Experimental Investigation of the Effect of High Pressure Nozzle Geometry on Spray Characteristics

C. Jiang[1], J. Hélie[2], M.C. Parker[1], G. Piccini-Leopardi[2],
A. Spencer[1], C. P. Garner[1], G. Wigley[1]
[1]Loughborough University, UK
[2]Continental Automotive, France
*Corresponding author: Jerome.helie@continental-corporation.com

Abstract

Phase Doppler Anemometry (PDA) measurements [1] are applied to low length to diameter ratio (L/D) multi-hole nozzles operating with at high fuel pressure (20 MPa) that are implemented in the new Euro6 generation of Gasoline Direct Injection engines. For these multi-jets spray, the authors intend to demonstrate; the importance of the spray shape, the effect of hole design and the reorganisation dynamic of the drop size distribution by turbulent mixing. To do so, we report significant experimental effort along with careful data reduction, exercised to understand the spray behaviour, in particular separating the sources of experimental uncertainty from the flow physics. A practical methodology is adopted as a compromise between measurement effort, error removal, and the need to understand underlying physical processes within the spray plume. The present work focuses mostly on the drop size and velocity profiles (two-component) perpendicular to the plume direction.

Introduction

With increasing concerns over climate change caused by the greenhouse effect, stringent CO_2 emissions legislation is applied worldwide. In Europe, the new law, effective since 2015, requires that vehicles emit an average of 130 g/km of CO_2 or less. The fleet average CO_2 emission target for 2021 is 95 g/km, which will equate to an average fuel consumption of approximately 4.1 l/100km for gasoline vehicles and imposes significant challenges on automotive manufacturers. Engine downsizing with direct injection is proven to be a viable route to reducing CO_2 emissions in the short term thus it has been adopted by major automotive manufactures in recent years. It has the potential to reduce the CO_2 emissions while not significantly increasing other harmful emissions. Successful operation of this concept requires well controlled fuel spray atomisation and placement, thus it is important that this process is well understood. This includes understanding the design of the injector as well as the influence of in-cylinder conditions on the spray development.

In this study, the authors intended to focus on the effect of nozzle design on the spray, by making PDA measurements of an injector featuring holes of varying geometry. Three different hole design features are reported here; conicity, direction and diameter. In addition, the development of droplet size at the plume centre with distance from the injector tip is studied to understand why an increase in droplet size with distance is identified.

PDA System

The Phase Doppler Anemometry system used in this study is a high power system, developed specifically to make measurements in dense automotive fuel sprays, illustrated in Figure 1. A water-cooled Argon-ion laser is used to generate both blue (488 nm) and green (514 nm) light, allowing two component velocity measurements to be made. The two desired wavelengths of light are first split from the emitted laser beam by a mirror arrangement (1) before passing through a half-wave plate (2) and lens (3) configuration to steer them into the Bragg cell (4). This ensures that plane parallel wave fronts and the beam waists are at the measurement volume location where the four beams intersect. The laser beam expander, lenses (5) and (6), expand and collimate these diverging beams to produce a beam separation of up to 50mm with an expanded beam diameter of 5 mm. A mirror at 45 degrees folds the two pairs of orthogonal beams to a three element front lens (7) and focuses the two collimated and parallel beams to form the diffraction limited measurement volume (8). The receiver optical system (9) was the larger aperture `classic' Dantec 57X10 located at a scattering angle (10) of 70°. The signal processing was performed by the Dantec enhanced 58N50 PDA covariance processor linked to a PC by the 58G130 interface. By changing the focal length, adjusting the beam separation or altering the detection aperture, the resolution and sensitivity of the velocity and diameter measurement could be changed. Further detail of the system configuration can be found in [7].
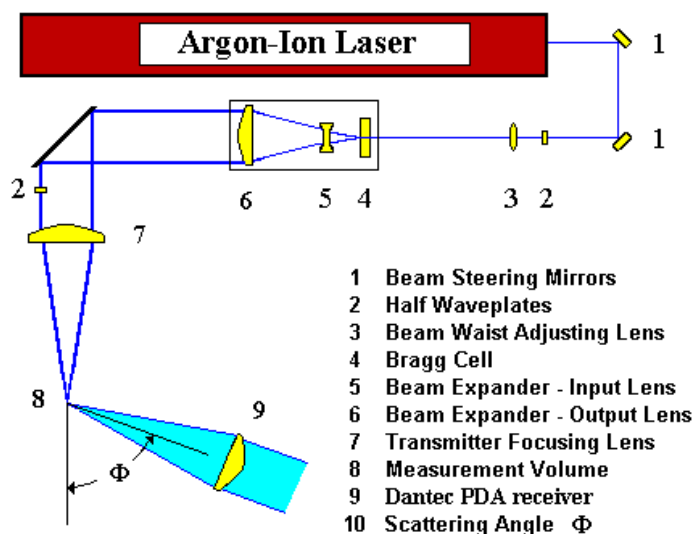
Figure 1: Schematic diagram of the PDA system used at Loughborough University

