AUTOMATED QUANTITATIVE INTERROGATION OF VOLUMES TO SIZE HIGH SPEED SPRAYS

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ABSTRACT
A recently developed digital image analysis technique capable of sizing particles of arbitrary shape is explored and assessed in the present study. As with other single droplet counter sizing methods such as PDA, digital image analysis can be used to determine the properties of individual droplets or particles such as velocity, size, shape and particle concentration over a finite region of interest in the flow. In addition to the greater simplicity of the method over PDA, another major advantage is that a visual record of the spray under investigation is available, providing a simple means to verify what is, and perhaps more importantly, is not being measured. A series of experiments were conducted in order to assess the robustness and accuracy of the technique in its application to the sizing of relatively small droplets whose diameters are predominantly in the range 5 to 30μm.

Following a description of the fundamental principles of the technique, a thorough description of the calibration procedure is provided in which the image processing routine has been calibrated down to 18μm. The depth of field characteristics as a function of object diameter were determined experimentally for the optical set-up and confirmed an approximately linear relationship. In order to verify whether this linearity was still valid for object diameters in the range 10<D<18μm, simulations using a single lens approximation were performed and is of particular interest when measuring fuel and other finely atomised sprays. The measurement performance of the PDIA system has been assessed in terms of individual object diameters, number and volume probability density functions of object diameters and this data has been compared to phase Doppler anemometry (PDA) results of the same spray in space and time. It is shown that the larger objects are measured correctly and PDIA is arguably more accurate since object diameter is based upon the measured area/perimeter rather than local object curvature as is the case of PDA. Smaller objects may also be measured correctly by both methods although sensitivity to signal-to-noise ratio, for both methods can generate spurious and contradictory errors.

1. INTRODUCTION
A recently developed digital image analysis technique capable of sizing particles of arbitrary shape is explored and assessed in the present study. As with other single droplet counter sizing methods such as PDA, digital image analysis can be used to determine the properties of individual droplets or particles such as velocity, size, shape and particle concentration over a finite region of interest in the flow. In addition to the greater simplicity of the method over PDA, another major advantage is that a visual record of the spray under investigation is available, providing a simple means to verify what is, and perhaps more importantly, is not being measured. A series of experiments were conducted in order to assess the robustness and accuracy of the technique in its application to the sizing of relatively ‘small’ (defined as 5<D<30μm) fuel droplets produced by a pressure-swirl atomiser. Following a description of the fundamental principles of the technique, a detailed assessment of the calibration procedure is made for D>18μm. In addition, and of particular interest in the present study, the extension of the technique to measure smaller object sizes accurately is also investigated. Droplet size measurements obtained through this digital image analysis method are subsequently assessed and compared with relevant data obtained by phase Doppler anemometry (PDA) whilst consideration is also given to the determination of appropriate pdf correction procedures.

Until recently the error and time required for manual analysis of the images has been one of the main reasons why direct quantitative imaging methods have not been more prevalent (Bayvel & Orzechowski, 1993). A second reason has been the lack of an unbiased and objective criteria for determining acceptance, based on degree of focus to define which droplets or particles in an image should or should not be measured. A third reason is that there still remains the difficulty in attempting to quantify the effects of droplet image defocus on the actual droplet size such that the diameter corresponding to a defocused droplet image can be accurately corrected. Recent image analysis based sizing techniques reported for example by Malot & Blaisot (2000) and Nishino et al (2000) have generally been restricted to flows in which the droplets or particles are relatively large, of the order of 100μm and above. The aim of the present study was to determine the suitability and accuracy of the PDIA method as a means of measuring droplet size distributions in a hollow cone spray producing much smaller droplets, typically in the range 10 to 30μm. The particle/droplet image analysis (PDIA) technique has previously been applied in the determination of droplet size distributions in agricultural-type sprays where the droplet size range of interest is in the range 100 to 400μm (Herbst, 2001). These results showed quite good agreement when compared with average size measurements obtained via the laser diffraction and phase Doppler methods. Wigley et al (2000) verified the accuracy of the imaging technique, again for relatively large diameters of 200μm, by measuring the size distribution of droplets produced by a mono-disperse droplet generator. These studies showed that, for droplets of order 100μm, the accuracy of the measurement technique for both in-focus and out-of-focus droplets is comparable with PDA. The attempts of Wigley et al (2000) to accurately size droplets within a hollow-cone fuel spray similar to the one used in
the present study was limited by the magnification of their imaging system which restricted the smallest measurable diameter to 20\(\mu\)m and it is this aspect that the present study addresses.

