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PDA Characterisation of Dense Diesel Sprays Using a Common-Rail Injection System

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ABSTRACT

To meet the future low emission targets for Diesel engines, engineers are optimising both the fuel injection and after treatment systems fitted to Diesel engines. In order to optimise the fuel injection system there is a need to characterize the fuel spray for a given injection nozzle geometry and injection pressure/duration. Modern Diesel common rail systems produce very dense sprays, making in-cylinder investigation particularly difficult. In this study the measurement of droplet sizes and velocities in dense Diesel sprays has been investigated using Phase Doppler Anemometry (PDA). PDA has been proven to be a valuable technique in providing an understanding of the structure and characteristics of liquid sprays in many studies. It is often applied to finely atomised and dispersed particle flows. However, the application of PDA to dense sprays is complex and therefore the measurements reported in the literature are performed under conditions that are not representative of modern Diesel engines.

This paper reports both on the processes undertaken to optimise a classic PDA system so that it may be used to gather data in such difficult conditions and on the interpretation of the results obtained. The PDA technique was applied to the instantaneous measurement of Diesel droplet sizes and velocities in a rapid compression machine operated at realistic engine conditions. Results are presented for in-cylinder pressures ranging from 1.6 MPa to 6 MPa and injection pressures from 60 to 160 MPa.

INTRODUCTION

The Diesel engine, due to its associated fuel consumption efficiency and durability, has become a popular power source for many vehicles. The market share for Diesel powered passenger cars is increasing in Europe and more than a third of the car buyers choose Diesel-powered cars. Unfortunately, compared to the conventional, catalyst equipped, gasoline engine, the Diesel engine is notorious for being a source of particulate matter and nitrogen oxides (NO_X) emissions.
In order to improve air quality, legislation regarding emissions from mobile sources has tightened considerably over the past 20 years, in the U.S., in Japan and in Europe. A detailed understanding of the fuel injection and combustion processes of Diesel engines is required in order to reduce the undesirable products of combustion whilst at the same time maintaining good fuel economy [1].

In recent years, comprehensive research work has been carried out in the area of Diesel injection and Diesel spray characterization. Numerical, theoretical and experimental studies have reported data that has provided guidelines for the design of injection and combustion systems [2]. The Diesel fuel injection process is the most dominant flow process in the combustion of compression ignition engines [3]. It controls the process of fuel atomisation, and the subsequent fuel/air mixing, mixture ignition, combustion and pollutant formation. High injection pressure was demonstrated [4] as a way of decreasing smoke emission without an increase in nitrogen oxide (NO_X) emissions.

The different studies previously reported attempt to explore the effects of such strategies upon droplet distributions and behaviour, with the emphasis on data collected from the core of the spray. Understanding droplet behaviour will help explain the benefits of these injection strategies.

PREVIOUS PDA STUDIES

In the current study the Phase Doppler Anemometer technique was used to provide velocity and diameter measurements of individual droplets at a single point within the spray. Before describing the experimental procedure used in this study a brief description of previous PDA studies and some of the experimental difficulties will be outlined.

Phase Doppler Anemometers are among the most accurate flow measurement devices. The technique is complicated and it is important to identify the sources of error when making a PDA measurement. Hence, an appropriate phase Doppler system has to be tailored and tested under real injection conditions. As shown in Figure 1, most of the PDA investigations on Diesel spray properties, so far, have been undertaken at unrealistic engine conditions (low injection pressure and atmospheric conditions). This may be attributed to the associated difficulties with measurements in dense sprays.

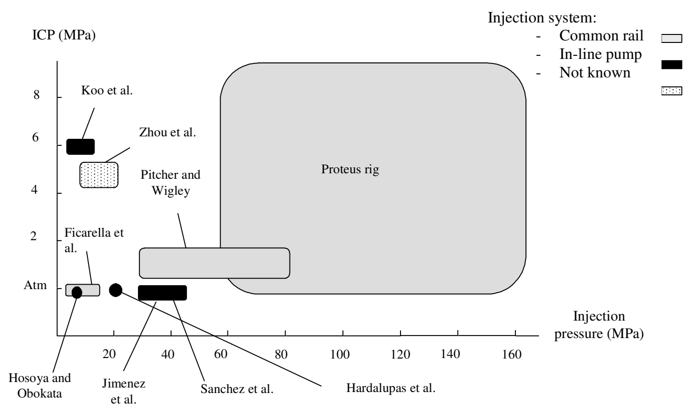


Figure 1: Comparison between the testing conditions of the Proteus and those from the PDA literature.

The Proteus rig is capable of reaching an in-cylinder pressure of 12 MPa and injection pressure of 160 MPa; however in this study the in-cylinder pressure was limited to 6 MPa.

Hosoya and Obokata [5] performed LDA (Laser Doppler Anemometry) and PDA measurements on a Diesel spray injected at 9.8 MPa and obtained droplet diameters up to 500 µm. Koo et al. [6] reduced the chamber pressure from 21 MPa to 0.6 MPa in order to avoid the problems with dense spray measurement. Araneo and Tropea [7] investigated sprays produced by a common rail system with a PDA method. A laser of 488 nm wavelength was found to provide a higher validation rate than the conventional 514.5 nm one. The authors used injection durations of 8 ms in order to reach a quasi-stationary spray. In this work an unrealistic sphericity factor (30%) was used to obtain data. Droplets would no longer be spherical at these velocities and the results would become skewed towards smaller drops, biasing the distribution. Ficarella et al. [8] had to restrict the probe volume (by cutting it with a spatial filter) and increase the laser power up to 5W, to ensure that reliable results were obtained. Several attempts were made at different injection pressures by the authors who found that they had to reduce the injection pressure to 15 MPa, in order to obtain repeatable measurements. The rejection rate was around 30% in the LDA mode (velocity measurements only) and about 70% in the PDA mode (velocity and diameter measurements). PDA measurements were taken at axial distances from 5 mm up to 30 mm from the nozzle and at all the radial positions with an interval of 1 mm. The limitations of the phase Doppler anemometry technique to investigate dense sprays are viewed by Ficarella et al. as the main explanations for their lack of accurate results. But their lack of measurement in the region close to the injector tip could be caused by an un-atomised spray. Moreover, at these conditions the spray no longer represented that found under real engine conditions.

Previous PDA research in fuel sprays using a common rail injection system tends to suggest that the technique cannot easily be applied to dense sprays. It may be argued that examples of PDA measurements are available in the literature, but careful examination of the experimental conditions reveals that in many of these cases both injection pressures and in-cylinder conditions were reduced substantially to obtain a reasonable data rate. These conditions then become unrealistic of those in a modern engine. For instance, Wigley and Pitcher [9] used a bespoke optical system with a large beam separation and thick beams, which allowed the measurement of high injection pressure spray, something that Ficarella et al. could not achieve. By using this configuration, a small control volume could be obtained, reducing multiple droplet interference in the measurement process.

