Abstract

This paper discusses the measurement of transparent particles and droplets from a few microns to mm in diameter with the Droplet Imaging Velocimeter and Sizer (DIVAS), a two-dimensional technique to measure particle size and velocity. Unlike Interferometric Laser Imaging for Droplet Sizing (ILIDS), DIVAS can measure sprays with realistic concentrations, size distributions from microns to millimeters, and non-spherical spray features. The measurement of particles with a broad range of diameters is discussed to illustrate the capability of DIVAS and signal analysis strategies are suggested to expand the measurement envelop and accuracy of the technique. DIVAS uses a Particle Imaging Velocimetry (PIV) configuration; that is, pulsed lasers illuminate the droplets in the measurement plane and CCD cameras collect the off-axis scattered light, thus yielding a small measurement volume and correspondingly a high number density measurement capability. Particle sizing is based on measuring the separation of cross-polarized glare points captured by two separate cameras.

Keywords: Glare points, polarization, particle sizing

1. Introduction

Whole field spray measurements are currently made with the Interferometric Laser Imaging for Droplet Sizing (ILIDS) as was originally discussed by Glover, Skippon, and Boyle [1], a technique that works well for sparse sprays but does not work well in practical sprays, which are characterized by high droplet concentration. ILIDS measures the droplet size from the fringe frequency that results when the principal glare points expand and overlap to produce a fringe pattern (similar to Young’s fringes). These fringe patterns, however, limit the spacing between drops to avoid fringe overlap. Fringe compression [2] in the fringe direction mitigates this problem of image overlapping and enables the measurement of sprays with higher concentrations. However, even with compressed fringes the droplet concentration capability is rather limited. DIVAS extends this measurement capability since the measurements are made at the image plane, where the droplet images consist of glare points and are at their minimum size. Furthermore, non-spherical drops significantly confuse the fringe patterns in ILIDS yielding either signal rejection or erroneous measurements. DIVAS overcomes this serious limitation by recording the intensity pattern that follows the periphery of the drop or non-spherical feature for subsequent image processing analysis. Whole field measurements of the droplet size distribution may also be made with the Glare Point technique (GPT) as described by van de Hulst and Wang [3]. GPT, however, can only measure droplets larger than about 40 μm in a one-to-one imaging system. DIVAS overcomes the limitation of GPT and enables the measurement of smaller droplets with sub-pixel resolution.

2. Principles

The underlying principle of DIVAS is to capture two principal, cross-polarized glare points (e.g., refraction and reflection) on separate CCD cameras; therefore, the separation between glare points may be measured down to sub-pixel resolution. This enables the measurement of very small droplets (down to a few microns). Fig. 1 describes the glare points; the nomenclature is based on van de Hulst [4]. The figure shows three principal Debye terms: p=0 (ray reflected by the droplet), p=1 (ray passing once through the droplet), and p=3 (ray passing thrice through the
droplet). The point where the rays leave the droplet is the glare point. This geometric approximation of light scattering is well suited for droplets much larger than the wavelength. The separation between glare points provides an accurate measurement of the droplet size for spherical droplets.

![Fig. 1. Schematic of glare points.](image)

The relationship between the separation of the glare points (GP) and the droplet diameter, d is given by:

\[
d = 2GP \left[ \cos \frac{\theta}{2} + \frac{m \sin \frac{\theta}{2}}{\sqrt{m^2 + 1 - 2m \cos \frac{\theta}{2}}} \right]^{-1},
\]

where GP is the separation between glare points, \( \theta \) is the collection angle, d the particle diameter, and m the index of refraction. The current GPT measurement strategy is to find a configuration where the \( p = 0 \) and \( p = 1 \) Debye terms dominate in intensity over \( p = 3 \) as discussed in [5]. However, in this configuration glare points cannot measure droplets smaller than about 30 or 40 \( \mu \)m (with one to one magnification), because as the droplets get small, the glare points overlap and it becomes impractical to measure their separation. The DIVAS configuration enables the measurement of both small and large droplets from the separation between glare points by collecting cross-polarized glare points simultaneously on two separate cameras. For example, for water at angles close to 80 degrees, the image corresponding to S polarization will be characterized by a dominating \( P = 0 \) glare point, while the image corresponding to the P polarization will have a dominating \( P = 1 \) glare point (Fig. 2 and Fig. 3.) As stated above, the current measurement strategy is to collect the two glare points on a single CCD and to find an angle where the \( P = 0 \) and \( P = 1 \) have the same intensity. This angle is indicated by the red (left) arrow on Fig. 2. For water, the angle is about 68 degrees. DIVAS seeks an angle where different Debye terms dominate for the different polarizations. As indicated by the green arrows on Fig. 2 and Fig. 3, this angle is about 82 degrees for water. Notice that for S polarization the \( P = 0 \) term is about 10X stronger than the \( P = 1 \) term while the opposite is observed for P polarization.

3. Experiments

Fig. 4 shows the schematic of an experimental breadboard employed to acquire validating data. The basic PIV system is made by LaVision. The breadboard system employs a collection angle of 82 degrees. A half wave plate placed after the laser rotated the polarization of the laser beam to an angle such that the cross-polarized glare points have approximately the same intensity. The light from the glare points is separated into P-polarization and S-polarization by a
polarization cube beam splitter. The P-polarized light is collected by Camera 1 and the S-polarized light by Camera 2.