The PDIA technique as reported by Whybrew et al (1999) uses an automated segmentation thresholding algorithm for the quantitative analysis of droplet or particle images. This method is based on the original approach adopted by Yule et al (1978), in terms of determining the degree of image focus from the edge gradient intensity of a droplet image. Preliminary studies (Kashdan et al, 2000) examined pdf correction schemes to account for edge contact correction and depth of field (DOF) biasing effects which are diameter-dependent. The PDIA data presented here has been corrected for edge-contact bias but has not been DOF corrected. The aim of the present study is to assess whether the PDIA technique can be applied to moderately dense sprays containing objects of order 10\(\mu\)m as it has thus far only been evaluated for the measurement of relatively large particles as produced by agricultural-type sprayers (Herbst, 2001). The purpose of the present study is twofold:

- To verify the image processing routine with calibration data of known particle sizes. The objective is to characterise the lens-camera optical behaviour and to estimate the relative uncertainties of various parameters such as the depth of field dependence on particle diameter, threshold level sensitivity and the effect of image to image intensity variations. All of these factors are likely to affect measurement accuracy to some degree and may become non-negligible for measurements of small, fast objects.

- To assess the capability of digital image analysis for the measurement of small droplets in realistic DISI engine sprays. The results of spray measurements obtained using two different laser configurations are presented permitting a comparison of the droplet sizing accuracy to be made by comparing the accuracy with similar measurements obtained by PDA. Other aspects of the PDIA method such as the ease and time required for prior calibration of the optical set-up, signal/noise contributions and subsequent data acquisition rates are also assessed.

2. NUMERICAL SIMULATION OF THE PARTICLE IMAGING SYSTEM OF PDIA

It is known that the performance of the PDIA imaging system is affected by two main factors, the effects of diffraction and defocus. The first of these is related to the finite size of the imaging lens: a small, spherical particle placed in the path of an illuminating plane wave scatters light in a manner consistent with Mie theory (Born & Wolf, 1997; Van de Hulst, 1981). In most conventional imaging systems, both the scattered light and the illuminating beam are focused by a system of lenses onto a screen to produce an image (if the optical axis of the lens system is not in line with the illuminating beam) or a shadow if the optical axis of the imaging lens is coincident with the illuminating beam. In the present case the system is of the latter configuration and a shadow is produced. Most of the light scattered by the particle is directed near the Poynting vector of the illuminating beam, with much of the scattered intensity confined to the angle of the so-called “Airy-disc” (Hecht, 1998). As particle size decreases, the angle associated with Airy-disc is increased so that an increasing proportion of the information carried by the scattered light escapes the imaging system. The result is a blurred image, in which the definition of the shadow edge becomes progressively more difficult with decreasing particle size and increasing particle defocus.

Numerical simulation was used to investigate the performance of the PDIA imaging system for small droplets of 10 and 37\(\mu\)m diameter water droplets and is discussed here. The smaller diameter is below the minimum experimentally calibrated size and the larger diameter corresponds to a calibrated object size as shown later in Fig. 3. A Mie scattering calculation was used to determine the distribution of the electric field vector (associated with the scattered light field) at the surface of the imaging lens and then this result was numerically “projected” onto the CCD chip using a Huygens-Fresnel quadrature. The key assumptions of the simulation are that the particle/droplet is perfectly spherical and illuminated by an infinite plane wave of coherent monochromatic light and imaged by a single “thin” lens with optical properties equivalent to the real PDIA system. Full details of the numerical techniques used are beyond the scope of the present work, the reader is referred to the paper by Jones et al, 2002 which describes the simulation technique, but for the case of the imaging system of the shadow Doppler velocimeter (SDV). The difference between the two simulations is that the SDV is illuminated by two laser beams whilst the PDIA has only a single beam. The simulation presented here is analogous to the SDV simulation with the angle between the two illuminating beams set to 0°.

