

# Experimental Analysis of the Response of a PDA System to a Partially Atomized Spray

by

G. Wigley<sup>1</sup>, J. Heath<sup>2</sup>, G. Pitcher<sup>2</sup> and A. Whybrew<sup>3</sup>

<sup>1</sup>Aero and Auto Engineering, Loughborough University, LE11 3TU, UK

<sup>2</sup>Lotus Engineering, Hethel, Norwich, NR14 8EZ, UK

<sup>3</sup>Oxford Lasers Ltd., Abingdon, Oxford, OX14 3YR UK

## ABSTRACT

This work describes the systematic approach adopted to establish the LDA/PDA experimental technique that would allow measurements to be made over a wide droplet size range with confidence. The analysis considers the sprays generated by different gasoline direct injection (GDI) systems injecting into air under atmospheric conditions. The upper limit to the droplet size measurement range in the fuel sprays was confirmed using Oxford Lasers' VisiSizer and droplets of a known size produced by a mono-dispersed droplet generator.

GDI fuel sprays are highly transient, optically dense and provide a high degree of penetration and atomization. The measurement problem is therefore one of the detection of small, high speed droplets inside a dense cloud of surrounding droplets. Furthermore, under the transients found at the start and end of injection and at high fuel loads, fuel elements in the form of sheets, ligaments and filaments can also be injected. These liquid fuel elements subsequently break-up downstream from the nozzle forming droplets of a much larger size class but with a low number density (Wigley et al 1999).

The co-existence of these liquid fuel elements and the widely different size classes in the spray are considered to pose a problem for droplet size measurements by phase Doppler anemometry (PDA). In particular the wide dynamic range of light intensities scattered by the fuel elements and droplets, the trajectory of large drops through the edges of the PDA measurement volume with its Gaussian intensity distribution (Sanker et al 1992) and the probability of non spherical drops.

The work concludes that the applied LDA/PDA measurement technique is robust. It can discriminate between partially and fully atomized sprays, can accurately measure droplet sizes larger than the measurement volume with a high probability as long as the PDA system parameters match the measurement task and give a realistic indication of sizes for non spherical droplets.

## 1. INTRODUCTION

Although GDI fuel sprays generally demonstrate a high degree of penetration and atomization, fuel elements, in the form of sheets, ligaments and filaments, can also be injected at the start and end of the injection period as well as during the injection period under high fuel loading conditions. Although these liquid fuel elements subsequently break-up downstream from the nozzle they do produce droplets of a much larger size class but with a low number density (Wigley et al 1999). In configuring the PDA measurement system the instrumental parameters have to be chosen to allow for the conditions in the partially atomized spray in the near nozzle region and two, or more, different size classes in the fully atomized spray well downstream from the injector nozzle.

There is a conflict between the requirement for a small PDA measurement volume, to allow measurements to be made in dense sprays, and the recommended requirement to match the measurement volume size to the largest diameter droplets to be found in the spray to avoid droplet trajectory problems. This is the case where the light scattering from large drops passing through the outside limits of the Gaussian light intensity distribution of the measurement volume, on an edge trajectory, can demonstrate both refractive and reflective light components in such proportions so as to make the applied phase drops size relationship in appropriate.

These effects can be minimised by using:- (a) a transmitter with unequal measurement volume diameters so that coincident detection and processing only occurs for those droplets passing closer to the central trajectories of the larger measurement volume which is used for sizing, (b) a three detector receiver at a scattering angle that satisfies the Brewster condition to reduce the reflected light component and (c) signal processing with a high signal to noise validation threshold and tight phase comparison and limits on the three phase estimates and their maximum values. However, when fuel sprays are encountered as seen in Figure 1, justification has to be made for the accuracy of the measured data. This spray was generated by an injector with a solenoid driven piston to force the fuel through the nozzle. The left hand image showing a single shot and the right hand image an average of 16 injections. The PDA measurement volume is seen at an axial distance 20 mm downstream from the nozzle in the right hand image. Long ligaments, although not necessarily continuous, are clearly seen extending some 30 to 50 mm downstream.



*Figure 1 Single Fluid GDI Spray with Wide Poly-disperse Drop Size Distribution*

## 2. INSTRUMENTATION

The LDA/PDA transmitter system was designed to meet the criteria of high power, variable beam separation with a high beam expansion ratio and therefore high spatial resolution (Wigley et al 1999). In two component form two transmitters are paralleled and since independent transmitters are used for the two velocity components the beam separation and hence velocity range or resolution can be optimised for any given application. The Dantec 57X10 'classic' PDA receiver with its large, variable and three aperture light collection system was positioned at a scattering angle of 70 degrees for the best spatial resolution, rejection of reflected light and insensitivity of the drop size/phase relationship to refractive index changes (Pitcher et al 1990). The Dantec Enhanced 58N50 PDA signal processor was used at full bandwidth.

The main PDA features to be discussed here though concern the specification and alignment of the two component measurement volume, the use of the variable aperture in the PDA receiver and the laser power. To ensure that the measurement volume had a sufficiently high spatial resolution and fringe spacing necessary to probe the dense high speed spray the transmitter was configured with a beam width and separation of 4.5 and 45 mm respectively. With the final lens focal length of 450 mm this resulted in a measurement volume diameter of 65 microns. In order to cover the wide range of dropsizes encountered in the spray the optimum choice of receiver aperture micrometer setting was investigated. Three values were chosen 2.0 mm (maximum – representing full aperture), 0.5 mm and 0.0 mm (minimum). To allow for the lower detection efficiency of the receiver with a smaller aperture experiments were also made in which the laser power was increased to compensate. The operational parameters are summarised in Table 1.

