Laser Characterisation of a Port Fuel Injector to Provide Boundary Data for Computational Fluid Dynamics

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ABSTRACT

Phase Doppler Anemometry and laser sheet imaging have been performed on the spray from a multiple-hole, gasoline port fuel injector. Data has been collected for both continuous and pulsed operation, with the aim of providing initial boundary and validation data for computational spray modelling. The study showed that the injector produced two streams of finely atomised spray, with break-up taking place almost immediately. At the first measurement plane, 20mm downstream of the injector, the two spray streams overlap. Inputting these PDA data directly into the computational models is difficult, requiring knowledge about how the two streams interact. Instead it is proposed that data are applied at the injector tip and tuned until the correct downstream conditions are met.

1. INTRODUCTION

The need to meet ever more stringent emission regulations and the desire to increase fuel economy has led to significant development of the gasoline spark Ignition combustion engine in recent years. One area of development has been mixture preparation. That is the state of fuel air mixture entering the combustion chamber in terms of droplet size and distribution.

Port fuel injection (PFI) has been developed to increase engine responsiveness whilst meeting stringent emissions regulations. A metered quantity of atomised fuel is sprayed towards the intake valve, where it may evaporate, puddle or rebound. Furthermore, a portion of the fuel may flow directly into the cylinder or impinge upon the port walls. These phenomena occur in varying degrees and depend upon the engine design, injector location and engine operation. Potentially the fuel can enter the cylinder in a poorly atomised state, leading to incorrect metering and increased unburned hydrocarbon emissions. This is particularly true during cold operation, when evaporation is low.

Successful PFI designs depend upon good targeting of the fuel spray onto the back of the intake valve. Geometric predictions based on injector axis and spray cone angles have been used in the past, but require development to account for the momentum exchange between the spray and the charge air. Alternatively CFD (Computational Fluid Dynamics) can be used, but these models need both initial boundary data and validation. This is because although a few spray break up models do exist, they are generally tailored for diesel applications and can not be readily applied to port fuel injection. Instead, initial values of droplet size and velocity magnitude need to be input as boundary conditions. Their trajectory, as well as the heat and mass transfer is then calculated.

Determining these initial values is a non-trivial exercise, hence the data is not readily available. Despite there being a number of techniques available to measure sprays, only one method exists, PDA (Phased Doppler Anenometry), which is capable of measuring both spatially resolved droplet velocity and size. To complicate matters further, the injector performance is influenced by a number of factors, including injector design, atmospheric conditions, injector frequency, pulse duration and fuel type. It is therefore insufficient to make measurements at one operating condition and then assume them to be applicable for the wide range of conditions seen within an intake port. Instead, an injector needs to be characterised for a range of representative conditions.

The present study is aimed at characterising a multiple-hole port fuel injector to provide both initial boundary and validation data for CFD simulations. The injector will be characterised for a wide range of operating and atmospheric conditions. The first phase of testing has concentrated upon continuous and pulsed operation into atmosphere. Planar Mie scattering was employed to visualise the spray and PDA to determine spatially resolved velocity and droplet size. The findings from the first phase of testing are discussed within this paper.

2 EXPERIMENTAL APPARATUS

2.1 Multiple-hole injector

The injector tested was a Denso, duel stream multiple-hole injector, which represents the next generation in PFI technology. This injector delivers levels of atomisation previously only achievable using air assist injectors, through a combination of a 12-hole nozzle configuration and careful attention to the internal geometry (ref. 1). The injector was operated in both continuous and pulsed modes. Pulse frequency and duration's of 6Hz, 10ms and 50Hz, 16ms were chosen to represent full load engine operation at both extremes of the speed range. The injection frequency and duration were controlled using a pulse generator. Fuel was supplied at a line pressure of 3.8bar, giving a mass flow rate of 2.7g/s under continuous operation.

2.2 **Test** fuel

Fuel composition can significantly influence the performance of an injector, leading to variations in droplet size and velocity as well as the spray structure. This is especially true at low atmospheric pressures, characteristic of the idle condition, where the high volatile components of gasoline, even at low temperatures, can begin to flash boil enhancing the spray break-up. Conversely, the lower density of the continuous phase reduces the aerodynamic contribution to the spray break-up, potentially delaying its onset (ref. 2).