Simulated intensity distributions for the 10\(\mu\)m and 37\(\mu\)m water droplets are shown in Figs. 1 (a) and (b) respectively. Both in-focus and out-of-focus droplets were simulated, with the particle defocus being defined as the distance from the in-focus particle position to the actual particle position. The sign convention used for particle defocus is that particles closer to the imaging lens than the in-focus particle have negative defocus. Results for defocus distances of \(\pm 4\) and \(\pm 8\) times the droplet diameter, D, are shown with a magnification, \(M=10\). For the in-focus cases shown it is evident that the larger droplet has a much more clearly defined shadow edge at approximately \(\pm 0.5MD\).
Fig. 1 Simulated intensity cross-sections for in-focus and out-of-focus water droplets of (a) 37\(\mu\)m diameter and (b) 10\(\mu\)m diameter.

The simulation shows that the measured size of the in-focus particle has a low sensitivity to the level of the intensity threshold used, however, as the particle is moved out of focus the “sharpness” of the image is reduced as shown by the change of intensity gradient at the edge of the shadow. There exists an asymmetry in the results for positive and negative defocus of the same magnitude; this is shown both in the intensity of the glare-point as well as intensity-gradient at the edge of the shadow.

In the case of the 10\(\mu\)m droplet the edge of the shadow is not as clearly defined as that of the 37\(\mu\)m diameter droplet, even for the case of the perfectly in-focus droplet. The information required to reconstruct sharp images lies within the outer portion of the Airy-disc and therefore smaller particles, which are associated with larger Airy-discs, require relatively larger imaging lenses to produce images with the sharpness shown in Fig. 1 (a). The similarity of the shadow edge intensity-gradients at \(\pm 0.5\)MD is indicative of the fact that methods, which are solely based on the detection of the intensity-gradient of the shadow edge, are not capable of measuring particle defocus for particles of this size range using optical systems similar to that of the PDIA.

The results presented here for the PDIA system are in qualitative agreement with those given by Jones et al (2002) for the imaging system of the shadow Doppler velocimeter. The reader is referred to this work for a more complete description of the effects of particle defocus on shadow imaging systems.

3. PRINCIPLE OF PDIA
3.1 Droplet identification from in-focus images

The novelty of PDIA in comparison with previous image analysis methods lies in the automated image post-processing routine which has recently been developed by Oxford Lasers Ltd and is now described. For a typical in-focus image of two opaque calibration discs printed on a quartz plate (Fig. 2 (a)), a threshold is applied in order to distinguish the discs or droplets from the illumination background within the image.

Fig. 2 (a) Typical in-focus image of two opaque calibration discs of diameters \(D=145\)\(\mu\)m and \(D=110\)\(\mu\)m and (b) corresponding image intensity histogram showing background peak and associated with the discs.
The 8-bit digital shadow image as shown in Fig. 2 (a) consists of pixels with grey scale intensity values which vary between 0 to 255 where 0 is black and 255 is white. The grey scale intensity histogram of this 8-bit image is shown in Fig. 2 (b). Ideally the image intensity histogram should have a large separation between the object and background intensity peaks and also a narrow distribution of typically 30 to 40 grey levels in width which implies that the pixel to pixel intensity variation of the background is small. This implies that the illumination conditions should be uniform and the spray relatively disperse. It is clear from the histogram in Fig. 2 (b) that although the distributions are narrow the grey scale separation between object and background should be greater as this would further improve image contrast and reduce measurement error as discussed later. Figure 2 (b) shows that the background level peaks at approximately 180 on the grey scale level whilst a smaller peak, corresponding to the discs within the image is observed at a lower (darker) grey level of approximately 125. The threshold level should be set such that the illumination background is separated from the discs, which in the case of the image in Fig. 2 (a) would be somewhere between 140 and 170. In practice the threshold is generally set at a grey scale level corresponding to 10 below the position at which the background peak starts to rise. This is to prevent any background noise from being incorrectly accepted as foreground particles. In Fig. 2 (b) the background level starts to rise at a grey scale position of approximately 170 and a threshold level of 160 is used.

3.2 Depth of field calibration

In order to quantify the effects of object diameter and defocus distance on image properties a Patterson globe and circle calibration graticle was used onto which two-dimensional arrays of thin-film chromic particle images were photo-etched on a flat glass slide (Fig. 3). There were 10 discs of known diameters in the range of 18 to 450µm. The calibration graticle was mounted on a digital micrometer translation stage and traversed in 10µm intervals, with an accuracy of ±1µm about the plane of best focus up to a maximum defocus distance of approximately ±1500µm. Images of the graticle were acquired at each position and then analysed with the PDIA software which gave estimates of the total pixel area ($A_T$) and halo area ($A_H$) for a specified threshold.

