represents the reflected ray, the other the refracted ray. The existence of both glare points is contingent on the light scattering properties of the particle-medium and the off-axis angle of the receiver. In the out-of-focus field the scattered light from the glare points interferes to produce measurable fringes on a CCD array, as seen in Figure 1. The particle size can then be directly determined from the fringe number and spacing. The velocity of each particle is then separately determined using particle-tracking (PTV) techniques.

The IPI technique works best in scattering regimes where the intensities of the reflected and refracted light are relatively close. In the case of water droplets with parallel polarisation the optimum angle is often stated as 68 deg., even though 90 degrees, or orthogonal to the lightsheet, is a better angle. In practical terms, this orientation affords the best viewing of out-of-focus images. The size of the out-of-focused particle image is independent of particle size, but rather on particle position in the light sheet and the amount of user applied de-focusing.

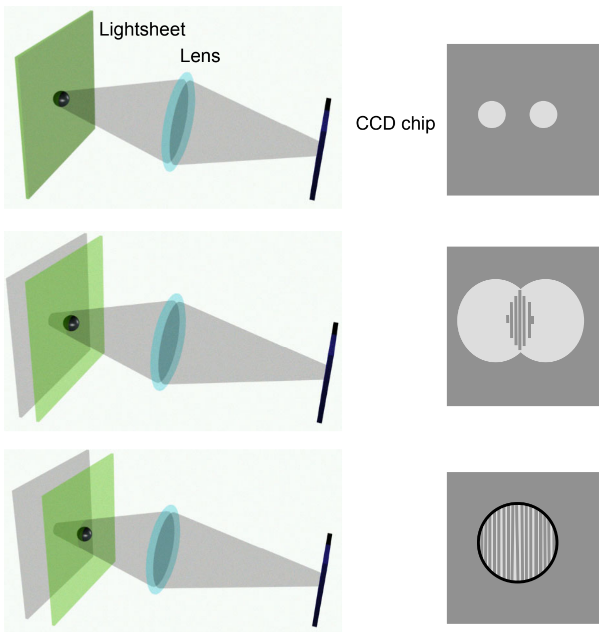

Figure 1. Effect of moving the focus plane of the camera away from the lightsheet on the captured particle image.

Once the images are acquired, the diameter of a particle can be determined by measuring the size of the out-of-focus particle images and determining the fringe frequency, eventually resulting with a fringe count. The relationship between the number of fringes and particle size is linear, and is defined by [5] as:

$$N_f = \kappa d_p \tag{1}$$

Where for a relative refractive index > 1:

$$\kappa = \frac{\sin^{-1}(d_a/2z)}{\lambda}\left(\cos\phi/2 + \frac{m\sin\phi/2}{\sqrt{m^2+1-2m\cos\phi/2}}\right) \tag{2}$$

For m < 1:

$$\kappa = \frac{\sin^{-1}(d_a/2z)}{\lambda}\left(m\cos\phi/2 - \frac{m\sin\phi/2}{\sqrt{m^2+1-2m\cos\phi/2}}\right) \tag{3}$$

Where d_a is the aperture diameter, z is the distance to the lightsheet, m is the relative refractive index, λ is the wavelength and ϕ is the off-axis angle.

The dynamic range of the measurement is dependent on a number of factors: the camera resolution, the size of the out-of-focus images, the laser intensity, the scattering angle and the properties of the particle and medium. As indicated by [4], the smallest measurable particle is defined by a fringe count of unity. This can be directly determined from equation (1). Increasing the magnification by reducing the distance to the lightsheet, will reduce this value. The generally accepted minimum diameter that can be measured is 5-8 microns. Another characteristic of (1) and (2) is that at 90 deg. κ is independent of m.

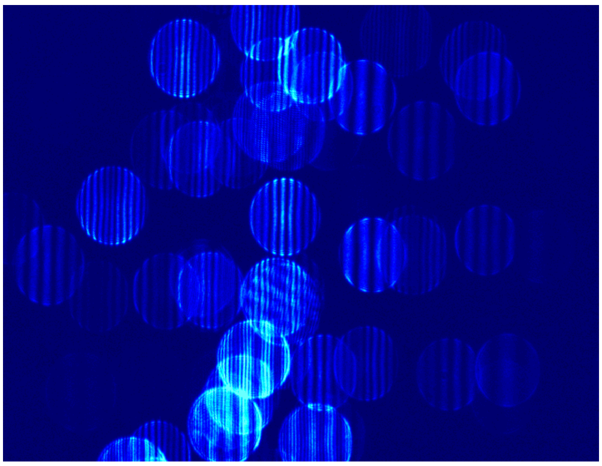

Figure 2. Out-of-focus image showing fringes**.**

The maximum particle size that can be measured will depend on the size of the out-of-focus particle image, the optic configuration, and the camera resolution.

