Spray characterization of a piezo pintle-type injector for gasoline direct injection engines

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Abstract. The sprays from a pintle-type nozzle injected into a constant volume chamber have been visualised by a high resolution CCD camera and quantified in terms of droplet velocity and diameter with a 2-D phase Doppler anemometry (PDA) system at an injection pressure of 200 bar and back-pressures varying from atmospheric to 12 bar. Spray visualization illustrated that the spray was string-structured, that the location of the strings remained constant from one injection to the next and that the spray structure was unaffected by back pressure. The overall spray cone angle was also stable and independent of back pressure whose effect was to reduce the spray tip penetration so that the averaged vertical spray tip velocity was reduced by 37% when the back-pressure increased from 1 to 12 bar. Detailed PDA measurements were carried out under atmospheric conditions at 2.5 and 10 mm from the injector exit with the results providing both the temporal and the spatial velocity and size distributions of the spray droplets. The maximum axial mean droplet velocity was 155 m/s at 2.5 mm from the injector which was reduced to 140 m/s at z = 10 mm. The string spacing determined from PDA measurements was around 0.375 mm and 0.6 mm at z=2.5 and 10 mm, respectively. The maximum mean droplet diameter was found to be in the core of the strings with values up to 40 μm at z=2.5 mm reducing to 20 μm at z=10 mm.

1. Introduction

Gasoline direct-injection engines (GDI) offer at present the best promise for simultaneous reduction of fuel consumption and exhaust emissions. It is well known that the fuel injection system in the spray-guided configuration represents the key component in this emerging technology as the spray structure and its stability play the dominant role in the mixture preparation process and subsequent combustion [1-2]. In particular, under part-load operation when the fuel is injected late during the compression stroke, the goal is to quickly transport the fuel/air mixture towards the spark plug with no fuel impingement on surfaces, and to achieve complete evaporation of the droplets in the short time available between the end of injection and the start of ignition.

Previous studies in direct-injection engines have focused mainly on swirl pressure atomisers representing the “first generation” injection systems. In general, this system has proved to offer lower fuel consumption of up to 20% in the case of stratified, overall-lean part-load operation, but not significant improvements in HC and NOx emissions [3]. The main disadvantage identified in this type of injector was that the spray cone structure was very sensitive to the back pressure so that a complete collapse of the spray structure could take place when injected during the compression stroke [4-7].
This is a very undesirable feature for stratified charged operation when the fuel is injected late and is clearly inappropriate in the spray-guided configuration when spark plug and injector are closely spaced and ignition starts at the recirculation zone formed at the spray periphery.

New generations of high pressure injectors have emerged incorporating nozzles with multi-hole geometry, similar to those used in diesel engines [8], and of annular cone geometry, similar to a swirl atomizer but with no pre-swirl imposed. The latter type used in this study is a prototype high pressure Siemens piezoelectric pintle-type injector that produces a hollow cone spray with a nominal cone angle of 90°. In the present investigation the performance of this injector was characterized at an injection pressure of 200bar under atmospheric conditions. The injector was installed in a constant volume chamber in order to maintain constant back pressure and temperature. The following sections describe, in turn, the experimental arrangement and instrumentation, the results and their implications and the most important conclusions.

2. Experimental Set-up

The common rail system used in this study is shown schematically in Figure 1(a) with the piezo pintle-type injector installed inside a constant-volume chamber. A three-piston-type pump coupled to an electric motor is responsible for delivering high-pressure fuel up to 200bar to the common rail, which has been specifically built with one injector outlet. This common rail was connected to the injector via a pipe with a specific diameter and length which was fixed to the high-pressure chamber. The chamber is equipped with four quartz windows and connected to a pressurised bottle of nitrogen for maintaining the required high pressure inside the chamber up to 25bar. A fuel pressure regulator attached to the common rail, a solenoid valve in the chamber’s exhaust pipe and the injector itself were all controlled electronically. In order to simulate elevated temperature of the gas inside the chamber, two heating plates were installed in the walls of the constant volume chamber and the nitrogen was also heated before entering the chamber. There were several thermocouples inside the chamber to ensure constant gas temperature was maintained.