The difficulties in attaining measurements in the dense spray environment within a Diesel engine require a different approach to those traditionally used in LDA/PDA measurements. In this study, droplet velocity and size measurements were undertaken at realistic engine conditions and in a pressurised chamber. An "optimisation" of the measurement technique has been undertaken.

EXPERIMENTAL SET-UP

PROTEUS ENGINE

The details of the test rig are described in a number of previous publications [10, 11]. The spray rig consists of a high-pressure engine and common rail injection system. The Proteus is a single cylinder, two stroke operated rapid compression machine. The engine is fitted with an optical chamber in place of the cylinder head to enable the visualisation of the fuel spray in quiescent air at high pressures and temperatures. The engine specifications are summarised in Table 1.

Bore	135 mm
Stroke	150 mm
Displacement	2.2 litres
Compression ratio	9:1

Table 1: Engine specifications.

Operating temperatures and pressures representative of a modern Diesel engine at start of injection are achieved by boosting the intake charge up to 0.6 MPa. In-cylinder pressures and temperatures up to 12 MPa and 750 K respectively can be attained at start of injection. In-cylinder pressures were monitored using a 6121 Kistler pressure transducer. A dynamometer connected to a 6:1 ratio gearbox drove the Proteus at an engine speed of 500 rev/min. This was the operating engine speed for the test that was carried out in this study. The optical cylinder head chamber has a diameter of 50 mm and a length of 90 mm. A three-window optical cylinder head, with 55 mm × 25 mm sapphire windows, was specially designed for forward scatter PDA experimentations.

FUEL INJECTION SYSTEM

A second generation Bosch common-rail, electronically controlled injector was used to generate and introduce the high injection pressure sprays into the chamber. This injection system gives flexibility in controlling the injection timing, injection duration and rail pressure. The FIE (fuel injection equipment) included a fuel pump, a common rail, an injector, a delivery pipe (kept short to be representative of an automotive vehicle), an electric motor and an electronic control unit. Figure 2 shows a schematic of the system. The fuel pump powered by an electric motor was running at 1400 rev/min ensuring a stable rail pressure with minimal fluctuation. A 4067 Kistler pressure transducer connected to an oscilloscope monitored the rail and the delivery pipe pressure.

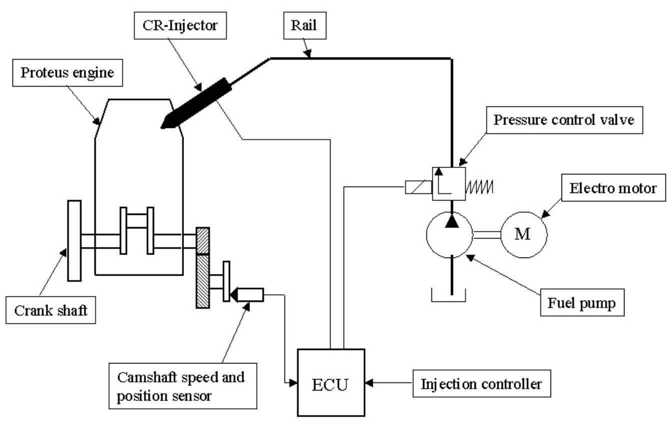


Figure 2: Schematic diagram of the fuel injection system.

The fuel pump pressurises the fuel inside the common rail to pressures up to 160 MPa. The pressure regulator located at the exit of the high-pressure fuel pump is controlled by the ECU (electronic control unit) and sets and maintains the correct pressure in the rail. The ECU regulates the fuel pressure to a set pressure ranging from 60 MPa to 160 MPa.

The injection system is controlled by a custom electronic control unit and an injector controller, controlling the rail pressure (PID control), the injection duration, the injection angle, the number of skipped injections and the camera trigger angle. The rail pressure is set as a percentage of the high-pressure pump load, the injection angle in crank angle and the injection timing in milliseconds with a resolution of 0.05 %, 0.5° and 0.01 ms respectively.

The fuel injector was mounted on top of the spray rig chamber for these tests. For these the fuel was injected into the chamber through a 0.2 mm diameter VCO (valve covered orifice) single-hole injector.

PDA INSTRUMENTATION

The optical experimental set-up, shown in Figure 3, consists of nine components. The light source was a Spectra Physics Argon-ion laser operating in “all lines” modes.

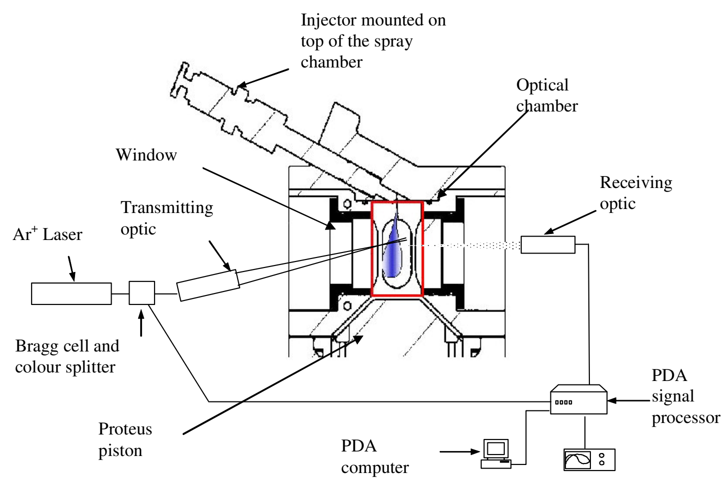


Figure 3: PDA set-up.

The beam passes through a Bragg cell and colour separator, which splits the incoming beam into two beams and shifts the frequency of one of them. The beams then travel to the transmitting optic through an optical fibre. A lens mounted on the transmitting optic focuses the two beams to form the measurement volume at a focal length of 310 mm. The receiving optic was positioned at 310 mm from the measurement volume, at an angle of 70°. The collection optic consists of a 310 mm focal length lens and four photomultipliers. The lens focuses the scattered light from particles crossing the measurement volume onto four detectors. These convert the fluctuations in light intensity into fluctuations in a voltage signal that could be interpreted by the Doppler signal processor (Dantec BSA P70). The PDA transmitting and receiving optics are mounted on optical rails that are secured onto an air cushioned optical table to avoid ground-transmitted vibrations.

Laser	
Wavelength	514.5 nm
Beam diameter	2.2 mm
Focal length of lenses	
Transmitting optic	310
Receiving optic	310 mm
Beam separation	36 mm
Beam intersection angle	13.116°
Fringe spacing	2.252 μm
Number of fringes	20
Probe volume	9.01×10^{-4} mm^3

Velocity bandwidth	-56.3 to 146.4 m/s
Maximum diameter	45.3 µm
Particle refractive index	1.41
Medium refractive index	1.0002
Signal-to-noise ratio level	-3 dB
Sphericity factor	10%

Table 2: Optical parameters of the PDA system used to analyse the Diesel sprays.

The alignment and focus of the optics were checked periodically with a water spray generated by a pharmaceutical nebuliser. The nebuliser was also used to validate the measurements by generating a cloud of water droplets of a known diameter (3 to 6 µm) so as to compare them with the obtained PDA data.