Such phenomena can be missed when using a test fuel (ref. 2). Despite this, test fuels are often used in preference to gasoline. Gasoline comprises many different components and as such exhibits a non-linear evaporation behaviour, making it difficult to control its physical properties over time. The task therefore becomes to choose a test fuel, which will behave in a similar manner to gasoline when injected, yet remain physically consistent. For these reasons Iso-Octane was chosen. Iso-Octane offers comparable density and viscosity (Table 1) and boils close to the middle of the range of gasoline. Iso-Octane is however unlikely to suffer from flash boiling and the surface tension is almost 50% of gasoline's. Tests are to be conducted at a later date using premium gasoline to quantify any differences.

Table 1 - Fuel Properties

Property	Gasoline (Premium)	**Iso** Octane
Density (g/cm^3)	0.73 to 0.78	0.69
Viscosity (cSt)	0.516 @ 25 °C	0.503 @ 20 °C
Surface Tension (10^{-2} N/m)	25.8	14.7
Flamibility Limits (by % vol)	0.6 to 8	1 to 6
Boiling Range (°C)	25 to 215	99

2.3 The Test Rig

The tests were performed in a purpose built spray rig at Cranfield University (Figure 1). The rig consists of a chamber 0.7m diameter and 1m in length. Optical access is provided through a number of ports located on the drum's circumference and one at the downstream end. Purge air can be applied to prevent any misting of these windows.

The injector is mounted in a shroud, which is in turn attached to an airbox. The airbox is fixed onto the end of the air feed pipe, supported by a Newport Microcontrole traversing system. Exhaust fumes are vented through a pipe at the downstream end of the chamber.

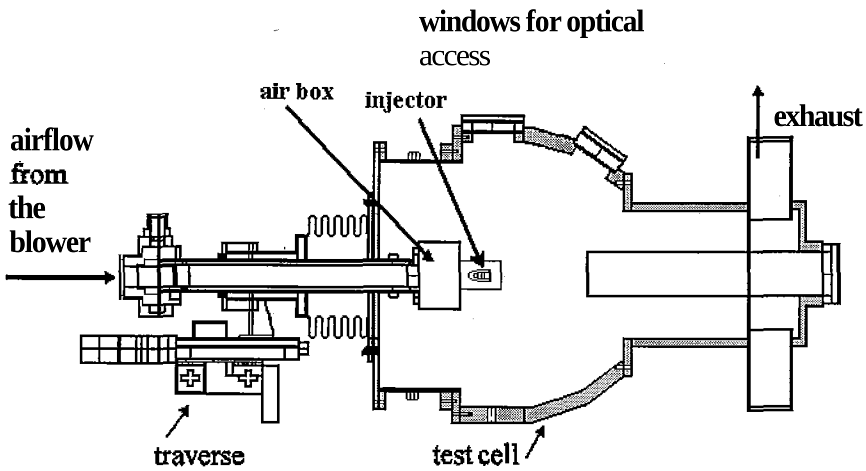

Figure 1 - Schematic diagram showing the spray rig

2.4 Planar Mie Scattering

Images were generated using the Planar Mie Scattering technique. Fifty images were collected at each operating condition from which both RMS and mean images were derived.

The spray was illuminated with a Coherent SureLite I Nd:YAG laser, frequency-doubled to give an 8ns pulse of 532nm (green) light. The light was formed into a sheet with a waist in the spray plume, by a 2m spherical, a -25mm and a +150mm cylindrical lens. The images were captured with a Wright Instruments AT1 slow-scan CCD camera, fitted with a 1024x1240 pixel chip binned to give an effective resolution of 500 by 400 pixels. The camera was fitted with a 105mm Nikon lens. Both the laser and camera were synchronised to a frequency generator with the appropriate delays. The laser was pulsed at the injector frequency, except for at 50Hz, when the laser was fired every other injection. The camera was operated at a rate of ~2Hz and the shutter opened for 110ms.

2.5 **PDA Equipment**

PDA is an extension of the LDA (Laser Doppler Anenometry) technique, and is capable of measuring droplet size as well as velocity. Both techniques are based upon the detection of the Doppler shift of light scattered from droplets as they pass through the interference fringes generated by two laser beams. The frequency of the scattered light provides information about the droplet velocity. The droplet size is determined from the phase shift of two Doppler signals and therefore requires two or more detectors.