<u>Transmitter</u>		
Wavelengths	514 nm	488 nm
Power (Total) High	450 mw	250 mw
Low	250 mw	150 mw
Beam Separation	45 mm	51 mm
Beam Width	4.5 mm	5.1 mm
Focal Length	450 mm	450 mm
Measurement Volume Diameter	65 $\mu$ m	56 $\mu$ m
Fringe Spacing	5.15 $\mu$ m	4.40
Number of Fringes	13	13
Light Polarization	Parallel to Fringes	Parallel to Fringes
<u>Receiver (Classic)</u>		
Scattering Angle	70 Degrees	
Lens Focal Length	310 mm	
Measurement Volume Length	110 $\mu$ m	
Apertures / Max. Dropsize	2.0 mm / 100 $\mu$ m	
	0.5 mm / 165 $\mu$ m	
	0.0 mm / 260 $\mu$ m	
<u>Processor</u>		
Bandwidth / Gain	45 MHz / Low	
<u>Validation</u>		
Signal Level / Velocity	Yes	
Validation Level	0 dB	
Diameter / Spherical	Yes	
Phase error	10 degrees	
Spherical Deviation	10 %	

*Table 1 LDA/PDA operational parameters*

A back-lit single shot imaging technique was also used simultaneously to visualise the spray morphology and provide details of the transient structure and temporal development of the sprays. Planar light sheet imaging was not used as it has been shown that it can lead to false conclusions being drawn about the atomization of the fuel in the near nozzle region of the spray (Wigley et al 1999).

The light source was an EG&G MVS 7020 Xenon flash unit with an output pulse duration of approximately 8  $\mu\text{s}$ . This was coupled to a Fostec fibre optic back-lit panel to provide a uniform light intensity distribution against which the nozzle and spray was imaged. The light intensity during the 8  $\mu\text{s}$  light pulse was not uniform and the period too long for sharp images. The flash timing corresponding to maximum intensity was used as the trigger to activate the camera with the exposure time set to 0.5  $\mu\text{s}$ .

The single-shot images were digitally recorded with a PCO Sensicam Fast Shutter CCD camera which provided 1280 by 1024 pixel images at a resolution of 12 bits. The maximum frame rate for the camera, at full pixel resolution, was 8 Hz and was synchronised with the injection frequency so that only one image per injection was recorded. The injector control unit provided a trigger referenced to the opening pulse of the injector solenoid. This trigger was passed through a variable delay unit to control both the flash and image capture.

As a validation exercise dropsize measurements were also made with an Oxford Lasers VisiSizer Pro system. A schematic of the optical arrangement is shown in figure 2. An Oxford Lasers HSI 5000 pulsed diode laser [Whybrew *et al.* 1999] was used to provide backlighting for the fuel spray of 1  $\mu\text{s}$  duration. One image was obtained for each injection event. An 8-bit monochrome CCD camera, with a resolution of 512x480 was used for image capture, and 256 frames were captured in succession and analysed.

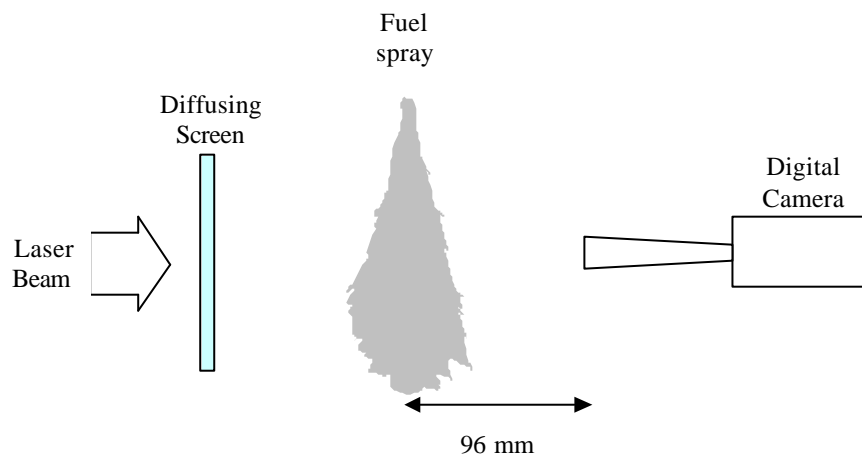


Figure 2 Schematic of Imaging System for the VisiSizer

It is possible to estimate dropsize by analysing the images using a simple thresholding algorithm. However, it has been found that this approach gives several biases, the main ones of which are:-

- Out-of-focus drops appear typically up to 30% larger than they are. Furthermore, techniques for rejecting out-of-focus drops tend to produce a different depth-of-focus for different sized particles (Yule *et al* 1978).
- Drops that touch the edges of the image must be rejected, since there is no way to establish how much of the drop is invisible. But large drops are more likely to touch the edges, and this introduces a bias.

The image analysis performed by the VisiSizer Particle/Droplet Image Analysis software, PDIA, corrects for both of the above biases.