PDA CALIBRATION

Phase Doppler Anemometry is usually considered as a technique that requires minimal calibration. However this is not true, when very high accuracy is required [12]. Measurements of Diesel sprays remain difficult, due to the density of the spray, and are affected by uncertainties introduced by bias effects. Some of these errors are however unavoidable. Nevertheless, a thorough study and careful selection of the operating parameters of the system can significantly improve the statistical significance of the data collection.

Tests carried out for the calibration of the PDA were performed at 45 mm from the nozzle and for 60 MPa injection pressure and 1.6 MPa in-cylinder pressure.

EFFECT OF PHOTOMULTIPLIER VOLTAGE

The sensitivity of the photomultipliers (PMT) is determined to ensure reliable and repeatable measurements with an acceptable SNR. It is affected by the PMTs voltage. This voltage is controlled via computer software. The PMTs voltage can be varied between 900 V and 1700 V. Below 900 V, the processor calibration procedure cannot be successfully completed because of the weakness of the signal, and above 1700 V the signal is saturated and may influence the reliability of the data obtained. It should be noticed that saturation of signals from large droplets can also occur. Arithmetic mean diameter (AMD) and Sauter mean diameter (SMD) can be used to determine an optimum photomultiplier voltage. However SMD is more erratic due to the influence that a few additional large droplets may have upon the mean.

Figure 4 shows how the arithmetic mean diameter varies with the PMT voltage. When the voltage is low, small droplets with relatively weak signals are less readily detected. As fewer small droplets are detected, the mean diameter increases. The greatest spread in droplet diameter distribution is observed. The data rate is also affected by the voltage; an increase in voltage will increase the data rate.

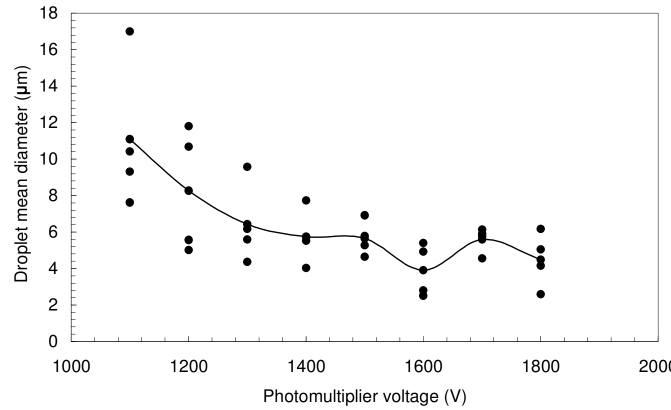


Figure 4: Droplet mean diameter as a function of the photomultiplier voltage.

The photomultiplier voltage was chosen to maximise the acquisition of small particles and to avoid signal saturation. The appropriate voltage was then selected as the value where the mean diameter drops to a “plateau” (Figure 4). The voltage saturation can be observed above 1600 V, where the curve does not follow the trend previously taken. Signal saturation is also accompanied by the generation of spurious velocity and droplet size data.

EFFECT OF LASER POWER

The laser power effects show a similar trend as photomultiplier voltage (Figure 5). Increasing the laser power will decrease the AMD, because small droplets will be detected. However, the system noise is increased; the validation rate decreases and spurious data are generated.

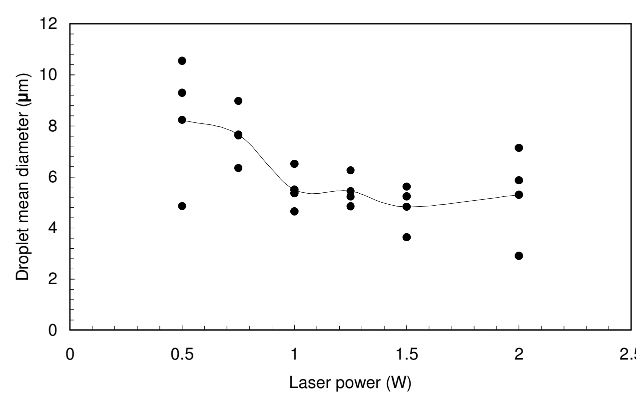


Figure 5: Droplet mean diameter as a function of laser power.

However, the effects of laser power on AMD are less pronounced than the photomultiplier voltage effects. As it can be observed on the above figure, a plateau is reached for a laser power ,at the laser head, of between 1 and 1.25 watt.

EFFECT OF THE MEASUREMENT VOLUME SIZE

The physical size of the measurement volume is inversely proportional to the beam separation. A large beam separation on the transmitting optic will produce a small measurement volume. A large measurement volume allows larger diameter and high velocity particles to be measured. However, for a given laser power, the intensity of the scattered light will be reduced, and smaller droplets possessing weakened signals will not be detected. A larger measurement volume is also susceptible to multiple droplets occupancy at a single instance and will lead to the rejection of the signal by the processor (multiple scattering).

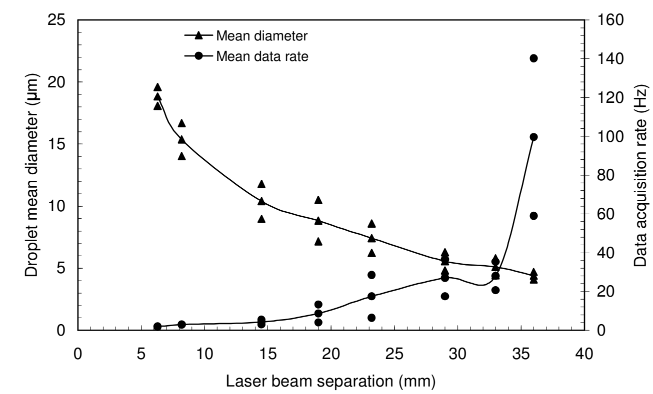


Figure 6: Droplet mean diameter and data acquisition rate as a function of beam separation.

Conversely, a smaller measurement volume will limit the maximum droplet velocity and diameter that can be measured. This will allow measurement of small droplets as it will improve the intensity of the scattered light and will minimise the probability of having multiple droplets within the probe volume. Under these spray conditions, reducing the size of the measurement volume will also increase the droplet acquisition data rate (Figure 6). This is due to the reduced risk of having more than one particle in the control volume, but also because the burst signal sent to the processor is greater in magnitude and shows increased modulation.

PRELIMINARY SPRAY CHARACTERISATION

TEST CONDITIONS

Following the calibration of the equipment, PDA measurements were performed at 15 locations in the high-pressure spray. The experimental test and conditions are given in Table 3.

In-cylinder pressure (MPa)	16, 40, 60
Injection quantity (mm^3)	30
Injection pressure (MPa)	60, 160
Injection pulse width (ms)	4.2, 2.4
Injection angle	TDC

Table 3: Experimental in-cylinder and injection conditions.

Measurements were taken along three lines at three axial distances from the nozzle (30, 45 and 58 mm). Each line comprised of 5 points. The locations are shown in Figure 7.