A prototype piezo pintle-type injector with a nominal cone angle of 90° and an operating pressure of up to 200 bar was tested; a schematic diagram of the nozzle injector is shown in Figure 1(b). The PDA measurements have been carried out at 200 bar injection pressure, 1 bar chamber pressure and constant injection duration of 0.33 ms. In the case of spray visualisation the effect of chamber pressure was also considered in the range of 1 - 12 bar. Iso-octane was selected as the working fluid since it is safer to use, is more convenient for optical studies than gasoline, and has a density, kinematic viscosity and surface tension of 692kg/m$^3$, 0.78cSt and 0.0188N/m, respectively.

Spray images were obtained by a non-intensified, 12-bit CCD camera (Sensicam) with a time resolution of 50μs, a spatial resolution of 512 x 640 pixels and minimum exposure time of 100ns. A strobe light of 20μs duration was used as the light source, which was synchronised to the camera. A 2-D phase-Doppler anemometer (Dantec) provided information on the axial and radial droplet velocity and diameter. The transmitting and receiving optics were installed in a 3-D traverse mechanism with a resolution of 12.5μm in X, Y axes and 6.25μm in Z axis relative to the injector position. A wall mounted Argon-Ion laser with a maximum power of around 1.5W was used and the output beam was aligned with the fibre optic unit which was responsible for the splitting of the laser beam into two pairs of different wavelengths, each pair having two beams of equal intensity. The first pair was green light with wavelength of 514.5nm, responsible for the axial velocity component and droplet sizing, while the second pair was blue light of 488nm wavelength providing the radial velocity component. A Bragg cell unit inside the fibre optical unit provided a 40 MHz frequency shift. The transfer of the four laser beams to the transmitting optics was through a fibre-optic cable. The collimating and focusing lenses formed an intersection volume of 47 μm diameter and 0.56 mm length. A 310mm focal length lens positioned at 30° collected the scattered light by the droplets in the plane of the two incident green beams to ensure that refraction dominated the scattered light. The signal from the four photomultipliers was transmitted to the processor unit where all the data processing was carried out.

The data were collected over a time window of 1ms during the injection process and up to 50k samples were collected over many injection cycles for each measurement point. The measurements were synchronised with the needle lift by an external reset pulse and restricted to the first 1 ms after the start of injection (SOI). The collected information about time, velocity and size were resolved over
a time interval of 0.1 ms to obtain the ensemble-averaged data. The number of validated samples in the 0.1 ms time interval varied from 250 to 1500 with a maximum statistical uncertainty of around 2.5% in the ensemble-mean velocity value.

Measurement difficulties were encountered during the main injection period in the core of the spray due to the attenuation of the laser beams and the scattered light as a result of the high concentration of droplets. This is a common source of uncertainty in the near-injector region of dense sprays as was reported in [9 & 10], and, although it has no effect on size measurements [10], its effect on the droplet number density could be considerable as the system fails to detect droplets during the main injection period when the number density is high.

**Figure 1** Experimental set-up: (a) constant volume chamber and fuel injection system; (b) schematic diagram of piezo pintle-type nozzle injector.
3. Results and discussion

The injector under investigation is a prototype piezo pintle type injector with a conical annular nozzle. It has been noticed that instead of a continuous hollow cone spray, the spray from this type of injectors exhibits a structure of strings right from the injector nozzle exit which is relatively stable. In particular, the number of strings and the string locations of a certain injector do not change from injection to injection. Since the string structure of the spray is not well understood, the aim of this study is to measure the spray velocities and droplet sizes around a string in order to understand the characteristics of the overall spray.

![Spray Images](image-url)

Figure 2 Vertical and horizontal images of spray visualization in the constant volume chamber at atmospheric pressure as a function of time after SOI injection, for an injection duration of 0.33 ms and injection pressure of 200 bar.

Figure 2 presents various spray images in both vertical and horizontal planes. The spray visualization serves two purposes, one is to visualise the spray development in terms of structure, cone angle and penetration and the other is to locate the control volume of the PDA system on a particular string; combining information from the spray visualization with that of the PDA measurements has been used for studying the spray characteristics.
By observing these images, the first noticeable feature was the string type structure of the spray which was identified by comparing the images in Figure 2 to be stable and almost identical from one injection to another, independent of imaging timing. The second feature with this injector was the presence of a natural gap in the spray, which may or may not be a designed feature of the injector. This gap as part of the string structure, was very stable and its location did not change at all which proved to be very useful in the PDA measurements. It provided an opening passage for the incident laser beams to reach the other side of the spray cone surface without an attenuation of the laser beams by the spray. The dense feature of the spray causes so much laser beam attenuation that PDA measurements were not possible in the core of the spray, where either the incident laser beams or the scattered light from the control volume have to pass through the spray twice.