![Image](a)

![Image](b)

**Fig. 3** (a) In-focus image of the Patterson globe calibration graticle with disc sizes ranging from 18µm (Disc 1) to 145µm (Disc 8) and (b) grey-scale and corresponding two-colour images of an in-focus and defocused calibration object showing effect on $A_T$, total pixel (sum of light and dark blue areas) and $A_H$, halo areas (light blue area only).

Figure 3 (b) shows the effect of object defocus on total pixel area, $A_T$ and halo area, $A_H$. PDIA images are analysed at two threshold levels. The first corresponds to the user-specified threshold and is determined from the image intensity histogram as described earlier and separates the image background from the particle. The second threshold level distinguishes between the halo grey area and the dark particle interior.

Calibration data obtained for diameters ranging from 18 to 110µm are shown in Fig. 4 which shows the effect of object defocus on the halo area ($A_H$). The graticle was defocused to the extent that the discs became indistinct from the background and could no longer be detected for a given threshold level. The sign convention used here attributes negative values of defocus for the graticle located between the plane of best focus and the microscope objective. It is clear from Fig. 4 for this range of diameters that the estimated halo area is a minimum at the plane of focus and increases almost linearly with positive and negative defocus distance. It is also evident that for all object sizes a maximum or peak halo area is clearly observed and with further positive or negative displacement from focus, further image defocusing reduces the estimated halo areas since the halo area progressively descends into the background and becomes indistinct within the image. The implications for measuring defocused small objects in noisy images are obvious. The calibration data shown in Fig. 4 also shows good symmetry about the plane of focus in the linear region where $A_H$ varies with defocus distance.

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Figure 4 also confirms that larger diameters effectively have a greater depth of field. Thus for a given defocus distance, small particles may be out-of-focus to the extent that they are no longer detectable and therefore immeasurable whilst at the same defocus distance, objects of larger diameters may be in-focus and thus measurable.

The literature has revealed that there exists numerous definitions of the “depth of field” and it is necessary to clarify how this should be interpreted in the present study. The depth of field has been defined here in terms of a ‘usable’ limit. In order to determine a ‘usable’ depth of field, the peak or maximum halo area is defined ($A_H^*$), beyond which an estimate of particle defocus based solely on $A_H$ could be erroneous due to the multi-valued condition. To ensure that the depth of field was still in the region where the halo and total pixel areas varied linearly with defocus distance, the acceptable depth of field in this case was arbitrarily defined as 70% of the critical value, $A_H^*$. This ensured an acceptable high sample rate without compromising sizing accuracy and is shown in Fig. 5 (a) for the 18µm diameter disc. For all calibration discs, as shown in Fig. 5 (b), the linearity of the depth of field variation with object diameter was again confirmed.

The calibration data for measurable defocus distance was subsequently incorporated into the automated image analysis processing routine. This allowed for diameter corrections to be made by determining the location of a defocused droplet relative to the plane of focus based on the intensity gradient across the droplet image as explained earlier.

3.3 Sensitivity of PDIA to applied threshold

PDIA measurement accuracy is dependent on good image signal-to-noise ratio and this is optimised by ensuring sufficiently wide grey-scale separation between the object and image background as indicated by the image intensity histogram. This improves image contrast and measurement accuracy as the sensitivity to threshold level is reduced. The present study was limited by poor illumination intensity and camera sensitivity and this exposed non-negligible diameter-dependent sensitivities which also varied with the applied threshold.
Fig. 6 illustrates the sensitivity of the PDIA method to threshold level for in-focus particles in the range 18 < D < 145 µm. The applied threshold level is normalised by the grey scale level corresponding to the peak intensity of the histogram. It is clear from Figs. 6 (a) and (b) that a decrease in the applied threshold level tends to reduce the calculated particle diameter and that the sensitivity to the threshold level increases considerably with decreasing particle diameter such that for a normalised threshold level of 0.74 the 18 µm particle was underestimated by approximately 40%. This compares with a 5% error for the 145 µm particle for a similar reduction in the threshold level. This marked dependence on the threshold setting for analysis arises, in this case, because of the relatively low contrast available between the object image and background illumination, (see Fig. 2 (b)). The small dynamic range between object grey level and background grey level means that the threshold level must be chosen very carefully. This is not typical for PDIA imaging setups where more light is available for illumination, but can be the case for measurement in very dense sprays. This however does not limit the technique for measurement under these conditions as it can be seen that the behaviour is predictable and by sizing known object diameters prior to performing real spray measurements it can be compensated for by post processing in the software, as will be demonstrated here.