The measurements were made with a Dantec system capable of measuring both axial and vertical velocity components. Laser light was supplied via a 5W Coherent Innova Argon-ion unit, operated at 2-3W total power in multiline mode, (514.5nm and 488.0nm for the axial and vertical velocity components respectively). The laser beam was colour separated, with each colour split into two beams and one of these given a 40MHz frequency shift, using a Dantec Fibreflow transmitting unit. The resulting four beams are fed via optical fibres to the transmitting head where a 600mm focal length lens combines and focuses them to create the measurement volume. The beams intersect with a half angle of 2.4° resulting in a measurement volume of 150x150x2000e-6m. The longest dimension is effectively reduced to 110e-6m by the collection unit's slit. The collection unit, a Dantec 2D unit, sat at 70° forward scattering angle, where refraction of the laser light through the droplet is the dominant scattering mechanism. The detectors were photomultiplier tubes with accelerating voltages of ~1200V. The photomultiplier signals are fed to a Dantec 58N20 signal processor controlled by a PC running SizeWare2.1. The processor has input filter bandwidths of 4MHz on the axial channel and 1.2MHz on the vertical channel. Measurements were based upon 3000 samples, and post processed to provide mean and RMS values using Sizeware2.1.

Assuming a relatively dilute spray, there are potentially three sources of error with this measuring technique. The laser wavelength and Doppler frequency measurement contribute negligible uncertainty compared to the error in setting up the measurement volume. Assuming perfectly straight fringes, the intersection angle of the beam dominates with a ±2% uncertainty to the velocity, originating from a ±1% uncertainty in determining the beam separation at the transmitter head. The size measurement is more complex and involves uncertainties in determining the phase difference between the signals seen by the different detectors, and in determining the phase/diameter relationship. For typical PDA configurations, the size error is approximately ±4% (ref. 3). The uncertainty in measurement volume position with respect to the injector has two components. The resolution of the traverse system is 1 micron for the axial and vertical directions and 10 microns for the horizontal. The dominant uncertainty of ±0.5mm comes from determining a datum position.

For dense sprays, further errors can be introduced through obstruction or bending of the laser beams. Both of these phenomena tend to cause preferential rejection of the small droplet signals resulting in an over estimation of the droplet size.

A few back to back measurements were taken to determine the repeatability of the tests. The velocity and size measurements were found to vary by up to 9.6% and 11% respectively. Fluctuations in fuel line pressure are thought to be the most likely cause.

3.0 RESULTS & DISCUSSION

3.1 Spray visualisation

Photographs showing the spray generated from the multiple-hole injector are presented in Figure 2. The top left photograph shows spray from the injector under continuous operation. The remaining three show the spray at time = 1.6, 14 and 16ms, pulsed at a frequency and duration of 6Hz and 10ms respectively, where the time is referenced to the start of injection demand, signalled by a TTL pulse.