There is a trade-off between de-focusing, which increases the size of the out-of-focus particle image, and image contrast. The larger the image, the more fringes that can be defined, but resulting with a lower signal-to-noise ratio. The Nyquist Criteria requires that at least two pixels define a fringe. In practice, fringes exhibit gradients and are not perfectly straight, so a more reasonable requirement is three or four pixels per fringe. In figure 2 is shown a representative image of fringes. Note the range of fringes present, from approx 2 to 30 fringes are present.

3. Experimental setup

A series of measurements were conducted on a pressure-swirl atomizer. A Danfoss oil nozzle type OD was chosen because this nozzle series can be used in most types of oil burners for domestic heating. The capacity of the chosen nozzle is 0.75 gal/h at an atomization pressure of 700 kPa in test oil with a viscosity of 3.4 mm^2/s and a density of 820 kg/m^3. The spray angle is specified to 80° and the spray pattern is specified as solid. The nozzle was mounted in a test rig in such a way that the spray propagated downwards. The test rig consisted of a pump, a flow meter and a barometer. The nozzle was operated with tap water at atomization pressures ranging from 700 to 850 kPa. Here only results obtained with an atomization pressure of 850 kPa is presented. At this pressure the water flow rate was approximately 3.2 L/h.

The droplet size and velocity of the produced spray was obtained using IPI and PTV techniques. The experimental setup consisted of a Dantec FlowMap Particle Sizer (FPS) system with a laser and two cameras. Using a beam splitter the cameras were placed orthogonal to one another and directed onto a common viewing area at a right angle to the light sheet, as shown in Figure 3. The laser source was a double-pulsed Nd:YAG laser at 532 nm in wavelength with a power of 100 mJ, repetition frequency of 15 Hz, and a laser sheet thickness of about 1.0 mm. The laser light was polarized perpendicular to the laser sheet. The cameras used were Kodak MegaPlus ES1.0 digital CCD cameras with 1008 × 1016 pixels. For the focused camera a 60 mm objective lens was used, while for the de-focused camera both a 60 mm and a 105 mm lens (with PK-11A extension tube attached) were used. The size of measurement areas were approximately 25 × 25 mm^2 and 10 × 10 mm^2 respectively. To measure velocity, double images were acquired and particle tracking carried out on the focused images.

The location of the measurement planes in the spray are defined by the axial distance from the nozzle (z) and the radius (y) according to Figure 4, with the origin defined as the exit orifice of the nozzle. The 60 mm lens was used near the edge of the spray where it is diluted. Due to the smaller measurement area with the 105 mm lens, this lens was used in regions with a higher concentration of droplets. It was also tried to conduct measurements in the centre of the spray, but here the droplet concentration was too high and thus overlap between droplets makes the measurement difficult. Figure 4 also shows locations of PDA measurement points. All measurements were carried out in a vertical plane at x = 0.

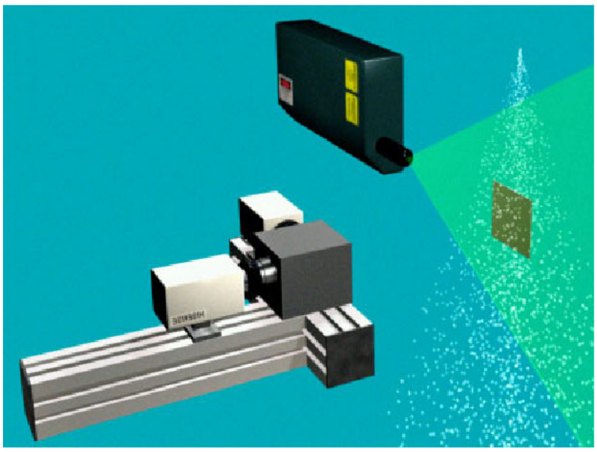

Figure 3. IPI measurement configuration with laser, two cameras, beam splitter and spray.