The spray images in Figure 2 were taken by a CCD camera with a time step of 25 μs controlled by an external trigger. Imaging timing displayed on each image uses the optical SOI as the beginning of time, and is defined as the spray emerging from the injector nozzle exit. This time is different from the SOI timing, quoted in the caption of the Figures, due to the electronic delay of the injector which was found to be 0.1 ms and constant at all operating conditions. Here, the SOI timings are used for spray visualisation in order to be able to compare with the PDA measurements where the electronic SOI is used as the start of data acquisition.

The images of Figure 2(a) were taken when the spray vertical penetration was 2.5 mm, which coincided with one of the selected PDA measurement locations. The flying time for the vertical penetration at 2.5 mm is 75 μs, which gives an average spray tip speed of 33 m/s during this period. Figure 2b shows the spray vertical penetration at about 10 mm, which is another selected PDA measurement z location. Figure 2(c) is selected by the PDA measurement at z = 2.5 mm, when the spray velocity reaches a maximum indicating full opening of the injector nozzle, which is consistent with the spray images as the spray image at this time shows a fully developed spray. The high velocity spray jet induces vortices at the outer edge of the spray which transport droplets away from the main spray. In Figure 2(b), in the vertical image, a fine layer of cloud can be seen to be formed around the cone spray at a distance between 4 and 7.5 mm from the injector exit. This cloud ring becomes more clear at 0.05 ms later in the vertical image of Figure 2(c), at the left side of the image 7 mm below the injector, where a ring vortex of fine droplets is evident. Figure 2(d) shows the closing period of the injector nozzle, when the spray near the injector is less dense than in previous images in the area away from the injector. Figure 2(e) shows the spray when the injector nozzle is completely closed. As expected, the string structured spray disappeared once the upstream flow was cut off.

The sequence of the spray evolution in Figure 3 is marked by using labelled lines (a, b, c, d and e) in the PDA measurements where the temporal variation of droplet velocity and size is presented for two z locations. At z=2.5mm, Figure 3(a), the location of the measurement point in the x-y plane is in the middle of a selected string of the spray. The dotted data represent the instantaneous variation of droplet velocity and diameter; the droplet mean and RMS velocities and the arithmetic mean diameter (AMD) and Sauter mean diameter (SMD) are superimposed on the same graph. The time window for obtaining the mean and RMS velocities, AMD and SMD values is 0.02 ms.

The temporal velocity variation at z = 2.5 mm, Figure 3(a), exhibits a sharp rise and fall in droplet velocities marking the start and the end of injection. At the time marked by line a, the spray tip has reached the measurement location. At the time marked by line c, the axial velocity of the droplets at each injection peaks between 140 m/s to 160 m/s. A mild double peak profile in the middle of injection suggests a small drop in velocity when the needle is fully open. After the time marked by line e, as the injector nozzle is closed, much higher data rate is achieved due to the lower light attenuation. Due to the low data rate during the main part of injection, no valid SMD measurements could be obtained. The size distribution in Figure 3(a) shows a large variation during the injection period with AMD and SMD of the order of 20 and 45 μm, respectively, reducing to 7 - 10 μm in the trailing edge. The odd number of large droplets during the injection period leads to larger SMD values.

The droplets velocity and size distribution at the axial location of z=10 mm are presented in Figure 3(b). The spray tip reaches the measurement location later than it reaches z=2.5 mm by 0.075 ms as marked by line b. The mean peak velocity of 140 m/s is slightly lower than that at z=2.5 mm, as expected. In the velocity distribution, a small gap exits during the main part of injection due to the absence of valid measurement data. Two arguments have been put forward for this: one is that the droplet shape is not spherical and the other is the significant laser light attenuation. Both arguments
could be true to explain the low data rate of the overall PDA measurements in the spray core not only at $z=2.5$ mm but also at $z=10$ mm. By comparing $z=2.5$ mm and $z=10$ mm, the decrease of data rate at $z=10$ mm where the gap of missing data is more evident, can be more likely contributed to the laser attenuation.