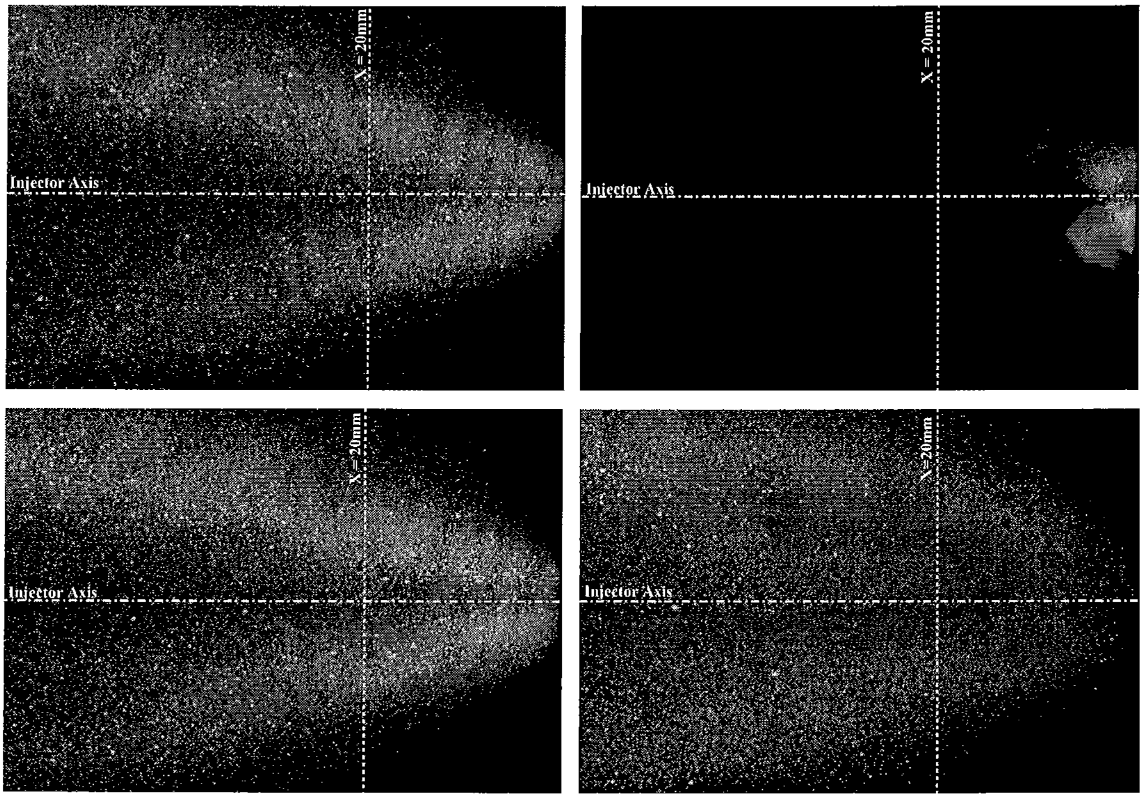

Figure 2 - Planar Mie scattered spray images (continuous: top left, pulsed (time = 1.6ms): top right, pulsed (time = 14ms): bottom left, pulsed (time = 16ms): bottom right)

The spray comprises two distinct streams angled approximately 12.3 degrees either side of the horizontal. The resultant 24.6 degrees separation angle compares well with the 25 degrees specified by Denso. From the photographs we see that there are no visible ligaments present. Since there is no fuel or air swirl with this configuration, and the illumination plane being of finite thickness and almost aligned with the injector axis, (8 degrees separation), we would expect some of the ligaments to lie within the light sheet. It would therefore appear that spray break-up occurs on exit of the injector nozzle or immediately downstream. By comparison, similar images for the earlier 'Pintle' type port fuel injectors have shown ligaments to exist several mm downstream of the injector tip (ref. 4).

Under pulsed operation, it is clear to see a delay exists between actual injection and demand. At time = 1.6ms we see the spray is just beginning to emerge. An even greater delay is apparent at the end of injection and by 14ms, 4ms after the TTL pulse, the injector is still operating. The actual lags were found to be 1.5ms and 4.5ms respectively. The initial time lag is thought to result from the time required to build up the injector solenoid current sufficiently, against the solenoid's back electromagnetic flux, to overcome the needle retaining spring. The larger closing lag may well result from a combination of mechanical damping as the needle displaces the fuel, and the electromotive resistance of the solenoid, which acts as a dynamo, when the needle returns. When calibrating an engine these lags can easily be accounted for, but clearly need to be taken into consideration when setting up computer simulations.

3.2 PDA Measurements

The PDA data are grouped into two categories, those measurements taken when injecting continuously and those when pulsed. Figures 4 & 6 present both velocity and size data for the continuous operation. In Figure 4 data are presented for vertical and horizontal traverses, at 20mm downstream of the injector tip. Whilst Figure 6 presents data for horizontal traverses at 20, 50 & 80mm downstream of the injector tip. Figure 7 presents data for the pulsed condition (6Hz-injection frequency, 10ms duration). Again, both velocity and size data are presented for a horizontal traverse at 20mm down stream of the injector tip, and at 3ms, 14ms and 18ms from start of the TTL pulse.

It should be noted that for all cases, the velocity data presented are relative to the rig axis rather than the spray axis, and the droplet size is characterised as the Arithmetic Mean Diameter (AMD) and not the more commonly quoted Sauter Mean Diameter (SMD). The injector was orientated as shown in Figure 3, with traverse origin positioned at the centre of the upper stream for all planes.