The operation of the atmospheric fuel injection rig has previously been described in-conjunction with a high pressure swirl GDI injector (Wigley et al 1999). This allowed injectors to be supported from a gantry incorporating three precision traverses, two horizontal and one vertical, to position the spray in three orthogonal dimensions relative to the static LDA/PDA measurement volume.

The measurements and analysis reported here will concentrate on the Solenoid type injector that produced the spray shown in figure 1, as this represents the most complex measurement task for the PDA technique, but will also consider the high pressure swirl GDI injector. The response of the PDA system to large drops produced by a mono-dispersed droplet generator (Brenn 1996) will also be considered.

### 3. RESULTS AND DISCUSSION

While the PDA technique measures properties relating specifically to spherical droplets there is little discrimination as regards the morphology of the light scatterer with the LDA technique. A comparison between velocity measurements made with the optical system configured in 1-component LDA and PDA forms is shown in figure 3 to demonstrate how the atomized state of the developing spray can be identified.

Axial droplet velocity data collected over 500 injections and time averaged over 100 microsecond time bins are presented in figure 3 for the LDA and PDA measurements made in the hollow cone spray of figure 1. The measurement plane was 50 mm downstream from the nozzle with data presented for the spray centre line and a location in the spray periphery corresponding to the maximum axial velocity. On the spray centre line good agreement between the LDA and PDA data indicates that only droplets are present. The discrepancy between the LDA and PDA data between 0 and 1 ms is purely due to a low sample count and zero time does not represent start of injection. In the spray periphery the converse is true, there is poor agreement between the LDA and PDA data as the spray contains large liquid elements, which will be moving faster than the smaller droplets. This is interpreted as an indication that the spray at this location in space and time is only partially atomized. This observation has been found to be quite general and not specific to this spray.

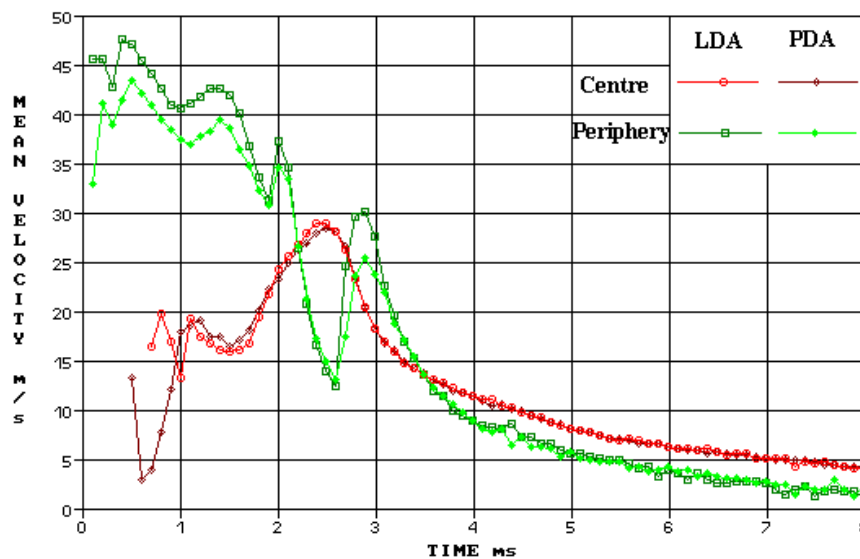


Figure 3 One -Component LDA and PDA Velocity Profiles in a Partially Atomized Spray

The size measurement range is determined both by the fringe spacing in the measurement volume and the azimuthal angle of the centroid of the collection aperture. The latter, in the Dantec 57X10 'classic' PDA receiver, is set by micrometer controlled knife edges. From its minimum to its maximum aperture, i.e. micrometer settings of 0 and 2 mm respectively, the dropsizing range can be increased by a factor of 2.6. However, as a consequence of this there is reduction in light collection efficiency of the aperture and the laser power or detection system gain should be increased to compensate or the small droplet size classes may well be below the detection threshold.

This part of the analysis was performed in two independent steps. The PDA measurement described above in figure 3 was performed using the 2 mm aperture scan, so the measurement scan was simply repeated but with the 0 mm aperture setting. The discrete droplet size data shown in figure 4 are for the measurement location on the spray periphery. With the maximum aperture (upper figure) the 100 micron upper limit to the size measurement range has truncated the data and there are more of the larger drops between 50 and 100 microns when compared with the data for the minimum aperture (lower figure). The measurement scan was then repeated for the minimum aperture setting but with the total laser power in the measurement volume increased from 250 to 450 mw. It was found that there was little increase in the number of the smallest droplet classes and therefore had very little effect on the discrete droplet data and on the time averaged velocity and droplet profiles.