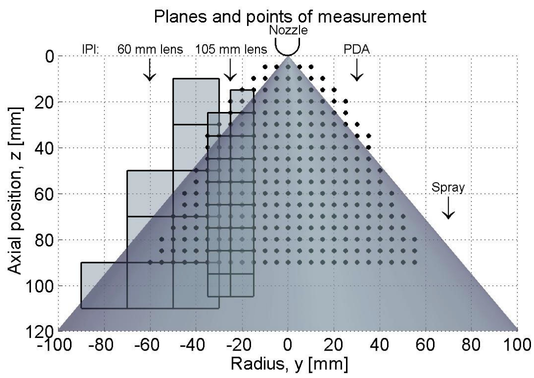

Figure 4. Location of IPI measuring planes and PDA measuring points.

For comparison, the droplet size and velocity were also measured using Phase Doppler Anemometry (PDA). PDA is widely used in research laboratories and in the industry for spray measurements. The measurements were carried out using a 2D Laser/Phase Doppler Anemometer from Dantec Dynamics. The system consisted of an argon-ion laser, Fiber PDA probe and detector and a Multi PDA signal processor from Dantec. The wavelength of the laser was 514.5 nm and 488 nm for the axial and radial direction respectively. The measurements were conducted with a 30° scattering angle in refraction mode. The focal lengths of the transmitting and receiving lenses were 161.8 mm and 400 mm respectively. This setup made it possible to measure droplets within the range of diameters of 0 – 110 μm. The measurement volume had a length of 0.8 mm and a diameter of 0.1 mm. The locations of measuring points are shown in Figure 4. For each measuring point a sampling time of 120 seconds were used.

4. Results

In this section results are given for both PDA and IPI measurements of the same spray. PDA measurements were conducted both before and after IPI measurements to ensure consistency in the data.

PDA results

The contour plots in Figure 5 and Figure 6 show the length mean diameter and the Sauter mean diameter (SMD) obtained from the PDA measurements, and the vector plot in Figure 7 represents mean velocity. The distributions of the two mean diameters are nearly identical in the spray where the smallest mean droplet diameters are found in the centre of the spray and as the radius increases the mean diameter increases. The length mean diameter ranges from 9.5 μm to 68 μm while SMD ranges from 16.7 μm to 72 μm. In the vector plot, the highest axial and radial velocities are found near the nozzle with maximums of 17.2 and 14.4 m/s respectively. From the PDA results, it can be concluded that the spray is nearly symmetrical around the nozzle centre axis.

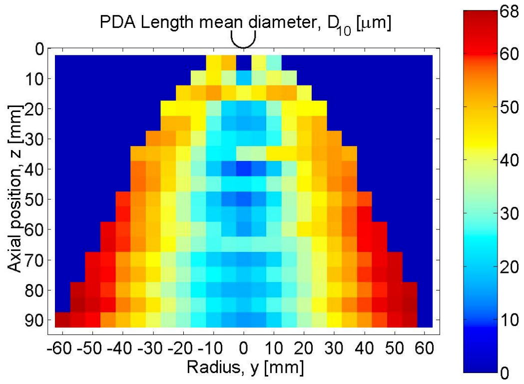

Figure 5. PDA Length mean diameter, D_{10}.

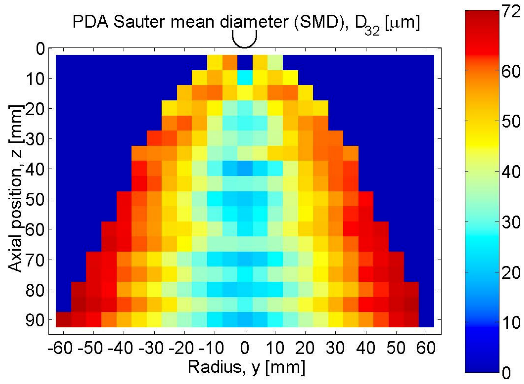

Figure 6. PDA Sauter mean diameter (SMD), D_{32}.

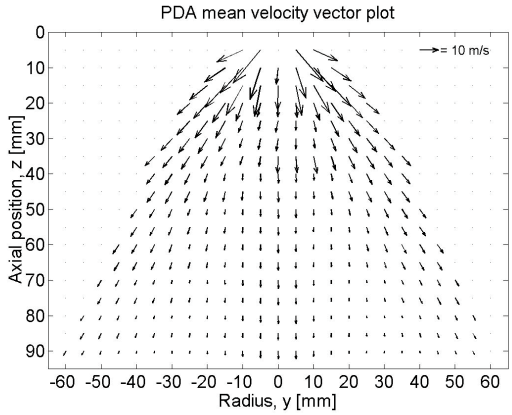

Figure 7. PDA 2D velocity vector plot.