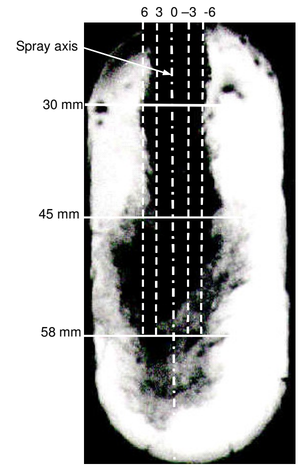


Figure 7: PDA measurement locations.

MEASUREMENT AT ENGINE CONDITIONS

At each in-cylinder position the velocity and the diameter of individual droplets were recorded over consecutive injections. For each test, validated data were acquired for a period of 360 s or until 20,000 samples were collected. This required between 40 and 210 injections depending upon the location. Each sample consisted of the axial velocity component, the droplet diameter and the droplet arrival time relative to the injection trigger pulse. The injections were then compared graphically relative to a common injection triggering point. The velocity and the diameter profiles were ensemble averaged over consecutive 0.5 ms time bins.

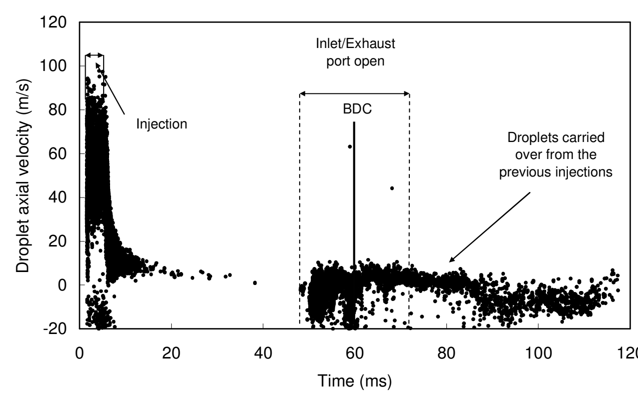


Figure 8: Axial droplet spray velocity over one engine cycle.

Figure 8 shows the instantaneous velocity data from consecutive injections over the engine cycle (120 ms). As one can see, droplets are recorded during the injection, but also during and after the scavenging process. When the inlet port is open, all the droplets carried over from the previous injections are forced towards the measurement volume by the air entering the compression chamber. As such, post-processing was required to ensure that the velocities and particle diameters were averaged over the injection pulse period to avoid bias towards droplets carried over from previous injections that had diameters below 5 µm.

MEASUREMENTS INTERPRETATION CLOSE TO THE NOZZLE

Figure 9 shows the radial data acquisition rates across the spray. At 45 and 58 mm from the nozzle, the data acquisition rates show a strong dependence to the measurement position. At the points where the distance to the receiving optic is increased (r = 3 mm), the path of the scattered light is disturbed by other droplets and the data rate decreases (signal obscuration). The forward scattered light from a particle crossing the laser beams outside of the measurement volume can also interfere with a signal generated in the measurement volume. The signal sent to the receiving optic is unlikely to be validated as a measurement. The low data rate observed on the spray periphery (r = -6 mm) is due to the relatively low number of droplets at these positions (Figure 8).

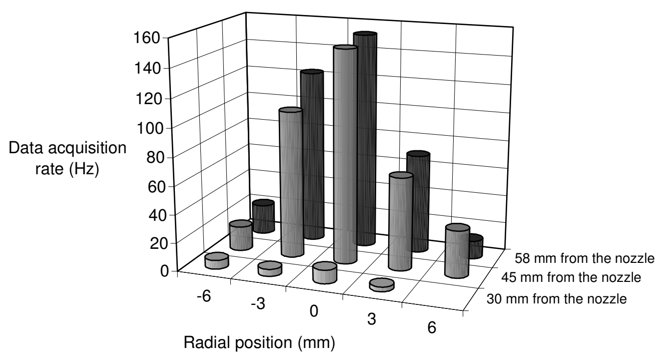


Figure 9: Data acquisition rate at 4 MPa ICP and 60 MPa.

The measurements performed closer to the nozzle (30 mm) showed a much lower data rate. Using a fast cinematographic technique Gülder [13], showed that Diesel sprays at lower injection pressure are completely atomised at 20 nozzle diameters, whereas Yule and Salters [14], using a conductivity probe technique, found that the Diesel spray breakup length was of the order of 100 nozzle diameters. In this study, at 30 mm from the nozzle (150 nozzle diameters), the lack of measurements and the poor data rate shows that the spray atomisation is not complete. Sections of intact liquid core or regions of high liquid volume fractions and other structures are present in the spray instead of discrete droplets. The PDA system is then unable to validate signals. Secondly, the particles are subjected to aerodynamic load and viscous stresses produced by gas density, turbulence and local flow accelerations may shape the droplets into ellipsoids. In addition to these phenomena, coalescence of droplets may occur in the spray, resulting in the additional formation of non-spherical particles. Therefore, if the particle is not spherical, a valid droplet measurement will not occur. The concentration of the particles is such that there is also a possibility that several droplets may occupy the measurement volume at the same time, leading to overlapping signals, with associated low validation rate. The reasons for the rejection of data outlined above would all be applicable in areas of the spray considered dense.

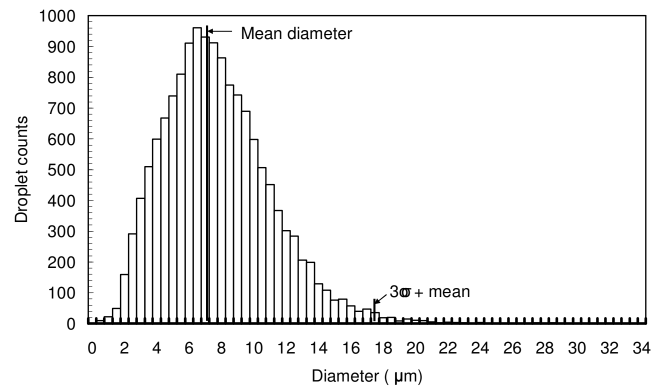


Figure 10: Typical droplet distribution at 45 mm from the nozzle along the spray axis at 4 MPa in-cylinder pressure and 60 MPa injection pressure.

Measurements gathered at 45 and 58 mm from the nozzle showed good phase plot linearity and Gaussian droplet size distribution (Figure 10) and were considered as statically reliable for a thorough description of the dense Diesel spray behaviour at such distances from the nozzle.

SPRAY STRUCTURE

The description of a high-pressure Diesel spray was divided into two parts. These are referred as the "spray head" and the "spray tail". A typical injection period is shown in Figure 11.