Fig. 2. Debye terms for water at S polarization.

Fig. 3. Debye terms for water at P polarization.

3.a. Monodisperse drops. The system was aligned using a Berglund-Liu monodisperse droplet generator and both cameras were focused to the droplet images, i.e. the glare points. The camera images were corrected for variations in magnification and other distortions. To perform this correction, we used a calibration dot pattern with a prescribed pitch of 1 mm and diameter of 0.25 mm (Edmund Industrial Optics P/N: 62211). We placed the dot pattern at the focal plane of the cameras and illuminated it with a CW green laser. The image correction routine was performed with the DaVis software of the LaVision PIV system. This image correction routine changes the pixel registration so that the images are true to the calibration target. The typical error of the calibration was about 0.5 pixel rms. The corrected monodisperse droplet images are shown below in Fig. 5 and Fig. 6. After image correction, the separation between glare points in the two images is almost equal (within a fraction of a pixel). Note that the Camera 1 image (P-polarization) shows brighter refraction (p=1) glare points; shown on the left side of the images while Camera 2 (S-polarization) shows brighter reflection (p=0) glare points shown on the right side of the images. This observation, as expected, confirms the above discussion of Debye terms; this is the premise of DIVAS.

Fig. 4. System schematic of cross-polarized glare point measurement system.
The glare point images were analyzed by auto-correlation and cross-correlation. Auto-correlation yields the separation between glare points as measured by each camera. Cross-correlation measures the separation between the left glare point of Camera 1 and the right glare point of Camera 2. The droplet diameter produced by the Berglund-Liu generator was 198 μm, and for this size droplet, the separation between glare points should be 0.877*198 = 173.6 μm. Both the auto-correlation and the cross-correlation yielded calculations that are within a few percentage points of error from the predicted size. Auto-correlation of the Camera 1 images yielded a mean glare point separation of 162 μm with a standard deviation of 6 μm. Auto-correlation of the Camera 2 images yielded a mean glare point separation of 167 μm with a standard deviation of 2 μm. Cross-correlation of the Camera 1 and Camera 2 images (DIVAS) yielded a mean glare point separation of 162 μm with a standard deviation of 3 μm.

3.b. Monodisperse glass beads. A dispersion of glass particles in water was used to test the ability to measure small particles with DIVAS. The Debye terms were computed for a relative index of refraction of 1.145 (glass in water) and the preferred angle of collection was determined to be 82°. At this angle, the p=0 term for P polarization is at its minimum and significantly smaller than the p=1 term, while for S polarization the p=1 term is significantly larger than the p=0 term. A modified aquarium with a built-in narrow channel was placed in the laser path so that the laser traveled parallel to the aquarium wall. Glass beads of 20 μm ± 1.4 with a standard deviation of 1.8 μm and 40 μm ± 2.8 with a standard deviation of 2.2 μm from Duke Scientific were independently weighed in an electronic balance and subsequently mixed with distilled water to produce dispersions with a concentration of about 5,000 to 20,000 particles/cc. The channel was filled with distilled water, and then the dispersions, one at the time, were poured into the channel and measurements were made at 10 Hz. The particle images served to focus the two cameras. The two cameras acquired several hundred frames with several dozen particles per frame. After completing the data acquisition, the particles were allowed to settle down until there was no evidence of particles in the images. The calibration glass plate with the dot pattern was placed inside the water channel at the object plane of the two cameras and the camera images were calibrated. The calibrated images were then analyzed with cross-correlation to obtain the separation between glare points.

More than two thousand particle images of the 20 μm glass beads were measured. The average glare point separation was 17 μm and the standard deviation 20 μm. Close to five thousand particle images of the 40 μm glass beads were measured and the corresponding GP separation was 35 μm and the standard deviation was 23 μm. The expected GP separation as
computed from Equation (1) for the case of $m = 1.145$ and $\theta = 82^\circ$ is $0.87 \, d$. Thus for the 20 $\mu$m particles we should expect a separation of $17.4 \, \mu$m and for the 40 $\mu$m particles a separation of $35 \, \mu$m. Therefore, the mean GP separations are very much in agreement with the expected values, although the standard deviations are large, suggesting a large error for single particle measurement. In observing the actual images, it is obvious that the images are not well focused, although every attempt was made to focus as best as possible. Some of the reasons for the variation in focus are 1) the laser sheet has a thickness of a couple of mm, 2) the angle is $82^\circ$ and the receiving optics are not at the Scheimpflug angle, and 3) aberrations in the endoscopic optics. Therefore, the cross-correlation analysis yielded erratic results depending on the shape and intensity distribution of the out-of-focus glare points. A potentially better method (not implemented yet) is one of segmentation where the geometric center of each out-of-focus image is located, and then the separations of these geometric centers corresponding to the two cameras are measured.

4. Conclusion
The DIVAS technique was described and experimentally demonstrated by measuring monodisperse water drops and glass beads dispersed in water. The cross-polarized glare points were imaged at a collection angle of 82 degrees and separated by polarization optics into two cameras. After correcting the images for distortions, the two sets of glare points were cross-correlated. The measured separations accurately agreed with the size of the calibrating particles.

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References