IPI results

At each position the image raw image data was processed to produce a velocity and size map, as shown in Figure 8. Roughly 60 % of the particles detected could be validated. 100 double images were then processed at each position and then averaged. The resulting data sets were then ensemble averaged to create the contour images in Figures 9, 10 and 11.

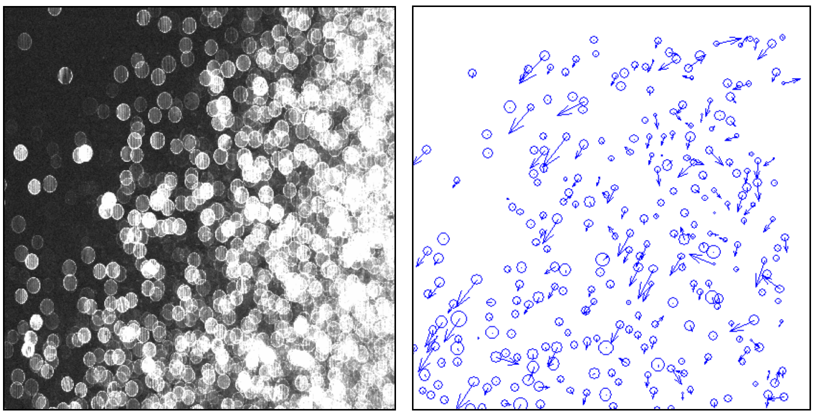

Figure 8. Instantaneous raw image and corresponding processed result showing relative particle size and velocity. (Position of center: Y=40 mm, Z=60 mm; Image area: 25x25 mm)

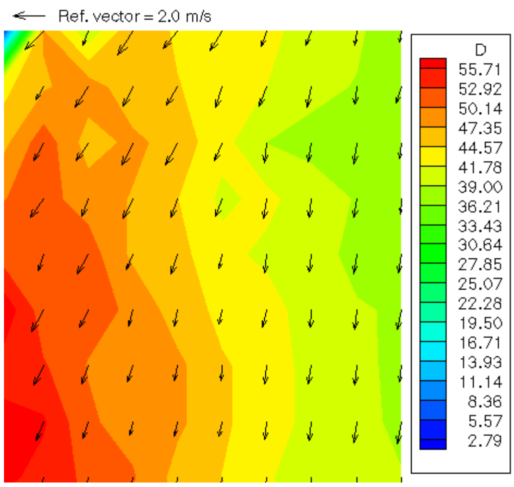

Figure 9. Ensemble averaged mean diameter and velocity at Y=40, Z=60 mm.