The size distribution at $z=10$ mm in Figure 3(b) shows similar magnitude of droplet size during the injection period and in the trailing edge as at $z=2.5$ mm; the reduction in droplet size from high values during injection to low at the trailing edge comes earlier at $z=10$ mm than that at $z=2.5$ mm.

Figure 3 Temporal droplet velocity and size distribution with an injection pressure of 200 bar, injection duration of 0.33 ms and atmospheric back-pressure.

The spatial droplet velocity and size distribution scanned across a selected string in the x and y directions are presented in Figure 4. The PDA measurements along the x-direction show the droplet velocity and size distribution from the inside edge to the outside edge of the spray, whereas the y-direction distributions show the change along the tangent of the spray circumference, which is aiming to cover more than one string; see the inserted schematic presentation of planes x and y in Figure 4.
The evolution of the spray jet is displayed by the spatial distributions at four instances between the start of injection and the tailing edge of the spray; full data at different instances are not presented due to the limited space. Low velocities and high droplet sizes are found at the beginning of injection while flat distribution of low velocity and small droplet sizes are found in the tailing edge of the spray.

**Figure 4** Spatial velocity and droplet size distribution along x- and y-planes at z = 2.5 mm and different times after SOI: (a) x-plane distribution; (b) y-plane distribution.
During the injection period at $t = 0.28$ ms after SOI, the spatial velocity variation in the x-plane shows an almost flat profile with a tendency of increasing from inner to outer edge (a difference of 15 m/s). On the other hand, the mean diameter varies from 20 $\mu$m in the core spray to 40 $\mu$m at the inner and outer edges.

![Spatial Velocity and Droplet Size Distribution](image)

**Figure 5** Spatial velocity and droplet size distribution along x- and y-planes at $z = 10$ mm and different times after SOI: (a) x-plane distribution; (b) y-plane distribution.

In the y-plane, the variation in velocity from string to string is not well defined, as they are too close to each other. However, a pattern of maxima and minima variations in mean velocity can be seen.
where maximum velocities belong to the core of the strings (corresponding to larger diameter droplets) and minimum velocities to the region in-between the two adjacent strings (where diameters are smaller). An estimate of string spacing can be made from these results at \( t = 0.28 \) and \( 0.44 \) ms, which give a value of around 0.375 mm while the overall mean diameter is around \( 20 \mu \text{m} \).

Figure 5 shows the spatial droplet velocity and size distribution at \( z = 10 \) mm and at four instances between the start of injection and the tailing edge of the spray. From the velocity distribution in the x-direction, the increase in the width of the spray is not significant compared to that at \( z = 2.5 \) mm but the peak velocity reduces from about 150 m/s at \( z = 2.5 \) mm to 140 m/s at \( z = 10 \) mm \((t=0.38 \) ms\). The mean droplet diameters in the spray core remain between 20 to 30 \( \mu \text{m} \), similar to those at \( z = 2.5 \) mm, whereas the mean droplet diameters at the spray periphery (both inner and outer edges) are much reduced to around 10 \( \mu \text{m} \). This may indicate convection of the smaller droplets away from the core of the spray and entrainment by the induced air motion, as evident in the spray visualisation images.

In the y-plane, the presence of the strings is clearly evident with mean velocities varying by up to 60% between maximum and minimum velocities. The spacing between the two adjacent strings is clearly identifiable from the results as the distance between two minima or two maxima velocities and was found to be 0.6 mm. Comparing this value with the estimated value at \( z = 2.5 \) mm, reveals an increase of about 60% in string spacing. Mean droplet diameter is about 20 \( \mu \text{m} \) in the middle of the spray core and reduces to about 10 \( \mu \text{m} \) outside the spray core between two adjacent strings. Overall, the droplet diameters at this location are smaller than those at \( z = 2.5 \) mm by up to 50% suggesting that strong secondary break-up takes place between \( z = 2.5 \) and \( 10 \) mm.

![Figure 6](image)

**Figure 6** Vertical images of spray penetration at different back pressures, 200 bar injection pressure and 0.33 ms injection duration: (a) 75 \( \mu \text{s} \) after SOI; (b) 150 \( \mu \text{s} \) after SOI.