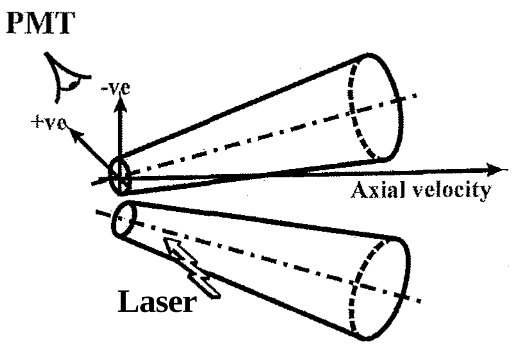

Figure 3 - Schematic Showing Spray Orientation

3.2.1 *Continuous Data*

The velocity profile along the horizontal traverse shows a reasonable degree of symmetry about the centre of the upper spray stream (Figure 5). The greatest velocity is seen at the centre, where the influence of the continuous phase is at a minimum. The velocity then tends towards zero at the edges, where the aerodynamic drag of the continuous phase brings the spray to rest. Similarly, for the vertical traverse data, we see two velocity peaks at the centres of the upper and lower streams, then tending towards zero at the upper and lower edges of the respective streams. In the region between, the streams would appear to overlap. In fact comparing both the horizontal and vertical traverse data suggests the two streams interact with one another, boasting the droplet velocity.

Looking at the droplet size distribution we observe a similar pattern to the velocity data. However, surprisingly the droplets are close to their minimum size at the stream centre, and increase with radial distance reaching a maximum at approximately 2/3 distance, after which they decrease. In the region between the two streams the droplet size remains close to the values seen at the stream centres, further evidence that the two streams are interacting.

It is possible that the droplet size generated, at the point of atomisation, may not be independent of injected angle, i.e. droplets injected along the spray axis are smaller than those at the edge. The drop size distribution observed however is more likely to be a result of one of two mechanisms or in fact a combination of both. Firstly, the cone expansion may give rise to a small depression, sucking small droplets into the centre of the stream. Alternatively, the droplets at the edge of the spray are slower for any given plane and hence are older. The spray at this point could therefore be partially evaporated, loosing the smaller droplets.

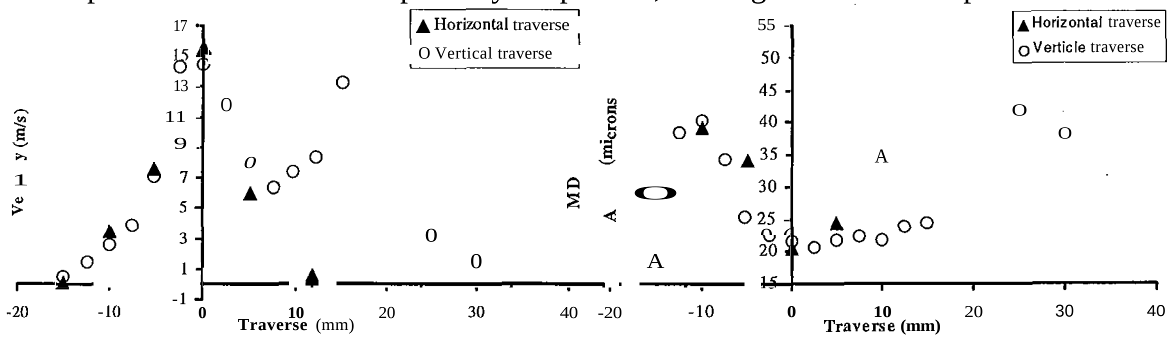

Figure 4 - PDA data at 20mm from the injector (continuous operation)

Whist processing the PDA data, it became evident that the spray exhibited a bi-modal distribution at the edge of the spray. Plotting each droplet on a graph of velocity against size it became clear that two distinct groups of droplets existed, a group of larger droplets travelling in a positive direction and a group of smaller re-circulating droplets. No such behaviour was evident at the centres of the streams or in the region between the two streams. A schematic diagram of the spray structure is presented (Figure 5).