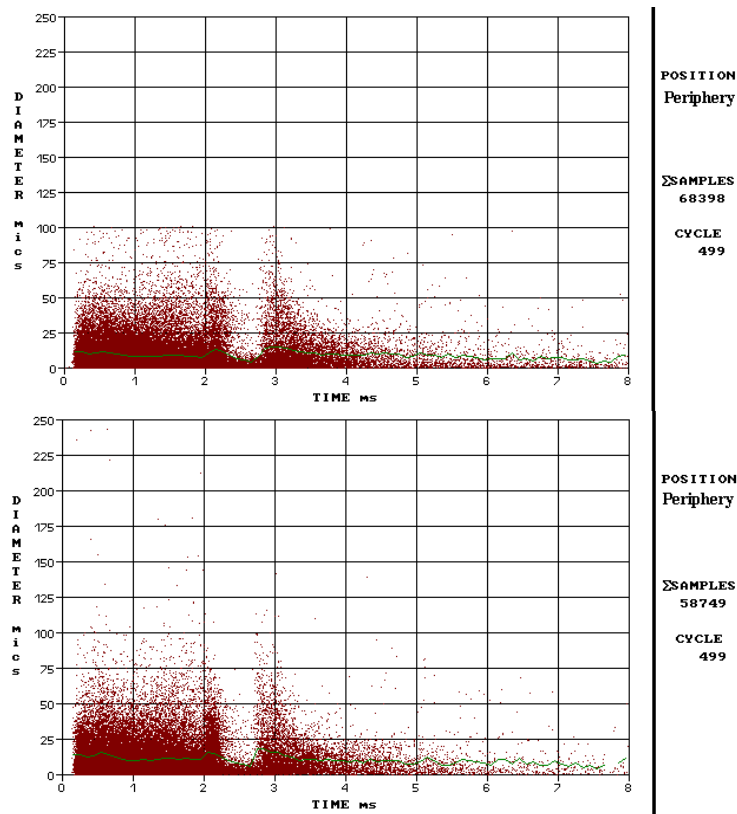


Figure 4 Comparison of Discrete Droplet Sizes for 2.0 mm (upper) and 0.0 mm (lower) Aperture Settings

This prompted an investigation into whether these effects could be attributed to trajectory and Gaussian beam effects. Large drops passing through the extreme of the measurement volume on the side further away from the receiving optics scatter light that could contain a significant contribution from reflection rather than refraction. Under these conditions the phase/droplet factor assigned to the phase measurement would be inappropriate and generally a high, false drop size recorded.

Since the transmitter optics were configured from two independent optic systems for the axial and radial velocity components their respective measurement volumes could readily be aligned for- 1) Perfect Coincidence, i.e. one measurement volume in side the other, or 2) 50% Coincidence with the control volumes displaced by half a measurement volume diameter. For the latter case the measurement volume for the radial velocity component was displaced, horizontally, either side of the axial measurement volume. The measurement volume diameter for the radial velocity component was 56 microns compared with 65 microns for the axial component. This allowed selective validation of droplet samples to be made from the near, centre and far side of the measurement volume used for the axial velocity and size measurement. The results for this experiment are shown in figure 5 and are expressed as the time varying Sauter mean diameter  $D_{32}$ .

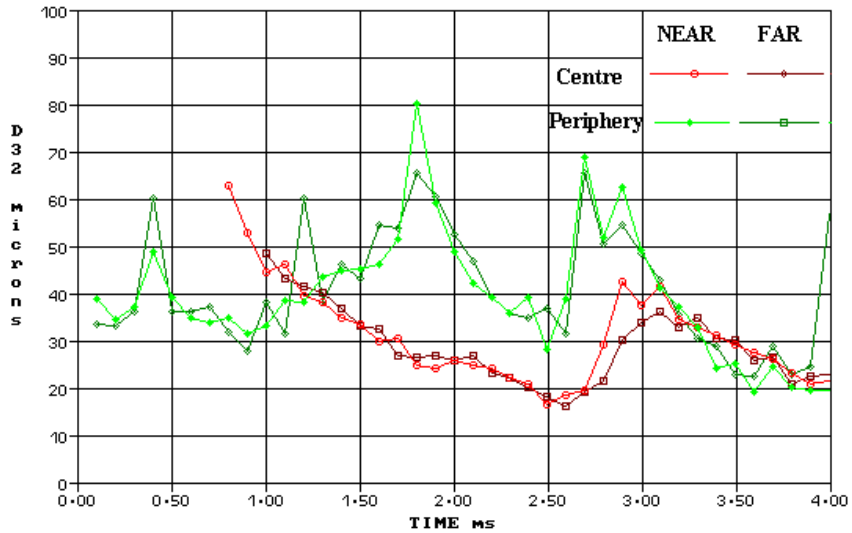
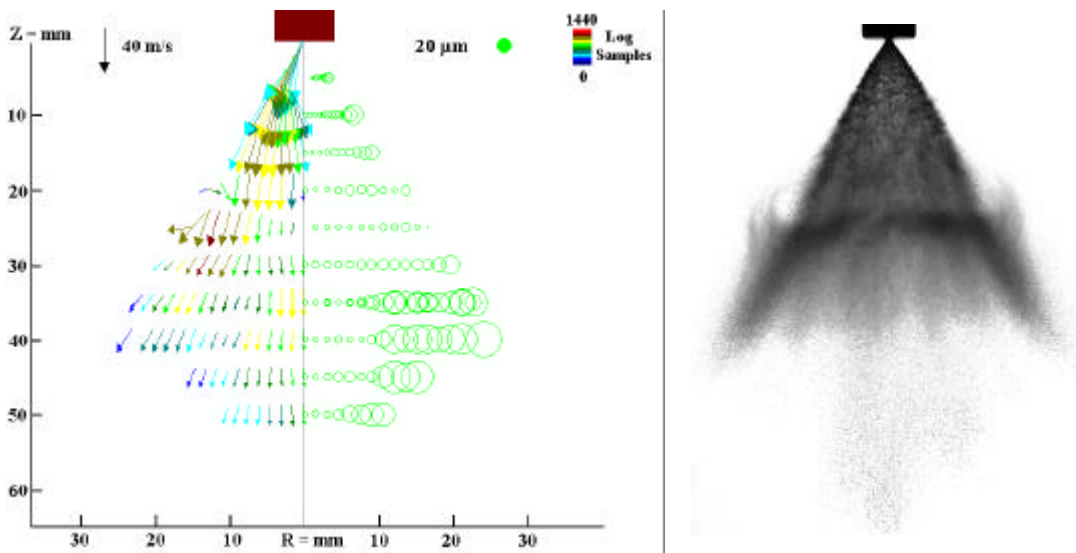