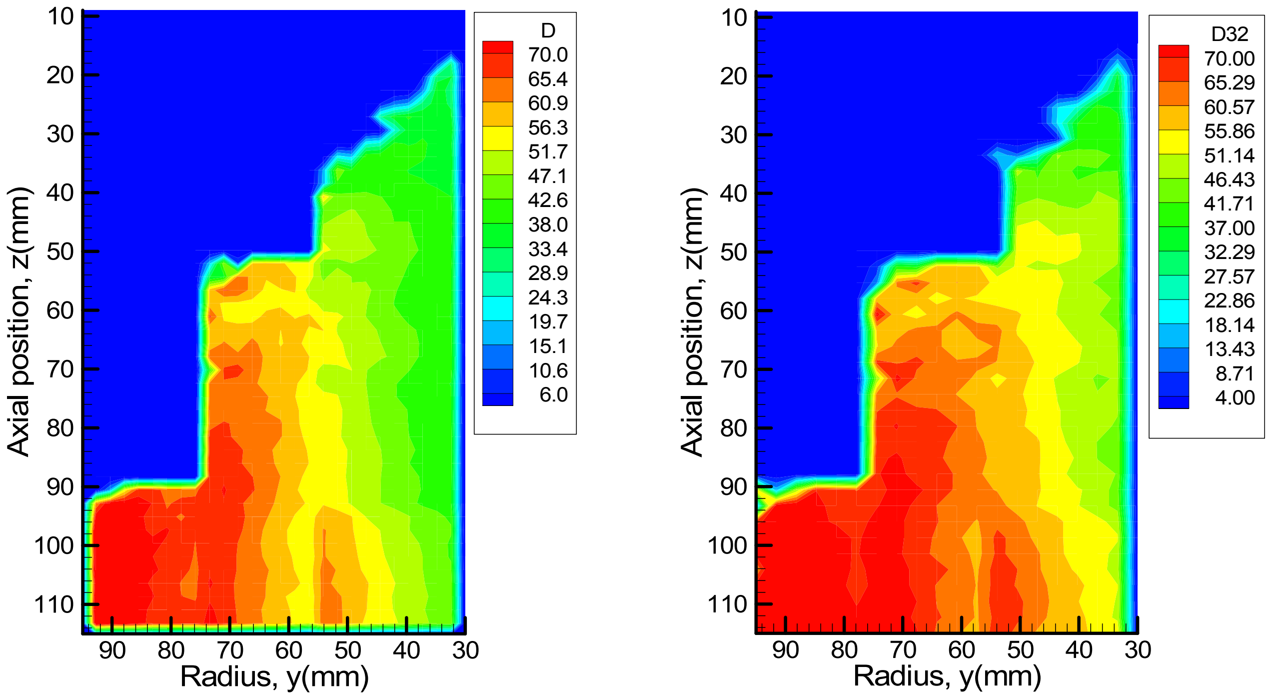

Figure 10. Ensemble averaged contour plot of diameter mean and Sauter mean.

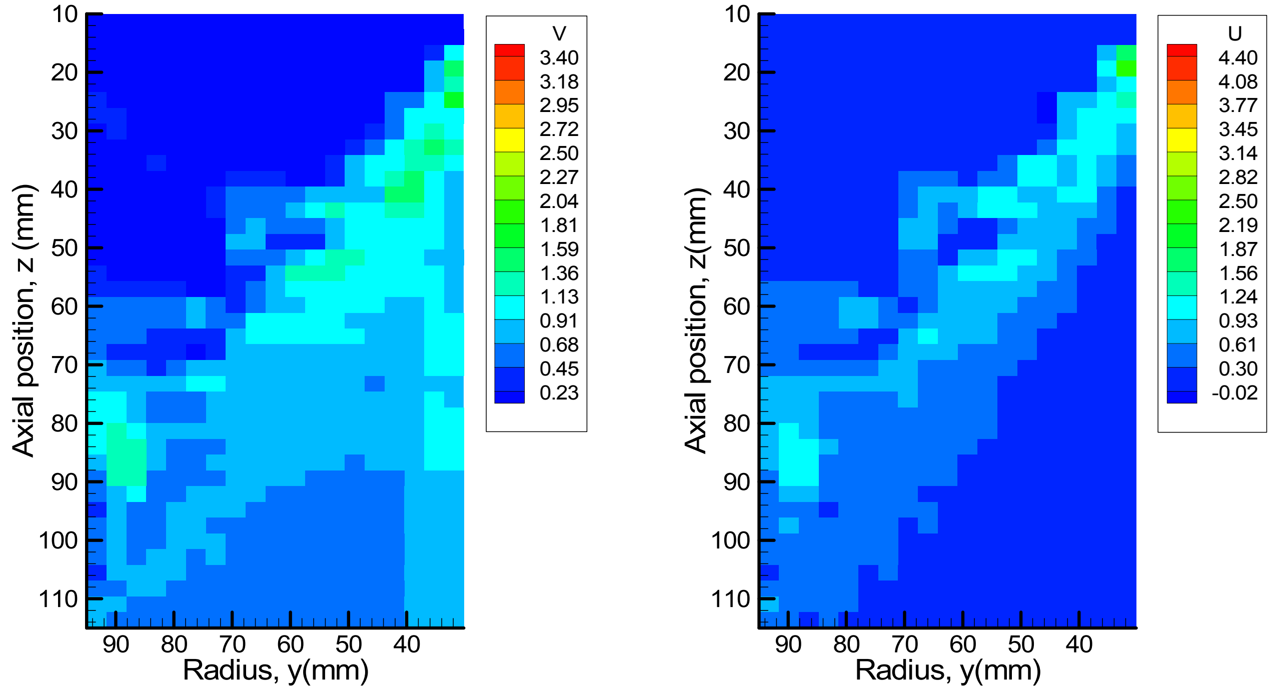

Figure 11. Ensemble averaged contour plots of mean axial and radial velocity.