In order to ensure that high quality PDA data is obtained, the optical system is aligned daily before testing, using an air brush to generate water droplets in the measurement volume. The coincidence of the blue and green measurement volumes as well as the detector focal point is checked and optimised by small lens adjustments to maximise the validation and spherical rates. Usually, both the validation and spherical rates exceed 95% during this process, however in practice the dense spray of a fuel injector limit these. Figure 2 shows examples of the validation rate (note: validation rate and spherical rates for the measurements in our study are very similar, so only validation rate is discussed here) and average data rate for measurements made at different locations indicated in Figure 2. It can be seen, from Figure 2 (a),that as the measurement location moves away from the injector nozzle (as the spray becomes less dense) both the validation rate and average data rate increase due to increased signal strength. This continues until around 50 mm where the data rate is slightly lower than that of 40 mm. This is because the decrease in the number of drops at the plume centre counteracts and outweighs the increase of the signal strength. Figure 2 (b) and (c) exhibit the data rate and validation rate for measurements made across the plume (perpendicular to the plume centreline). Similar trends could be observed on both graphs: (1) Data rate tends to be the highest in the plume centre as there are more drops at this location. (2) Validation rate in the plume centre is the lowest due to the dense spray obscuring optical paths. It should be noted that at 30 mm distance to the nozzle the validation rate is only around 25% in the plume centre. This is very low compared to the result observed for water droplets from the air brush during the system optimisation procedure. The measurement difficulty is caused by the dense spray of the GDI injector. The validation rate for measurements made at 50 mm to the nozzle improves significantly, with a lowest validation rate of 48% obtained in the plume centre.