Figure 5 Comparison of the Sauter Mean Drop Sizes in the Spray for Near and Far Validation Criteria

The measurement locations were the same as for the data shown in figures 3 and 4. The Sauter mean diameter has been chosen since the presence of even a single large droplet will exaggerate any small differences in averaged drop size measurements. As can be seen in figure 5 the differences are small and are attributable to the variation in the small number density of the larger droplets found between the different experiments.

The above demonstrates that the PDA technique, as applied, can produce consistent data in such sprays but the instrumental measurement range must match the actual droplet size range found in the spray. As regards the accuracy of the measurements, particularly in the upper droplet size classes, the PDA data were compared with quantitative imaging studies using the Oxford Lasers VisiSizer. For this exercise the Solenoid type GDI injector was replaced by a high pressure swirl GDI injector. In figure 6, the PDA data is compared with a single shot CCD image. It raises the question as to the origin and upper size limit of the drops found in the spray periphery below 35 mm downstream from the nozzle as these were not present earlier in the size time history.

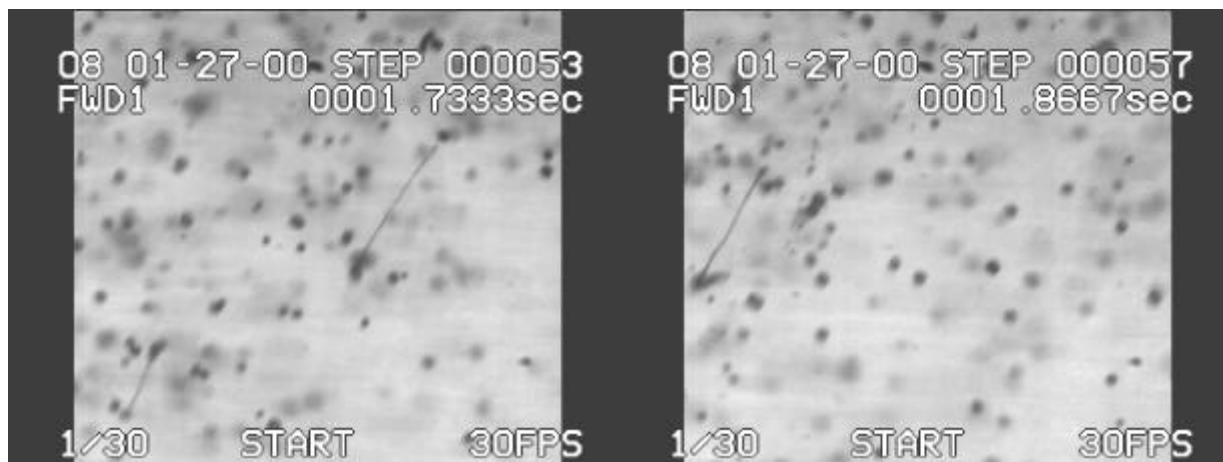


*Figure 6 Comparison of PDA data and Single Shot CCD Image at 1.72 ms*

The VisiSizer was set up to image a 2 mm square plane centred on the point 35 mm below the nozzle and 25 mm radially out from the spray axis. In comparing results from PDA and the VisiSizer PDIA, the following must be noted. PDA systems count droplets traversing a highly localised measurement volume as a function of time, while PDIA measures all droplets in the measurement plane only at the time the illumination pulse occurs. In other words, PDA measures flux, and PDIA measures instantaneous droplet size distributions in space. PDIA data therefore shows a sensitivity proportional to the reciprocal of the droplet velocity when compared to PDA results.

PDA time averaged arithmetic mean droplet sizes of 25 to 30  $\mu\text{m}$  were recorded in this part of the spray compared with the spatial average of 40  $\mu\text{m}$  obtained from the PDIA. A better match cannot be expected due to the lower accurate sizing limit of 20  $\mu\text{m}$  for the PDIA and since there was some motion blur on the droplet images. The most useful results of this part of the imaging experiment were:- (a) the maximum droplet size was determined to be less than 100  $\mu\text{m}$  and therefore agreed with the findings of the PDA, and (b) the insight and confirmation it gave for the fuel break-up mechanism responsible for generating the larger droplet sizes.

The hypothesis was that during the transients found at the start and end of injection and at high fuel loads, fuel elements in the form of sheets, ligaments and filaments could also be injected. These liquid fuel elements subsequently broke up downstream from the nozzle forming droplets of a much larger size class but with a much lower number density than compared with the droplets formed by prompt atomization at the nozzle (Wigley et al 1999). Two images showing the presence of filaments and a wide drop size distribution are shown in figure 7.