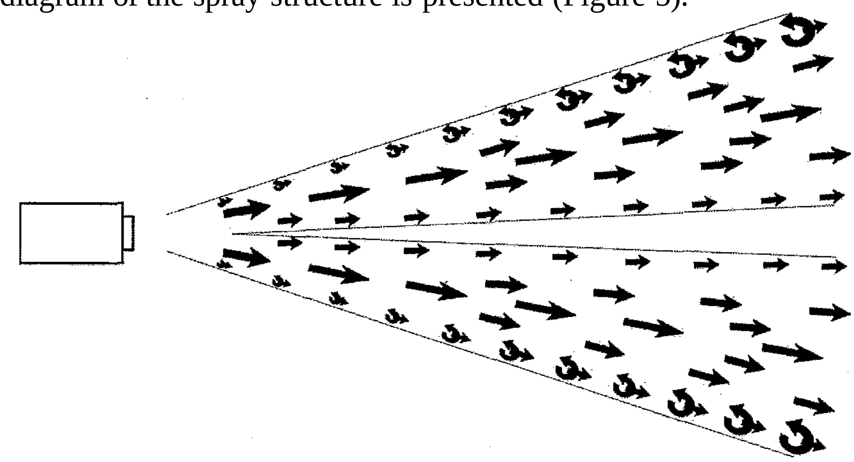

Figure 5 - Schematic showing the general spray structure

From Figure 6 it is clear to see how the top spray stream develops with distance from the injector tip. Both the velocity and size profiles show a widening of the stream with distance from the injector. Estimates based upon these data show the spray cone angle to be 20 degrees, 2 times greater than the value quoted by Denso.

Aerodynamic drag slows the droplets with distance from the injector tip. This difference is less apparent at the edges of the spray where the aerodynamic drag is greatest and the droplets are slower and hence older. Perhaps, less easy to explain is the fact that the average droplet size increases with distance from the injector tip. It is possible that some of the small droplets evaporate and disappear from the measurement over time, increasing the average droplet size. A more plausible explanation is that the smaller droplets, with their higher drag to momentum ratio are unable to penetrate as far as the larger ones.

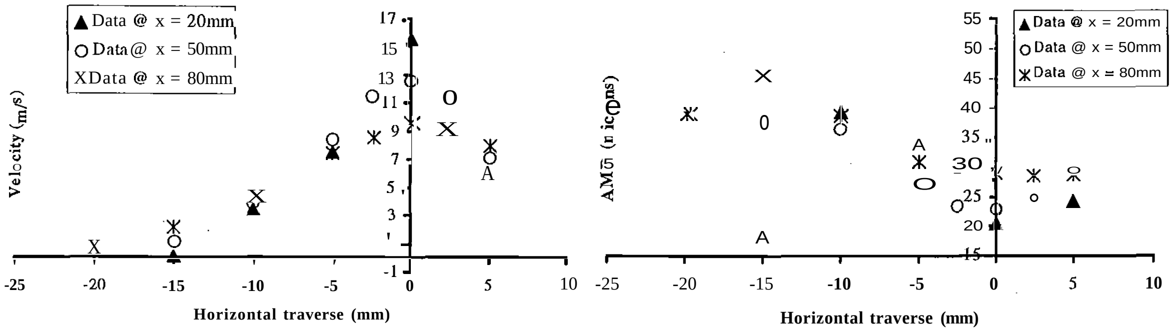

Figure 6 - PDA data at 20, 50 & 80mm from the injector (continuous operation)

3.2.2 *Pulsed Operation*

The spray exhibits two transitional periods at the start and end of injection (Figure 7). Between these periods the spray becomes established, and both the velocity and size profiles tend towards those seen when the injecting continuously.

During the early part of injection the spray consists of a narrow band of droplets, relatively uniform in both size and velocity. The drops are larger (50 microns) than those seen under continuous operation. The poorer atomisation would result from a lower fuel flow rate as the injector needle transitions from closed to open. We also see that, compared to the continuous operation, the droplet velocities are lower at the spray centre, yet greater at the edge, and can be attributed to a combination of mechanisms. The lower fuel flow rate would result in a reduced droplet velocity. Secondly, not enough time has elapsed for the injector to establish a flow pattern, and the drag acts more evenly across the width of the spray giving a more even velocity distribution. Finally, the greater size means that the drag to momentum ratio is lower, again contributing to a more even velocity distribution.

At the end of injection we see a narrow band of smaller, slow moving droplets. In fact, by 18ms, 3.5ms after the end of injection, the main body of the spray will have passed by the measurement plane, leaving this trail of smaller slow moving droplets.

Measurements were made for an injection pulse frequency of 50 Hz and 16ms duration. At this condition no transitional periods were evident. The velocity and droplet size data was comparible with the data collected under continuous operation.