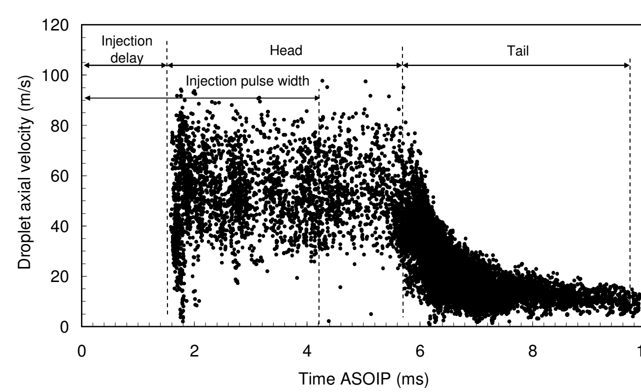


Figure 11: Spray head definition. Spray axis, 58 mm from the nozzle, 1.6 MPa in-cylinder pressure and 60 MPa injection pressure.

The temporal division between the head and the tail was selected at the point where the droplet velocities exhibited a steep negative gradient.

The range of velocities observed in the spray head is between 0 and 80 m/s (Figure 11). This spread is attributed to aerodynamic effects occurring in the spray head. Droplets located in the spray tip will be affected by shear between the surroundings gas and the spray envelope. Early injected droplets impart momentum to the gas are then quickly overtaken and hit by the droplets that follow them. Following those collisions, the particle trajectories are entrained towards the spray periphery. In the measurement volume, droplets with a true axial velocity are acquired but also those having a modified trajectory. The axial velocity component of those entrained droplets is then lower than those droplets with unmodified trajectories.

In all the cases along the spray axis, all the velocity profiles in Figure 13, 14, 15 and 16 are of a square form with a steep velocity gradient. Whilst at the lower injection pressures, this plateau is attained much more slowly. This can be explained by assuming that the first droplets sprayed into the chamber, are rapidly decelerated by the in-cylinder gas. Fuel sprayed after this initial stage will then be injected into a jet stream of air, and hence the relative velocity between the air and the droplets will be much less and the droplets are less readily decelerated. These particles will then catch up those first injected drops and overtake, collide or coalesce with them. Once this happens, they will then enter relatively quiescent air and once again be decelerated rapidly. This explains the velocity fluctuation in the spray which is a complex function that is temporally dependent upon the injection phases and their relationship to a fixed point measurement technique.

The diameter profiles displayed in Figure 15 and 16 (spray axis), show a reduction in droplet size towards the end of injection (spray tail). As previously described, particles introduced in the spray chamber during the early stage of the injection rapidly loose their momentum. Those droplets will then breakup into smaller ones (secondary breakup) and will reach the measurement volume towards the end of injection. This explains the diameter decrease which is a complex function related to the spatially fixed measurement volume. In such, under certain circumstances, a droplet measured in the spray tail may have had an origin within the initial phase of injection. It should be noticed that the gradient at which the diameter decreases is proportional to the distance from the nozzle. A more shallow gradient can be seen at 58 mm from the nozzle towards the spray tail. It is possible that small droplets measured at 45 mm from the nozzle evaporate before they reach a distance of 58 mm from the nozzle.

EFFECT OF RADIAL POSITION

The results presented in Figure 12 demonstrate the evolution of the spray droplet velocities and sizes from three radial locations along the spray axis at 58 mm from the nozzle. Droplet velocity and diameter are time resolved with the origin on the time axis corresponding to the injector pulse. From Figure 12:

- The axial droplet velocity range is increased as the distance from the spray periphery is increased.
- The droplets at the periphery of the spray are almost all small droplets (diameter less than 20 μm) with very low velocity.
- On the spray axis (r = 0 mm), the head is composed of droplets travelling at approximately 50 m/s on average at 58 mm from the nozzle and 160 MPa injection pressure.

The data set indicates that most of the droplets located in the head of the spray are less than 20 μm in diameter for an injection pressure of 60 MPa. The velocity profile shows that droplet velocities at the head of the spray range from 30 to 90 m/s.

Droplet velocity and diameter distribution both show a strong dependence upon the radial position in the spray. This is illustrated in Figure 13 and 14. The velocity profiles show that droplets measured on the periphery of the spray have smaller velocities than those measured on the spray axis. Consequently, particles travelling on the edge of the spray will be more affected by shear between the air and the spray envelope, and after the disintegration of the liquid column emerging from the nozzle. The generated droplets may breakup into smaller ones as they progress into the surrounding gas. Droplets located on the spray periphery may also be subjected to evaporation as in-cylinder temperatures at top dead centre attain 540 K.

Spray periphery measurements are not better than spray axis measurements in terms of data acquisition rate. However, when the radial distance from the spray axis is increased, few droplets with negative axial velocities can be observed at the start of injection (Figure 12). Droplets entrained by spray head vortices are believed to cause those negative velocities. Experimental results reported by Morgan et al. [15] showed similar phenomena.