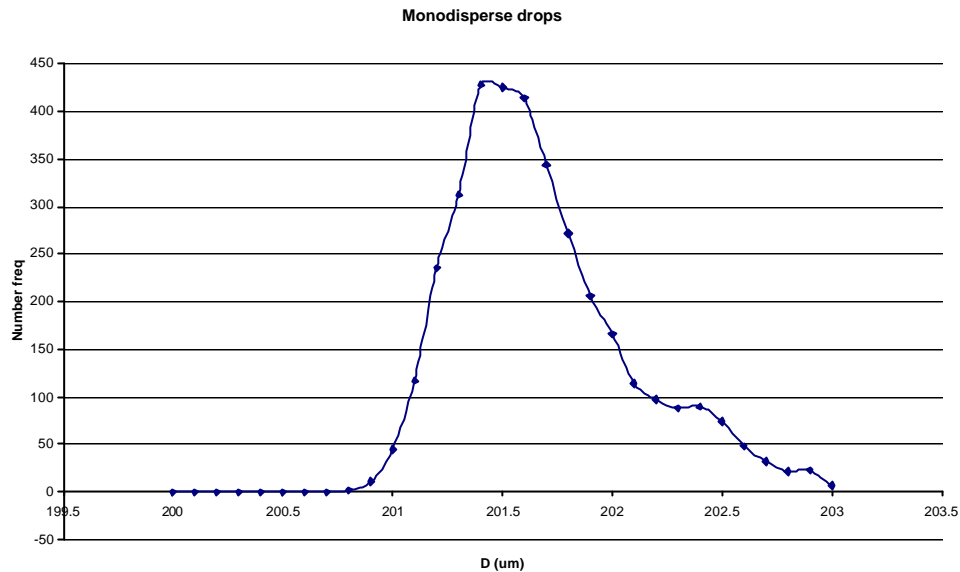


*Figure 7 VisiSizer Images Indicating Fuel Filament Break-up*

The study so far has indicated the robustness and confidence in the PDA technique as applied to these sprays. To examine the accuracy of the PDA response to single, large droplets a mono-dispersed droplet generator was used (Brenn et al 1996). It was set up with 50 and 100  $\mu\text{m}$  pinholes to produce well defined streams of droplets with diameters of nominally 100 and 200  $\mu\text{m}$  respectively. The PDA, in 1-component configuration, and single shot CCD imaging were performed simultaneously. The VisiSizer was applied later and only to the larger 200  $\mu\text{m}$  droplets as this was the most important case since the droplets were a factor of 3 greater than the measurement volume diameter. As this was the reference by which the PDA response was to be judged the PDIA analysis is presented first in figure 8. It indicates a volume mean diameter of 201.6  $\mu\text{m}$ , with a span<sup>1</sup> of 1%.

<sup>1</sup> Relative span is defined as  $\frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}}$





*Figure 8 PDIA Analysis of Mono-dispersed Droplets*

The PDA study investigated the response due to varying the receiver aperture, laser power and the trajectory of the droplets through the measurement volume. As the droplet stream was visible in the PDA receiver eye-piece it was easy to align the droplet stream with the slit in the PDA receiver. However, due to the nature of the droplet flow and the laboratory environment it was not possible to quantify the actual droplet trajectories relative to the measurement volume other than central or edge of cross-section and edge of slit.

For the 50 μm pinhole producing nominally 100 μm diameter droplets the PDA recorded an average diameter of 95 +/- 3 μm except for the droplet trajectories corresponding to the edge of the slit. The average value recorded here was 81 μm but, furthermore, a small range of dropsizes were also indicated. Discussion of this effect will be covered in the later analysis of the 200 μm dropsizes.

The average recorded diameter for the larger droplets was 203 +/- 7 μm. This result covered; all variations of the PDA receiver aperture from 0.25 to 0.0 mm, all laser powers and all trajectories through the measurement volume centre and edge of cross-section. However, inadvertently measurements were once made with an aperture setting of 1 mm. As this resulted in a measurement size range with an upper limit of 136.6 μm the data should have been rejected. It was not, in fact the processor indicated a mono-dispersed size histogram with 100 % signal validation but with an indicated droplet diameter of only 44 μm! There are no clear indications as to how this occurs but it demonstrates that the instrumentation must be configured so that the dropsizes bandwidth covers the complete size range to be found in the spray. If not, then dropsizes that exceed the instrumental upper limit may be assigned much lower values.

The light scattered by a stream of 200 μm diameter droplets produced at a rate of 10 KHz is high. The overall light levels were such that the Argon-Ion laser had to be run at ~10 mw of laser power so as not to overload the detection system. As an order of magnitude greater laser powers are necessary for use in a real spray the response of the PDA system with high laser powers was also examined. It was found that the PDA system faithfully recorded the correct droplet diameters. An analysis of the photo-multiplier and processor monitor signals showed that signal strength increased until the 1 volt limit of the photo-multiplier head amplifier clipped the envelop of the signal. This effectively reduced the AC component of the Doppler signal passed through to the processor input. At the limit the centre section of the signal, corresponding to the Gaussian peak of the laser beam intensity distribution, would tend to zero leaving two signals either side representing the droplet entering and exiting the measurement volume.