4. EXPERIMENTAL SET-UP

PDIA measurements were obtained via two separate experimental configurations which utilised firstly, an infra-red diode laser and subsequently a Nd:YAG laser as illumination sources with pulse durations of 1 µs and 5 ns respectively. By maintaining similar test conditions one was able to assess PDIA measurement repeatability by performing this second and completely independent series of experiments and compare both these datasets with PDA measurements (e.g. Kasdan et al., 2002). The experimental arrangement for the Nd:YAG set-up is shown schematically in Fig. 7.

Fig. 7 Schematic diagram showing PDIA set-up for calibration and spray measurements with Nd:YAG laser.
To generate an image with a uniform background intensity distribution it was necessary to diffuse the coherent light beam (10mm nominal diameter) produced by the Nd:YAG laser in order to reduce the laser speckle in the images to an acceptable level for analysis, this was achieved through the use of two opal glass diffuser plates placed in the beam path as shown in Fig. 7. Image acquisition was achieved with a non-intensified 12-bit CCD camera (PCO Sensicam) with a 1280x1024 pixel array. An Infinity (K2) microscope objective with a working distance of 51mm provided a magnification (M) of 10.7 offering a resolution of approximately 0.7µm/pixel. PDA measurements were performed using a standard 1-D instrument and detailed information regarding optical set-up is given in Kashdan et al (2000).

5. SPRAY MEASUREMENTS
5.1 Effect of image-to-image intensity variations on sizing accuracy

The spray images obtained at Z/d_o=36 and R/d_o=15 of the fuel spray injection system discussed by Kashdan et al (2002), in the ‘dispersed spray’ region permitted an evaluation into the effects of various software input parameters on droplet sizing accuracy which are now discussed. Arguably the single most important parameter in the automated analysis of digital spray images is the determination of an appropriate threshold level as this parameter has a significant effect on sizing accuracy. In general, specifying too high a threshold level was found to introduce significant errors as a result of dark pixels or groups of pixels associated with the image background being incorrectly sized as droplets. Conversely, applying an unsuitably low threshold would generally result in the loss of image information as grey pixels which might correspond to the halo area of a defocused droplet image will tend towards having grey levels which lie above the applied threshold and thus be regarded as image background and the object size be underestimated. The PDIA software has the capability of analysing an image sequence with either a fixed threshold level or an adaptive threshold depending on the image illumination conditions. The effect of applying a fixed threshold in the analysis of an image sequence where image to image intensity variations are non-negligible has been examined and compared with results obtained from the same image sequence which have been ‘corrected’ to compensate for intensity variations. Furthermore the robustness of using the adaptive threshold option has been evaluated and is discussed in this sub-section. The results shown in Fig. 8 compare droplet size number pdfs obtained by PDIA for an image sequence which was analysed twice, firstly without any correction for image to image intensity variations and secondly with image correction. A fixed threshold of 162 was applied in both cases and the corrected images were adjusted using an in-house Matlab subroutine such that the mean grey scale level was consistent at 190 for all images. The correction scheme amounted to linear shifting of the pixel intensities of each image such that the overall image intensity of a sequence of images had repeatable mean values. PDIA sizing accuracy was not compromised as a result of these image corrections as applying the correction scheme does not change the relative pixel intensities, only the absolute values and thus the intensity gradients are not altered. A total of 1268 images were obtained at the Z/d_o=36 location and the processing time using the PDIA software for this image sequence required ~5 minutes on an 800MHz Pentium III machine. The valid sample number was 6530 thus giving an average of 5.1 droplets per image frame.