A comparison of length mean diameters at different axial positions obtained by IPI and PDA is shown in Figure 12. The IPI yields smaller mean diameters than those indicated by PDA. These discrepancies arise from the two different methods of sampling employed by the measuring techniques. IPI employs *spatial sampling*, which describes the instantaneous measurement of drops contained within a volume. PDA employs *temporal sampling*, which describes the measurement of drops that pass through a fixed area during a specific time interval, with each drop individually counted. With pressure atomizers, the smaller drops in the spray decelerate more rapidly than the larger drops, and this leads to a high concentration of small drops downstream of the atomizer. Thus, spatial sampling yields mean diameters smaller than those indicated by temporal sampling. Theoretically, if all drops in the spray were moving at the same velocity, the results obtained by both methods should be the same.

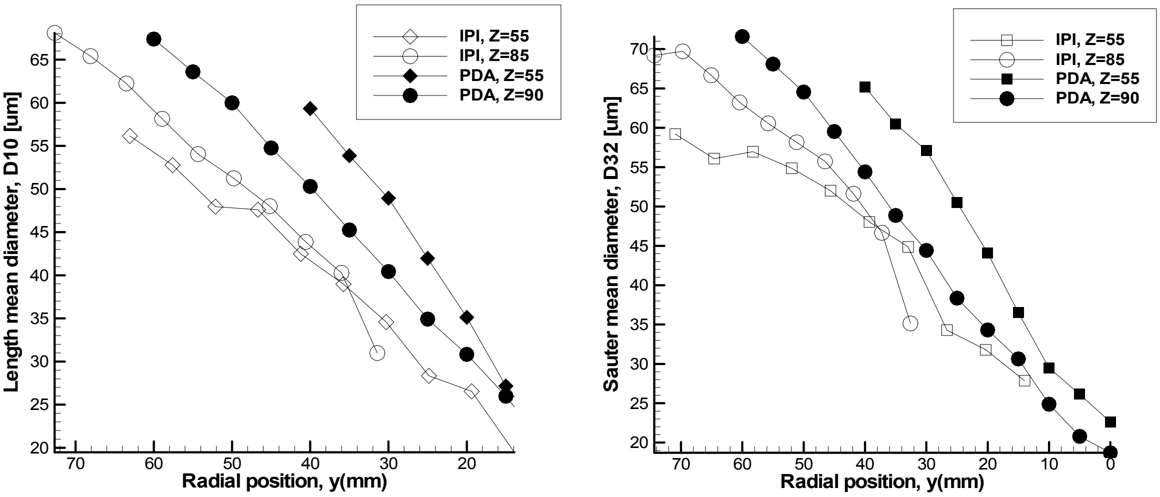

Figure 12. Comparison of mean diameters (D_{10}, D_{32}) at different axial positions obtained from IPI and PDA.

A spatial drop size distribution may be converted into a temporal distribution by multiplying the number of drops of a given velocity by that velocity [6], or temporal distribution may be converted into a spatial distribution by dividing by velocity. Which sampling method is best depends on the application. However spatial sampling might be advantageous in combustion applications, where ignition and burning rates are dependent on the instantaneous droplet population within a given volume.

5. Conclusion

Spray measurements have been carried out using the IPI technique for determining the size of droplets, and using particle tracking for determining the velocity of each droplet. With different focal length optics for the de-focused camera, the IPI technique was adapted to the dilute part near the edge of the spray and to the more dense part closer to the centre axis. At the centre of the spray the concentration of droplets was too high and thus the resulting overlap reduced the validation detrimentally. A solution to this problem is to magnify or reduce the measurement volume, thus spreading the particles farther apart, decreasing the overlap.

The IPI measurements have been compared to PDA measurements conducted on the same spray. In shape and trends the data acquired with IPI and PDA is very similar, however the comparison of mean diameters revealed that IPI yields smaller values than those measured by PDA. This discrepancy was expected due to the different sampling methods employed by the two measuring techniques.

Measurements with IPI have shown that the technique can be used effectively to map the spatial structure of a spray. Averaging many images revealed a consistent and repeatable structure. Even with the limitations of droplet concentration, the results show a marked improvement in spatial information over the PDA

6. References

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