The trajectory problem that was encountered came from the passage of the droplets through the sides of the measurement volume as defined by the slit. The response of the PDA system is best described using the 'phase shift diagnostics' and 'acquisition statistics' plots from the Dantec Sizeware software as shown in figure 9. The 'diagnostics' plot shows the measured phases recorded by the two pairs of detectors for each droplet and displays it relative to the calibration phase factor and the validation limits. The phase data presented takes the form of an inclined 'Y', and only that inside the three parallel lines is accepted. The upper part of the 'Y' has the same slope as the calibration but the remainder has a much shallower slope which is not comparable with that expected for a purely reflection based light scattering. The phase data was found to move down and away from the calibration slope as the droplets drifted further out of the measurement volume and were partially hidden by the slit.

The 'acquisition statistics' show that the recorded dropsize is underestimated as the mean of the distribution of the validated data is 179.5  $\mu\text{m}$  compared with the mono-dispersed value of nominally 200  $\mu\text{m}$ . Furthermore, the data rate is very low, 415 Hz, compared with a droplet production rate of 10 KHz and data are rejected due to failing the sphericity validation check. The conclusion here is that as droplets are obscured by the slit it leads to an underestimate of the dropsize before data is rejected. However, the low data rate indicates that the probability of this occurrence is low.

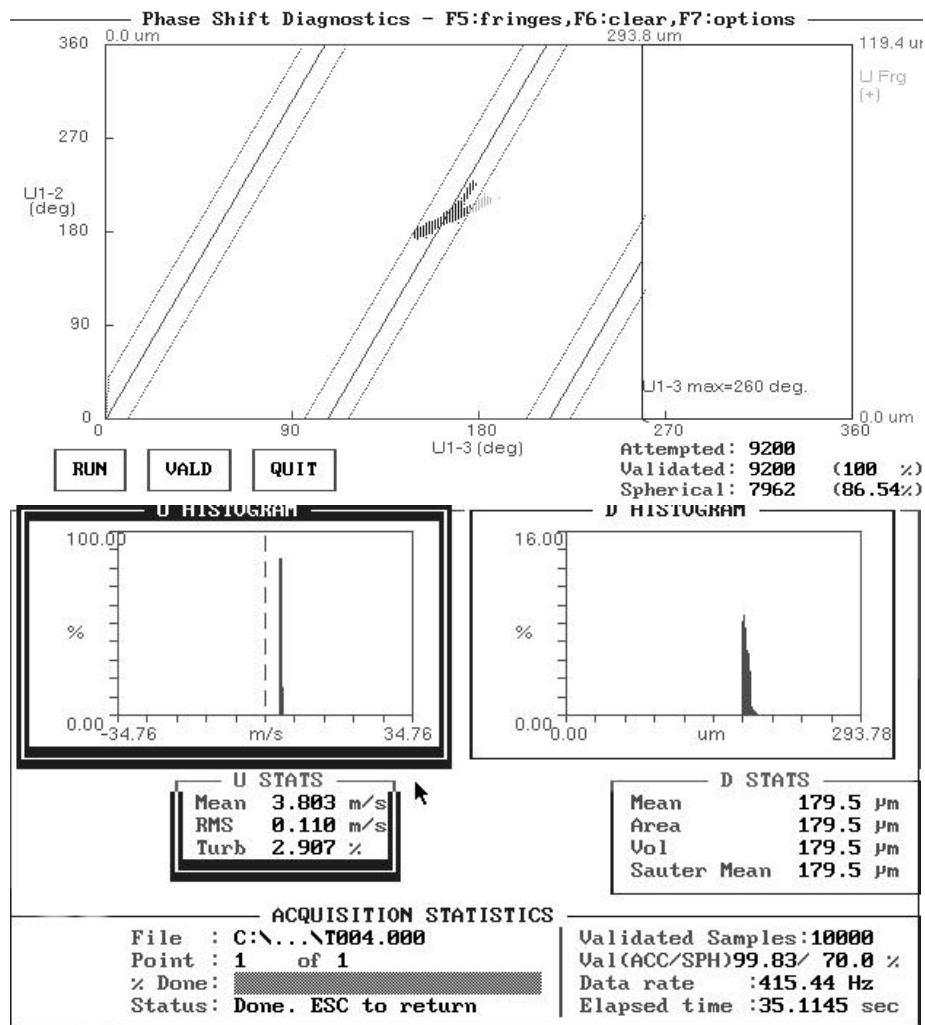


Figure 9 Diagnostic and Acquisition Statistics for Slit Trajectory Droplets

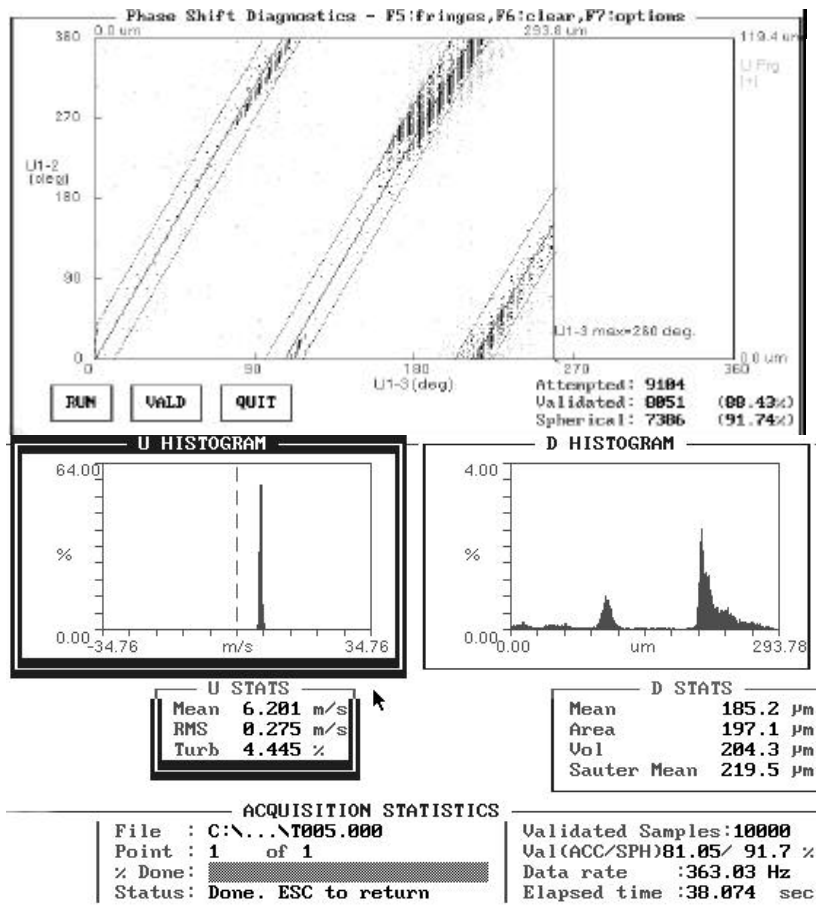


Figure 10 Diagnostic and Acquisition Statistics for Slit Trajectory Droplets

The last PDA system response to be considered is that due to elliptical droplets passing through the measurement volume. Elliptical droplets can be generated very easily by running the droplet generator at frequencies well away from its resonant frequency. The single shot CCD image in figure 10 shows a stream of both elliptical and spherical 'satellite' droplets. Included in the image is a reference image of a 200  $\mu\text{m}$  diameter wire. The 'diagnostics' plot shows that data validation is actually high especially for the sphericity check. This indicates that this validation is really only a consistency check for the measured phases. The dropsize histograms show distinct size classes, as can be seen in the image, while the largest size class histogram exhibits a tail skewed towards the upper limit of the measurement size range. As droplets of up to nearly 300  $\mu\text{m}$  can not be seen in the image the logical assumption is that the PDA response is indicating the local radius of curvature for the elliptical droplets. Obviously much more work has to be done to assess this but the over riding conclusion is that sensible and realistic 'sizes' are being produced by the PDA system which are suitable for spray characterisation.