![Fig. 8 PDIA data showing the effect of image intensity correction on (a) number pdf size distribution and (b) number cumulative size distribution at Z/d_o=36, R/d_o=15, PDIA parameters: S=0.01, N_images=1268.](image)

It is clear from Fig. 8 that applying a fixed threshold for the analysis of the uncorrected image sequence has two noticeable effects. The first is that the number pdf is shifted toward the smaller size classes which produces a much more significant peak at approximately D=10µm. The second effect of failing to correct the mean greyscale is that very few droplets are measured for D>40µm whilst the pdf corresponding to the corrected images and manual
inspection of these frames show that droplets in size classes larger than 40µm do contribute to the overall droplet population. This is shown more clearly in Fig. 8 (b) which compares the cumulative number distributions of the same two datasets. The observed shift towards smaller sizes for the uncorrected image sequence is the result of noise contributions from the image background being accepted and sized as large numbers of small droplets when bright or overexposed images were analysed with a fixed threshold. This problem would be expected to be particularly severe in particle plumes of high number concentration or near-atomiser regions. Without compensating for image to image intensity variations it is clear that significant discrepancies arise in the pdf and in estimated mean diameters. For example, without image correction, \( D_{10} \) and \( D_{30} \) estimates were found to reduce by 26% and 35% respectively compared with image-corrected data.

5.2 Fixed threshold versus adaptive threshold

Applying the image correction procedure also permitted an evaluation against the fixed threshold procedure outlined above, of the robustness of the adaptive threshold algorithm of the PDIA software. This adaptive algorithm, varies the applied threshold for each image relative to the grey scale value where the peak occurs in the intensity histogram of that image. A comparison was made between intensity-corrected images which were analysed with a fixed threshold of 162 (where each image had a mean intensity of 190) and uncorrected images which were analysed using an adaptive threshold. By maintaining the same ratio i.e. applied threshold/mean grey level (162/190=0.85) for the processing of the same image sequence with an adaptive threshold one would expect to obtain similar results. Figure 10 shows the number pdf for three datasets: PDA, PDIA image-corrected with a fixed threshold of 162 and PDIA with an adaptive threshold of 0.85. The PDA data presented here has been transformed from a temporal to a spatial equivalent as discussed by Kashdan et al (2000).

![Image of Fig. 9](image)

(a) Comparison of PDIA and PDA data on (a) number pdf size distribution and (b) number cumulative size distribution at \( Z/d_o=36, R/d_o=15 \), PDIA parameters: \( S=0.01 \), \( T_{adaptive}=0.85 \) (uncorrected images), \( T_{fixed}=162 \) (corrected images), number of images=1268.

It is clear from Fig. 9 (a) that the difference between the two PDIA distributions is negligible and thus confirms that the use of an adaptive threshold is a reliable approach as a means of accurately sizing spray images in which image to image intensity variations have been shown (Fig. 8) to be significant. Meanwhile, a comparison of the PDIA and PDA number pdfs and cumulative number distributions in Fig. 9 show very satisfactory agreement in terms of the overall shape of the distribution for D>25µm. It is clear that the discrepancy between the two distributions in the diameter range 8<D<25µm is due to the PDIA method which (a) measured a greater proportion of small droplets compared with PDA and (b) underestimates small object diameters at low thresholds as demonstrated by Fig. 6. The presence of these droplets was confirmed by the analysis of individual, randomly selected images. The good agreement between the two techniques at this spray location is further confirmed by a comparison of the spatial \( D_{10} \) and \( D_{30} \) estimates obtained by PDA and PDIA which are shown in table 1 below:

<table>
<thead>
<tr>
<th>( D_{10} ) (µm)</th>
<th>PDA</th>
<th>PDIA</th>
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<tr>
<td>( D_{30} ) (µm)</td>
<td>27.1</td>
<td>26.3</td>
</tr>
</tbody>
</table>

Table 1 Comparison of PDA and PDIA estimates of \( D_{10} \) and \( D_{30} \) at \( Z/d_o=36 \), \( T_{adaptive}=0.85 \).
It must be noted that the minimum measurable diameter for the PDIA processing was limited to D=8µm. This was necessary to avoid noise at the smaller size classes, explained in more detail below, whilst the PDA was able to nominally measure droplets as small as 2µm in the present set-up. The upper size limit of the PDA was 88µm whilst a software limit exists for PDIA such that the largest droplets measured should not have an area greater than 25% of the CCD sensor. This corresponds to approximately 450µm for the camera used in this investigation. Thus the useful dynamic size range is noticeably greater for PDIA in the configuration used here at 56:1 compared with 40:1 for PDA which is fundamentally limited by the non-linear scattered light intensity to diameter relationship. Where direct comparisons between the two methods have been made only data in the diameter range 8<D<88µm has been considered. In fact the PDIA data obtained at this location revealed that a few very large droplets up to a maximum value of D=130µm were present and subsequent analysis of these spray images confirmed that these droplets were highly deformed, non-spherical liquid masses.