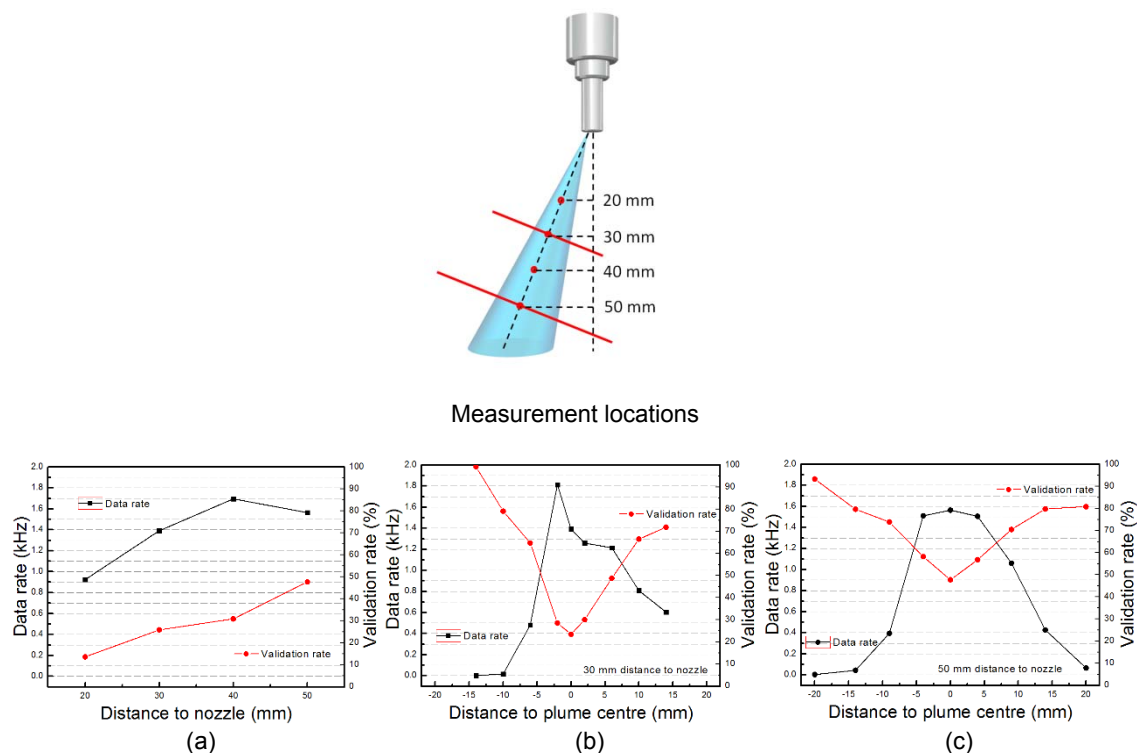Measurement locations

(a) (b) (c)

Figure 2: Data rate and validation rate for PDA measurements in typical spray plume
(a) different vertical distances to the nozzle tip in the plume centre
(b) different distances to the plume centre at 30 mm vertical distance to the nozzle
(c) different distances to the plume centre at 50 mm vertical distance to the nozzle

Tested injectors and operational conditions

The tests reported here were conducted under ambient temperature and pressure conditions and the analysis presented was based only upon data from the 'steady state' part of the spray to remove the complexity of unsteady flow and its potential impact on the results. 99% pure n-Heptane is used as the test fuel and was injected at 20 MPa for a duration of 5 ms. The injector is operated at 2 Hz and data is collected for 60 seconds (120 injections) at each measurement point, corresponding to approximately 10 thousand measurements per point. Other general features of the test method are detailed in [1].. The Table 1 indicates the main features of the holes of the various tested injectors. The hole conicity is defined as the percentage of diameter decrease vs. spray hole length, and positive values therefore relate to convergent flow.