#### **4. CONCLUSIONS**

This work has described the systematic approach to establish an LDA/PDA measurement technique that allows measurements to be made over a wide droplet size range with confidence. The analysis has considered the sprays generated by different gasoline direct injection (GDI) systems injecting into air under atmospheric conditions and droplets of a known size produced by a mono-dispersed droplet generator.

The recommendations are for:- (a) a transmitter system providing unequal measurement volume diameters so that coincident detection and processing only occurs for those droplets passing closer to the central trajectories of the larger measurement volume which is used for sizing, (b) a three detector receiver at a scattering angle that satisfies the Brewster condition to reduce the reflected light component, (c) the instrumental measurement range must match the actual droplet size range found in the spray and (d) signal processing with a high signal to noise validation threshold and tight phase comparison and limits on the three phase estimates and their maximum values.

This work therefore concludes that the applied LDA/PDA measurement technique is robust. It can discriminate between partially and fully atomized sprays, can accurately measure droplet sizes larger than the measurement volume with a high probability and give a realistic indication of sizes for non spherical droplets.

#### **ACKNOWLEDGEMENTS**

The Authors would like to thank Dr. Guenter Brenn of LSTM, University of Erlangen, Germany for the loan of, and guidance, in the use of the mono-dispersed droplet generator.

#### **REFERENCES**

- Brenn, G., Durst, F. and Tropea, C. (1996), 'Mono-disperse Sprays for Various Purposes – Their Production and Characteristics', Part. Part. Syst. Charact., Vol. 13, pp. 179-185.
- Pitcher G., Wigley G. and Saffman (1990), 'M. Sensitivity of Drop Size Measurement by Phase Doppler Anemometry to Refractive Index Changes in Combusting Fuel Sprays', Applications of Laser Techniques to Fluid Mechanics, Lisbon, Springer Verlag.
- Sanker, S.V., Inenaga, A. and Bachalo, W. D. (1992), 'Trajectory Dependent Scattering Sizing Error', 6<sup>th</sup>. International Symposium on Applications of Laser Techniques to Fluid Mechanics', Lisbon, Portugal.
- Whybrew, A., Nicholls, T.R., Boaler, J.J., and Booth, H.J. (1999) 'Diode Lasers - a cost effective tool for simultaneous visualisation, sizing, and velocity measurements of sprays'. ILASS Europe, Toulouse, France.
- Wigley, G., Hargrave, G. K. and Heath, J. (1999), 'A High Power, High Resolution LDA/PDA System Applied to Dense Gasoline Direct Injection Sprays', Part. Part. Syst. Charact., Vol. 16, No. 1, pp. 11-19.
- Yule, A.J., Chigier, N.A. and Cox, N. W. (1978), 'Measurement of Particle Sizes in Sprays by the Automated Analysis of Spark Photographs'. "Particle Size Analysis", Heyden Press, pp. 61-73.