The confirmed presence of non-spherical droplets might also explain why the PDIA measures a slightly greater proportion of droplets in the size range 40<D<60µm compared with PDA and is now explored by a comparison of the PDIA and PDA volume pdfs. The diameter measurement in PDIA is based on the area estimate of the shadow image which, for perfect spheres is straightforward. The image analysis technique also permits the sizing of non-spherical droplets where the diameter for a droplet of arbitrary shape, Da is based on the equivalent circular area as given by equation (1) where A is the pixel area (i.e. total number of pixels) and C is the microns/pixel calibration. In the present study, the sphericity, S (eqn 3) is defined as the ratio of the diameter of the non-spherical droplet, Da to the diameter of the droplet based on the equivalent circular perimeter, Dp defined in equation (2) where P is the number of pixels on the perimeter of the object.

\[
D_a = \sqrt{\frac{4AC}{\pi}} \quad (1) \quad \quad D_p = C \sqrt{\frac{P}{\pi}} \quad (2) \quad \quad S = \frac{D_a}{D_p} \quad (3)
\]

Figure 10 shows a comparison of the spatial volume pdf and cumulative size distributions obtained by PDA and PDIA at the same location Z/d₀=36.

![Comparison of spatial PDA and PDIA data](image)

**Fig. 10** Comparison of spatial PDA and PDIA data (a) volume distribution and (b) cumulative volume distribution at Z/d₀=36, T_{adaptive}=0.85.

The most obvious differences in Fig. 10 (a) are the large-scale fluctuations which are present in the PDIA distributions for D>40µm. For PDIA (S=0.01), the notable peak which is observed at approximately D=45µm. This is not simply due to a low sample number count as 81 droplets were measured in this particular size bin and the author believes this trend is due to the presence of large non-spherical droplets which, although few in number clearly possess a significant fraction of the total spray volume. This assertion was verified by re-processing the PDIA data and applying a more stringent sphericity constraint (S=0.7) such that only spherical or near-spherical droplets would be measured. Figure 10 (a) confirms that for S=0.7 droplets of diameter greater than approximately D=40µm were not measured. Despite the apparent discrepancies observed in Fig. 10, the spatial volume mean estimates (shown in table 1) obtained by PDA and PDIA were found to compare extremely well with values of D_{30}=27.1 and 26.3µm respectively.
The results shown in Fig. 11 compare droplet number pdfs obtained by PDIA and PDA where the PDIA valid sample numbers obtained from analysing 1793 and 1268 images were 1075 and 5818 for the Nd:YAG and diode set-ups respectively. One would expect a reduction in the data rate (0.6 droplets per frame) for the measurements obtained with the Nd:YAG laser due to the much smaller effective camera depth of field as a result of having to fully open the aperture to ensure sufficient light intensity was obtained. Figure 11 (a) reveals extremely good agreement between the two PDIA datasets which gives further confidence in the robustness of the PDIA technique given that the datasets were obtained through two completely independent series of experiments in which the depth of field characteristics and image properties differ significantly.

Figure 11 shows good agreement between the PDIA datasets in the range 15<D<80 µm which means that the effect of motion blur due to the long diode laser illumination pulse was not significant in the measurement of droplets in this size class. There is however discrepancy at the lower size classes (D=10 µm) where the peak appears to be higher for the data obtained with the Nd:YAG laser arising from ‘noisier’ images. This is probably due to the difference in contrast and depth of focus between the images from the two set-ups and more of the droplets being undersized at the selected threshold level for the Nd:YAG images. This effect is discussed in more detail below.