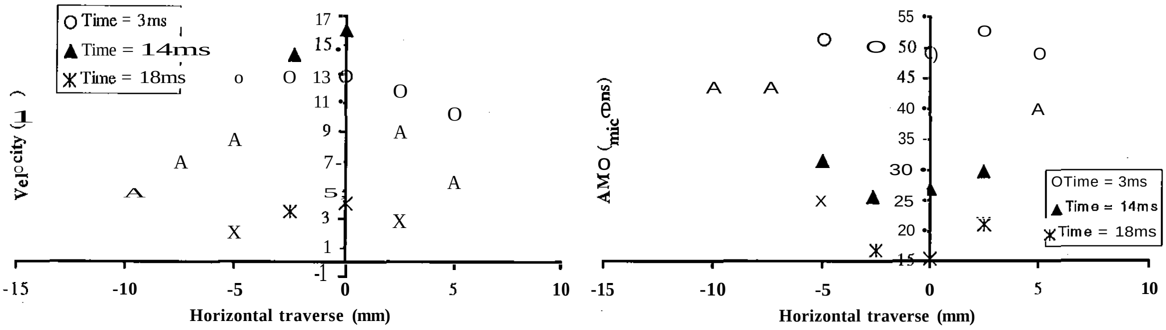

Figure 7 - PDA data at 20mm from the injector (pulsed a 6Hz for 10ms)

3.3 Determing CFD boundary data

Specifying spray boundary data for CFD predictions based upon these measured data is not straight forward. Firstly, it is clear that by the first measurement plane, the two spray streams are not, and cannot be treated as being independent of one another, or indeed symmetrical about their respective axes. Explicitly defining the spray would therefore require significantly more data points or some assumptions as to the degree with which the streams interact with one another.

For these reasons an alternative approach is proposed, the Assumption of a Fully Atomised Jet concept (AFAJ) [ref. 5]. The AFAJ approach neglects the spray break-up process assuming fine droplets are released at the injector tip. Instead of known values of droplet velocity, direction and mass being applied at a given point downstream of the injector, fictitious boundary conditions are applied at the injector tip. These parameters are then tuned through trial and error until the desired downstream values are achieved. In the past this approach has proven difficult to apply to port fuel injectors. The problem seems to be that if the spray penetration is modelled correctly, then the downstream drop size is over estimated and vice versa [ref. 6]. This is because for the same initial velocity, droplets will not penetrate into the continuous phase like a liquid core will. With the multiple-hole injector, where spray break-up occurs at or close to the injector tip, this approach should prove to be less problematic. By adopting the AFAJ approach, and hence applying the data before the spray streams begin to interact with one another, it should be possible to apply symmetrical boundary data.

Secondly, under pulsed operation, the spray exibits two transitional periods at the beginning and end of the injection. At high engine load, where the injection frequency is high and the pulse duration long, these transitional periods are not evident and can be ignored. Instead the boundary data can be applied in a stepwise manner. At the lower frequencies though, these periods are significant and need to be represented in the boundary data. The measurements made so far do not have sufficient temporal resolution to fully define these transitional periods. Further measurements are therefore scheduled. For these tests the PDA will be operated in encoder mode. In this way the arrival time is recorded for each droplet referenced to an internal clock. The data can then be binned by arrival time showing the evolution of each size and velocity moment as a function of time.

4.0 CONCLUSIONS

The fuel spray from a Denso multiple-hole port fuel injector has been characterised using Planar Mie scattering and PDA laser techniques. The study showed the injector produces two streams of finely atomised spray, between 20 and 50 microns (AMD). Spray break up would appear to take place at or close to the injector tip, as there were no visible ligaments present.

At 20mm downstream of the injector the two streams over lap, destroying for what is in the most part, a symmetrical spray distribution. Further down stream we see a widening of the streams and peak velocities reduce as the droplets are slowed by aerodynamic drag. The average droplet size increases, as the smaller droplets are unable to penetrate as far.

Under pulsed operation, the spray exhibits two transitional periods at the start and end of injection, between which the spray becomes established, and both the velocity and size profiles tend toward those seen under continuous operation. At a combination of very high operating frequencies and long pulse duration, these transitional periods are not evident.

The asymmetric spray distribution resulting from the overlapping streams makes it difficult to apply the PDA data directly as CFD boundary conditions. Instead the AFAJ approach will be adopted where droplet velocity and size, tuned through trial and error, are applied at the injector tip.

At the lower pulse frequencies the transitional periods are significant and need to be represented in any CFD boundary data. The measurements made so far do not have sufficient temporal resolution to fully define these periods. Further measurements are scheduled.

5.0 ACKNOWLEDGEMNTS

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