Table 1. List of measured injectors holes

| Tested injector	Conicity	Measured Beta-angle, in degree (definition fig 3)	Hole length over diameter	Fuel	Measurement type
#1	+7	34 (hole direction)	2.03	N-heptane	Figure 3 (a), (b)
#2	0	39 (hole direction)	2.03	N-heptane	Figure 3 (a), (b)
#3	-7	40 (hole direction)	2.03	N-heptane	Figure 3 (a), (b)
#4	0	13.5 (measured)	1.68	N-heptane	Figure 2
#4	0	25 (measured)	1.76	N-heptane	Figure 2
#4	0	26 (measured)	1.90	N-heptane	Figure 2
#5	7	29.5(measured)	2.08	Gasoline RF-02-08	Figure 2
#5	7	30.4(measured)	1.75	Gasoline RF-02-08	Figure 2
#5	7	28.0(measured)	2.54	Gasoline RF-02-08	Figure 2
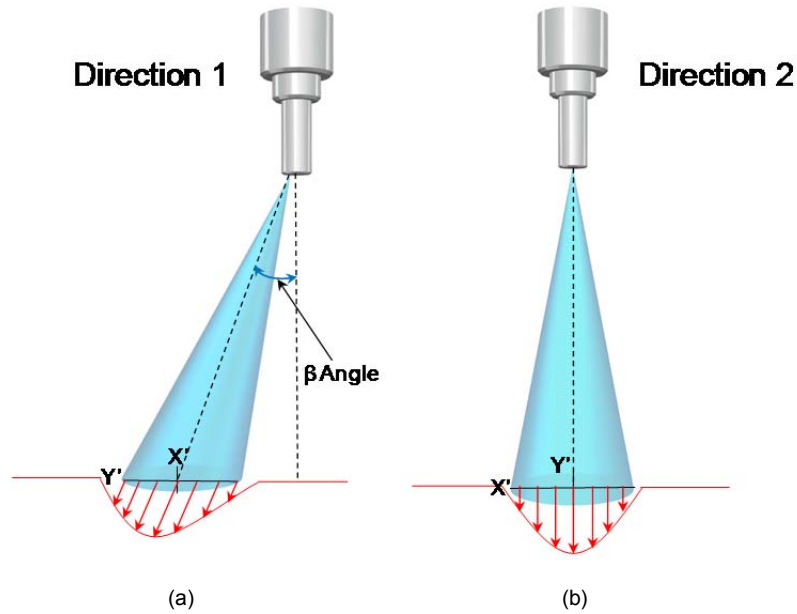
Figure 3. Acquisition profiles

Measurement along the spray centre

As a precursor to the hole geometry investigation, which is the focus of this paper, an investigation of the commonly observed phenomenon of increasing mean droplet diameter with distance from the injector [2, 3, 4] was conducted. An increase in D10 and D32 average number with distance is also found in our case shown in Figure 4. The figure suggests the number of small droplets were found to reduce proportionally to the number of large ones. This trend is usually attributed in the literature to evaporation of smaller fuel droplets leading to an increased weighting towards larger droplets the farther the spray has travelled away from the injector. As this explanation is speculative, a step-by-step investigation was conducted.
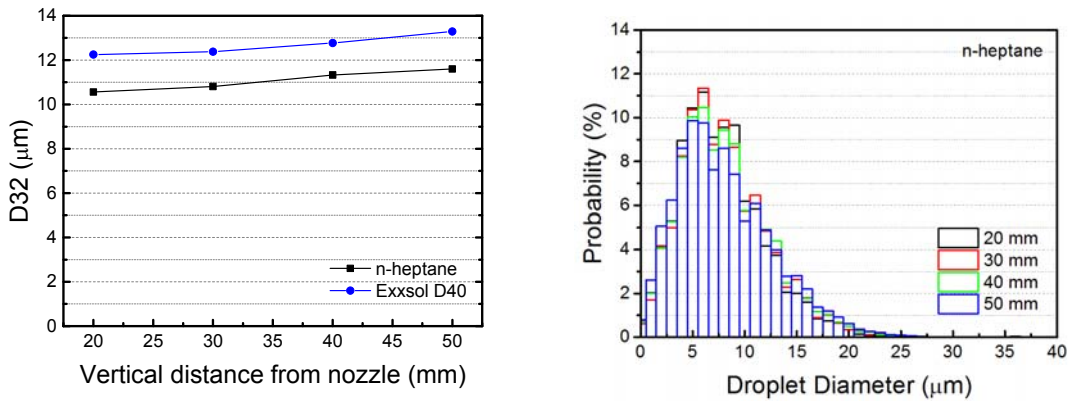

Figure 4. Left: droplet diameter vs. distance from injector nozzle for n-Heptane and Exxsol D40. Right: Histogram of n-heptane and D40 droplet size at different distances.

First the definition of the spray centreline is considered. Typically, the spray centre is measured in space along a geometrically straight line. However, the spray in reality is influenced by jet-to-jet interaction (as found for instance in [5]) producing curved droplet pathlines, therefore the result could be biased because it does not follow a true streamline within the plume. Presently in our work a more appropriate identification of the spray centre position and direction is conducted (presented in the next section). The spray centre is defined here in space by the locus of the maximum velocity along the plume at any axial distance from the injector tip. Results plotted in Figure 4 already utilise this plume centre identification strategy, so this possible explanation for drop size increase is significantly weakened.