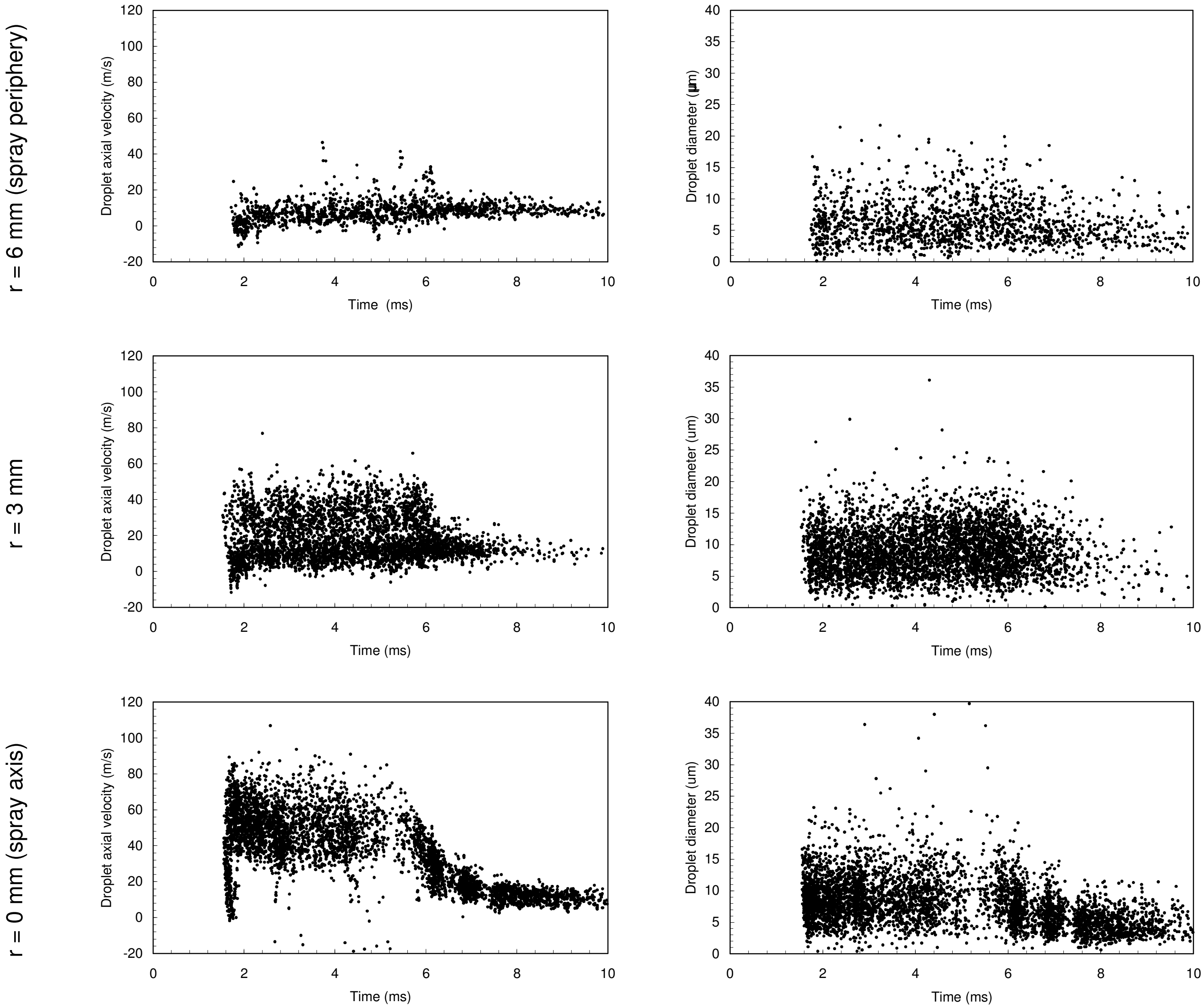


Figure 12: Time resolved axial droplet velocities and sizes at 58 mm from the nozzle at 60 MPa injection pressure and 1.6 MPa in-cylinder pressure for different radial positions.

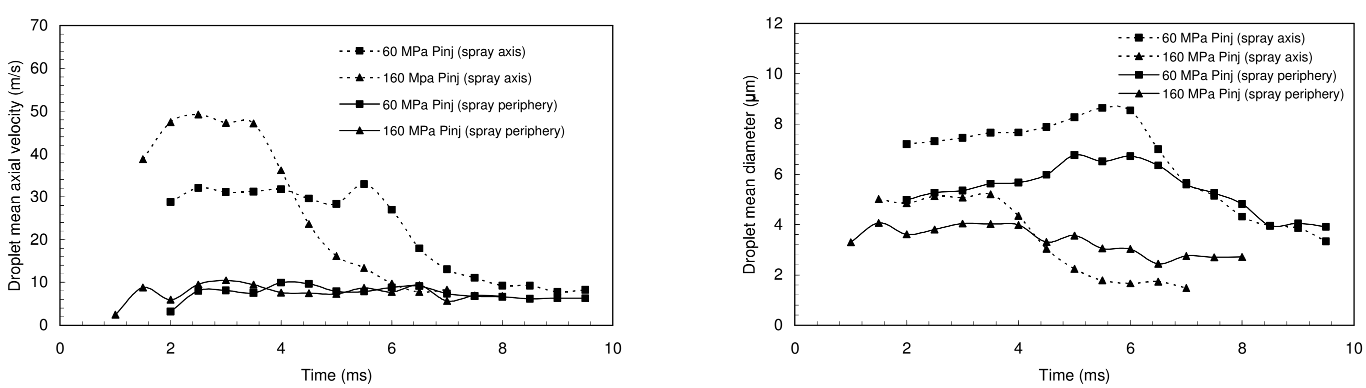


Figure 13: Mean droplet axial velocity and diameter profiles at 45 mm from the nozzle and 4 MPa in-cylinder pressure at different radial positions (spray periphery and spray axis).

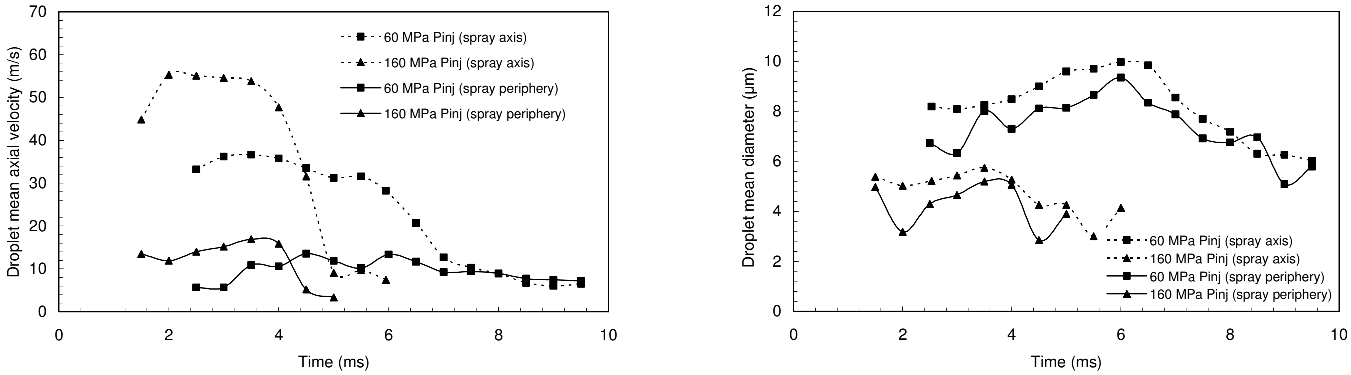


Figure 14: Mean droplet axial velocity and diameter profiles at 58 mm from the nozzle and 4 MPa in-cylinder pressure at different radial positions (spray periphery and spray axis).

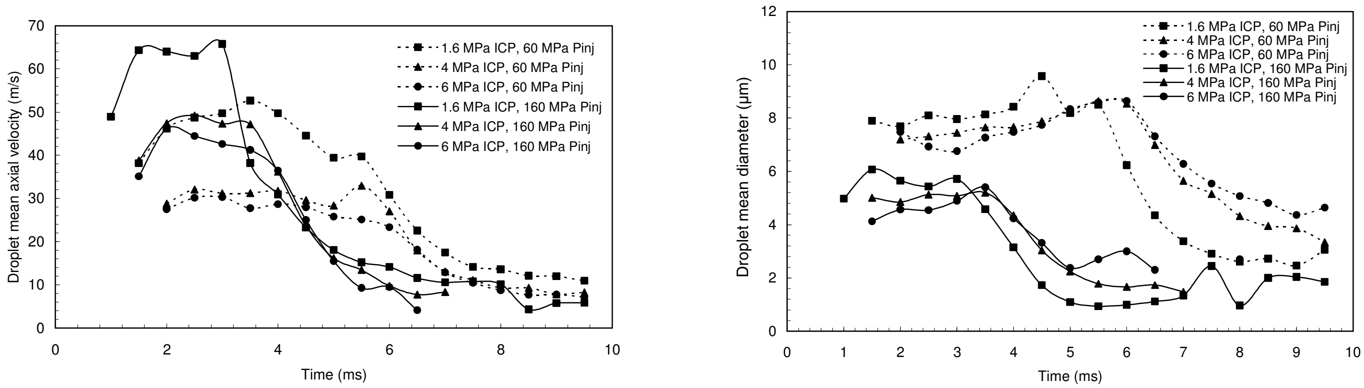


Figure 15: Mean droplet axial velocity and diameter profiles at 45 mm from the nozzle on the spray axis for injection pressures ranging from 60 to 160 MPa and in-cylinder pressures from 1.6 MPa to 6 MPa.