Figures 6 and 7 show the vertical and horizontal spray penetrations for back pressures of 1 bar, 4 bar and 12 bar. The results clearly show the effect of back pressure on spray penetration with higher chamber pressures causing a reduction (up to 50%) in spray penetration due to the increased drag at higher chamber pressures. Details of the vertical penetration as a function of time are shown in Figure 8 for the three back pressures. A similar effect of back pressure on spray penetration can be seen in the horizontal images of the spray in Figure 7. Reduced penetration at high back pressure is an advantage for an injector, since it can prevent spray impingement on the piston crown at late injection when the piston is near TDC.
Figure 6 shows that the spray cone angle remains constant as the back pressure changes from 1 bar to 12 bar with values around $88\pm2^\circ$ which is almost the same as the given nominal cone angle of the injector. Also the location of the larger strings, which can be easily identified in the string structure of the spray, do not change with back pressure. As back pressure increases, the ambient air density also increases causing deceleration of the droplets; as a result, the strings seem to be denser and the gaps between strings less clear, which makes the strings to look cloudier and joined up.

![Figure 6](image1)

**Figure 7** Horizontal images of spray penetration at different back pressures, 200 bar injection pressure and 0.33 ms injection duration: (a) 75 $\mu$s after SOI; (b) 150 $\mu$s after SOI.

![Figure 8](image2)

**Figure 8** Effect of back-pressure on the vertical penetration of the spray.

According to the gradients of the penetration graphs in Figure 8, the vertical spray tip velocity accelerates after leaving the injector nozzle, as the injector needle opens up, and starts to decelerate as it is losing momentum further downstream. Averaged vertical spray tip velocities of 73 m/s, 62 m/s and 46 m/s are estimated by curve fitting of the vertical penetration graphs (Figure 8) in the period between 50 $\mu$s and 150 $\mu$s at back pressures of 1 bar, 4 bar and 12 bar, respectively. From Figure 8, the vertical penetration distance at 150 $\mu$s was found to be 10 mm, 8.5 mm and 6.2 mm for a back
pressure of 1, 4 and 12 bar, respectively; this leads to a maximum reduction of 37% in penetration for an increase of back pressure from 1 to 12 bar. The same reduction can be seen in the average tip velocity.

![Figure 9](image)

**Figure 9** Horizontal images of spray penetration at 100 ms after SOI, atmospheric back-pressure and 0.33 ms injection duration: (a) 200 bar injection pressure; (b) 100 bar injection pressure.

The effect of injection pressure can be seen in Figure 9 where typical spray images at 0.2 ms after SOI for 100 and 200 bar injection pressure are presented. As expected, the main effect is a reduction in spray penetration at the lower injection pressure.

4. Conclusions

The sprays from a high-pressure piezo pintle-type injector have been investigated in a constant volume chamber in order to provide physical understanding and experimental data for validating CFD simulations. The spray has been visualised by a high resolution CCD camera and quantified in terms of droplet velocity and diameter with a two-component phase Doppler anemometry (PDA) system at an injection pressure of 200 bar, back pressures varying from atmospheric to 12 bar and injection duration of 0.33 ms.

Spray visualization illustrated that the spray has a string structure and that the locations of the strings do not change from one injection to the next. The string structure remained the same at elevated back pressures similarly to the overall spray cone angle which presents a significant advantage relative to swirl pressure atomisers. The main effect of back pressure was to reduce the spray tip penetration; the averaged vertical spray tip velocity of 73 m/s under atmospheric back pressure was reduced to 46 m/s when the back pressure was increased to 12 bar which represent a reduction of 37%.

Detailed PDA measurements were carried out under atmospheric conditions with the aid of spray visualization which allowed location of a particular string in the spray cone. The results provided both temporal and spatial velocity and size distributions of the spray droplets at 2.5 and 10 mm from injector exit. Maximum axial mean droplet velocity of 155 m/s was reached at 2.5 mm from the injector which was reduced to 140 m/s at z = 10 mm. The string spacing was determined from PDA measurements to be around 0.375 mm and 0.6 mm at z=2.5 and 10 mm, respectively. The maximum mean droplet diameter was found to be in the core of the strings with values up to 40 μm at z=2.5 mm reducing to 20 μm at z=10 mm. Higher quality data were obtained towards the end of injection where mean droplet diameter of less than 10 μm were measured across the spray.

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