5.3 Correction for threshold dependence

It was shown from the calibration (Fig. 6) that for this set-up, the PDIA sizing accuracy was sensitive not only to the applied threshold but that these errors also increased at smaller object diameters for a given applied threshold due to image noise which affects the accuracy with which \( A_H \) is measured. It was revealed that that for smaller sizes, the measured object diameters were consistently underestimated relative to their true sizes. Thus, in order to account for this bias, the PDIA data were post-processed, which amounted to correcting the individual droplet diameter estimates based on the known size-dependent errors which were exposed in the calibration (Fig. 6 (b)). The effect of this post-processing correction is shown in Fig. 12 on which the PDA and uncorrected PDIA data are superimposed for comparison.

Fig. 12 clearly shows that correcting the PDIA droplet size data by taking into account the threshold level dependence has the effect of shifting the pdf towards larger sizes. For the threshold corrected (\( T_{\text{corrected}} \)) PDIA data, although at the lowest size class there remains a noticeable peak which is probably due to random changes in spray character whereby large and particularly defocused liquid masses cause significant changes in the breadth and symmetry of the image intensity histogram and rather than being considered as image background the large masses tend to be sized as a number of small discrete droplets. Figure 12 shows that the true peak at
approximately 18<D<25µm which clearly coincides with the droplet size pdf obtained by PDA. At larger size classes, the effect of applying this correction shows that the number distribution of droplet for D>30µm would otherwise have been significantly under weighted. Therefore, in situations where the imaging conditions and illumination are less than ideal (i.e. in dense sprays), the PDIA technique can be extended to include a correction for threshold dependence which can be derived from the calibration of the system and allows for more accurate sizing of the droplet distributions.

The fact that the PDIA technique clearly estimates the presence of a greater number of droplets in the larger size classes compared with PDA is undoubtedly due to the greater accuracy with which non-spherical objects can be sized as estimates of droplet diameter are obtained from the measurement of pixel area in PDIA. In PDA these droplets would not be measured correctly due to their high non-sphericity.

6. SUMMARY

This paper has presented the results of an experimental investigation in which the performance of a digital image analysis technique has been assessed quantitatively as a particle or droplet-sizing tool. The size range of interest in the present study was 5 to 50µm diameter. The main conclusions relating to the findings presented in this chapter are listed below:

1. Calibration of object diameters in the size range 18<D<145µm at known defocus distances had the effect of increasing both the total pixel and halo areas which were defined as necessary quantities providing a means of determining the true object diameter. In addition, the depth of field was found to vary linearly with defocus distance for all object diameters in the range 18<D<145µm and the gradient evidently decreased with increasing object diameter until a limiting value of defocus distance was reached beyond which, the object ultimately merged into the image background. These properties exposed the dependence of object diameter on measurement depth of field and were exploited as a suitable means of defining appropriate measurement volume dimensions which improved both the PDIA sizing accuracy and measurement bias.

2. Spray data obtained by the PDIA technique was shown to detect the presence of very large, mostly non-spherical droplets whose diameters were in excess of 100µm. These droplets, although few in number constitute a significant proportion of the total spray volume and would have otherwise been either erroneously measured or have passed through the probe volume undetected using PDA due to non-sphericity.

3. A direct comparison between the PDIA datasets obtained from two separate series of experiments where the optical set-ups produced significantly different image characteristics revealed very similar results confirmed robustness of the technique.

4. Consistent discrepancies in a comparison with PDA data at smaller droplet size classes suggested that a source of systematic error was responsible. The low image contrast between background and droplets manifested itself as a sensitivity in the sizing process to the applied threshold level which, with the calibration graticle was shown to increase with decreasing object diameter. It was revealed that for small sizes, the measured object diameters were consistently underestimated relative to their true sizes. For a given applied threshold, the diameter dependence was corrected for by post-processing the droplet size data and this was shown to further improve the agreement between PDA and PDIA in the size range 10<D<30µm.

5. The low contrast of the images in the Nd:YAG laser setup can be largely attributed to the lack of illumination intensity that could be provided at the measurement region, this is because of the number of diffusers required in the illumination chain in order to reduce the laser speckle in the images to an acceptable level. This setup could be improved upon for future experiments with the use of a fluorescent diffuser (Whybrew et al 2002) in place of the opal glass diffuser plates, such a diffuser removes laser speckle by removing the coherence of the illumination without a significant loss in illumination intensity.

7. REFERENCES