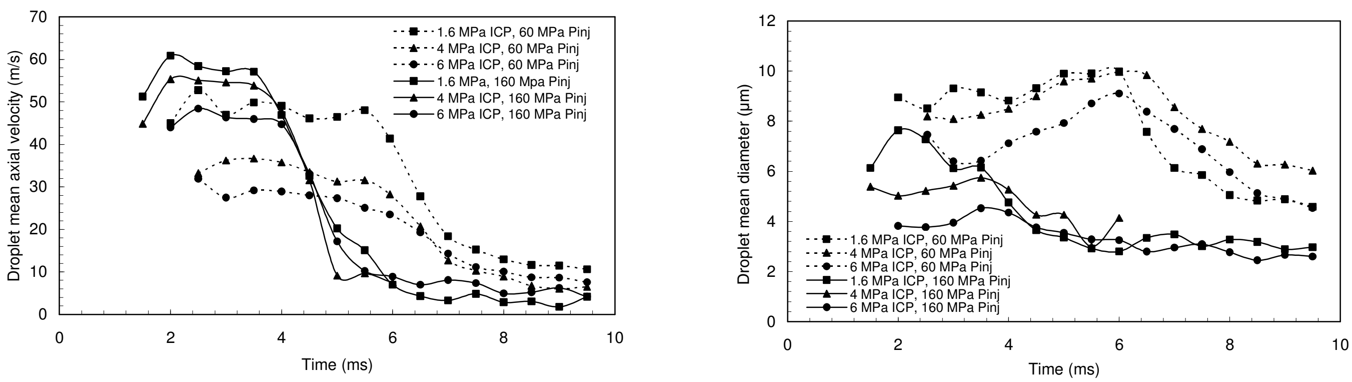
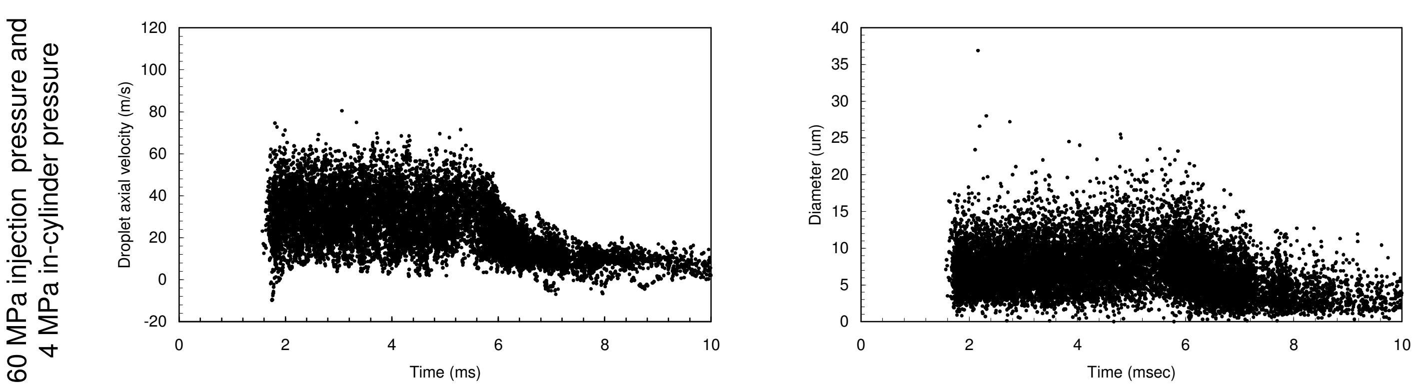


Figure 16: Mean droplet axial velocity and diameter profiles at 58 mm from the nozzle on the spray axis for injection pressures ranging from 60 to 160 MPa and in-cylinder pressures from 1.6 MPa to 6 MPa.



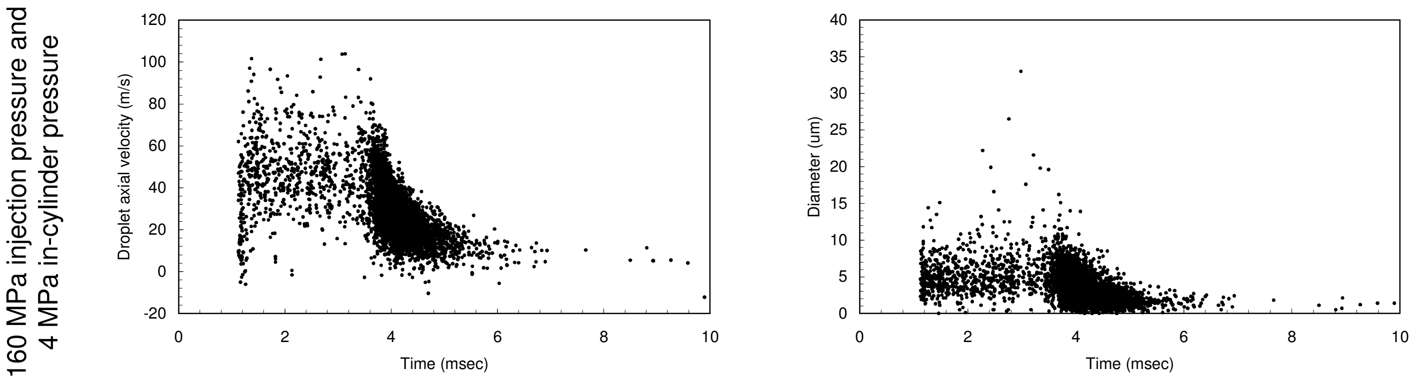


Figure 17: Time resolved axial droplet velocities and sizes at 45 mm from the nozzle at 60 and 160 MPa injection pressure and 4 MPa in-cylinder pressure.

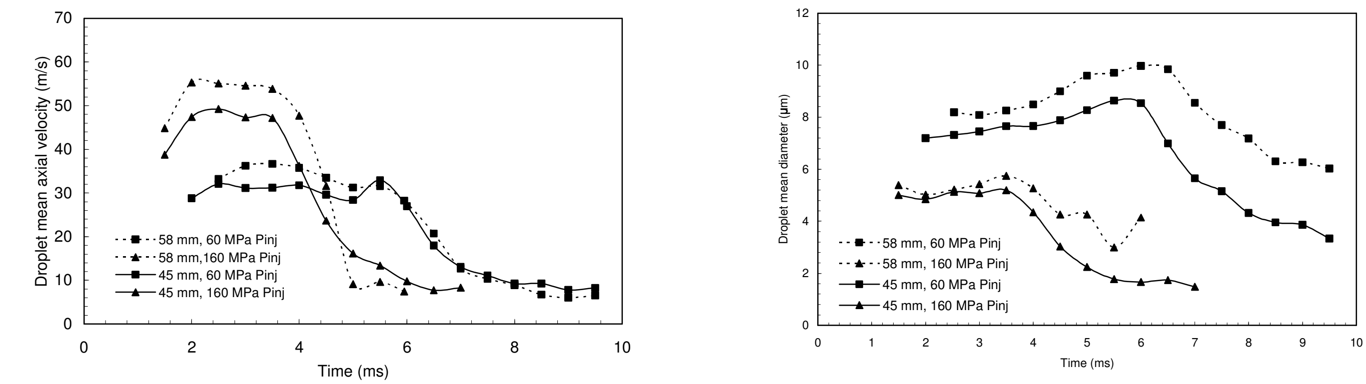


Figure 18: Mean droplet axial velocity and diameter profile at 4 MPa in-cylinder pressure on the spray axis at different axial position (45 and 58 mm from the nozzle).

EFFECT OF INJECTION PRESSURE

The measured average droplet diameters for four injection pressures are plotted in Figure 19. This figure clearly shows the effect of injection pressure on droplet diameter, which decreases at higher injection pressures. The trend observed is consistent with other publications reported in the literature [16, 17].

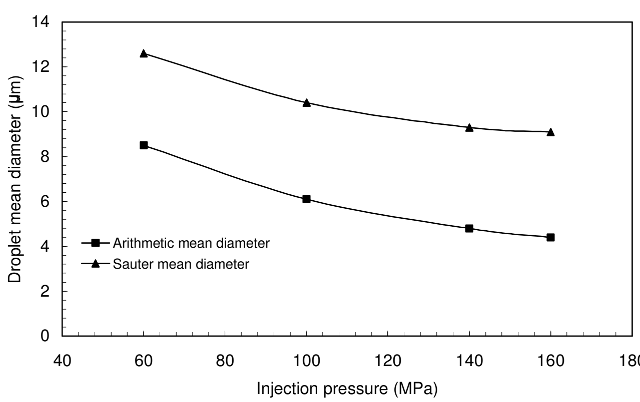


Figure 19: Injection pressure effect on droplet mean diameter at 45 mm from the nozzle on the spray axis.

It is clear that the injection pressure has a strong effect on the behaviour of the spray. The results presented in Figure 15 and 16 reveal the spray behaviour at 45 and 58 mm from the nozzle tip on the spray axis for two different injection and in-cylinder pressures. The following observations can be made throughout Figure 15 and 16:

- The peak velocities increased as the injection pressure increased.
- The peak velocities and the velocity ranges decreased as the in-cylinder pressure increased.
- The rate at which the velocity dropped after the end of the injection reduced as the injection pressure increased.
- The droplet diameter ranges were much larger at low injection pressures (60 MPa).
- Increasing the injection pressure reduced the particle size (enhanced atomisation).
- Fewer droplets were validated in the spray head at high injection pressure.

The lack of measurements observed in the spray head for an injection pressure of 160 MPa could be due to incomplete spray atomisation (Figure 17). However, at such a distance from the nozzle (45 mm from the nozzle) this is unlikely to be the case. There are several explanations for the poor acquisition of droplets in the spray head, in terms of measurement rejections by the PDA. High injection pressures produced faster particles and made the droplets more susceptible to aerodynamic breakup; the spray atomisation will then be improved. Therefore, the number of small droplets present in the spray increased. This could lead to the violation of the single particle constraint due to the high droplet number density. Disturbance of the transmitter beams and obscuration of the scattered light could also have affected the droplet acquisition rate.

For an injection pressure of 60 MPa, the spray velocity was steady for approximately 4 ms and for an injection pressure of 160 MPa, the spray was steady for 2 ms. This is due to the fuel injected quantity being kept constant to 30 mm^3, corresponding to an injection timing of 4.2 ms and 2.4 ms at 60 MPa and 160 MPa injection pressure respectively.

EFFECT OF IN-CYLINDER PRESSURE

PDA measurements of Diesel sprays show that increasing the in-cylinder pressure can dramatically slow droplets down. At high in-cylinder pressures the difference in droplet velocity profile between the head and the tail of the spray becomes small at low injection pressures. The ambient pressure also has an effect on the measured diameter; measurements undertaken at 45 and 58 mm from the nozzle and at 60 and 160 MPa showed a small decrease in the droplet diameter with an increased in-cylinder pressure. However, in well atomised sprays, an increase in the ambient pressure should result in an increase of the mean diameter due to a higher droplet concentration [18, 19]. It is believed that these discrepancies can be explained by the fact that for the elevated in-cylinder pressures used in this study, the shear and aerodynamic forces are more significant than the coalescence effects.

EFFECT ON AXIAL POSITION

Figure 18 shows the velocity and the diameter profiles for the spray axis locations at 45 mm and 58 mm from the nozzle. Velocity and diameter profiles measured on the spray axis at 45 mm from the nozzle appear similar to the one measured at 58 mm. For an increasing distance from the nozzle, an increase in droplet mean velocity and mean diameter is observed. The evolution of the droplet sizes can be explained by different processes. Coalescence of droplets is due to collisions; small droplets can gather together to create large ones. At such in-cylinder conditions (4 MPa in-cylinder pressure and 540 K in-cylinder temperature), droplets will be subjected to evaporation therefore droplets with small diameters may be significantly reduced at 58 mm from the nozzle. In Figure 18 a diameter increase can be observed in the spray head, while the diameter decreases towards the end of the injection. Due to the aerodynamic drag effect, droplets possessing small diameters will suffer more retardation than the large ones and will then reach the measurement point later.

CONCLUSION

This study described an approach to establishing reliable measurements in dense Diesel sprays using the PDA technique. This investigation found the following:

- A study of the PDA system parameters (laser power, photomultiplier voltage and measurement volume size) is required to tailor the system to the measurements of dense sprays.
- The photomultiplier voltage, the laser power and the size of the measurement volume all show significant effects on measured droplet diameters.
- The effects of injection pressure, in-cylinder pressure, at various axial and radial locations, on the spray behaviour have been studied.
- The droplet velocity and diameter profiles were shown to be dependent upon the position in the spray (radially and axially), the injection and in-cylinder pressures. An increase in mean droplet velocity was seen when the injection pressure or axial distance from the nozzle was increased.
- Increasing the cylinder pressure reduced the droplet velocities.
- Increasing the injection and cylinder pressures improved the spray atomisation.
- The injection pressure effect upon the droplet mean diameter showed similar trends to those reported previous by [16, 17].
- Difficulties in gathering reliable data at 30 mm from the nozzle. This may be caused by the presence of a liquid core in the spray.
- The spray head exhibits a wavy structure with a high frequency component that is subject of current investigation.

LIST OF SYMBOLS

AMD	: Arithmetic mean diameter
ECU	: Electronically control unit
FIE	: Fuel injection equipment
ICP	: In-cylinder pressure
NO_X	: Nitrogen oxides
P_{inj}	: Injection pressure
PMT	: Photomultiplier
SMD	: Sauter mean diameter
SNR	: Signal-to-noise ratio
VCO	: Valve covered orifice

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