Secondly, the error from PDA system itself is considered. As the spray becomes less dense the further it travels from the injector nozzle tip, the measurement of all droplets becomes easier, since there is less optical obscuration within the measurement paths from other passing droplets. At any condition, large droplets within the system measurement range present the easiest PDA measurement, since they return the largest signal level. Therefore in dense sprays it can be possible for the averages recorded to be biased by larger droplets, however the fact that the D32 continues to rise here with distance as the spray density decreases gives strong evidence that there is a genuine increase in the number of large droplets compared to smaller droplets as the distance from the injector is increased.

Thirdly, the hypothesis of unsteadiness is considered. The identification of a quasi-steady phase during spray propagation is necessary for statistical analysis purposes but questionable for scientific reasons. Figure 5 shows the instantaneous measurement of drop size and velocity versus time during a complete injection. The tip arrival is visible with a short change in running average, followed by a "plateau" period – where the drop size and velocity appear statistically stationary, then followed by the plume tail with a continuous decrease of each measured variable. In the case of the SMD, the main results concern the relative probability of capturing small and large drops at a given time. As the plume tail wake entrains a population of small drops after the plateau time range, logically the proportion of small drops will decrease in the main jets, i.e. the average SMD can increase. In terms of measurement methodology, it appears important to clearly identify a plateau range that is not dramatically affected by this dynamic, i.e. ending early.
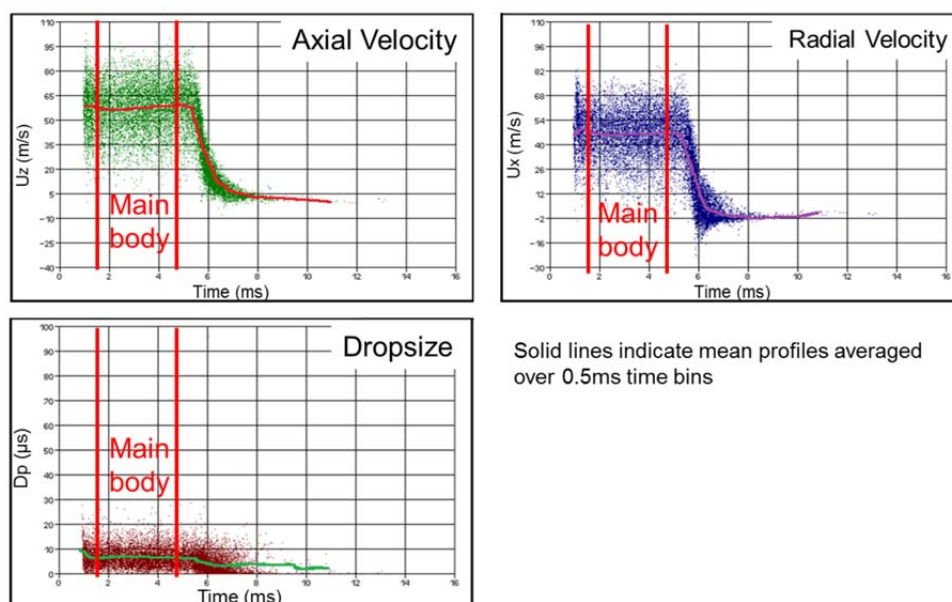

Figure 5 Quasi-steady portion of injection event measurements showing a running average

Fourthly, the evaporation hypothesis was tested by repeating the test with Exxsol D40, to provide a significantly reduced evaporation characteristic of the fuel: with a vapour pressure higher by a factor of around 20. An offset in the drop size level is logically found as shown in Figure 1, as the fluid properties are different. However no difference was found in the SMD evolution, refuting clearly the hypothesis of a dominant evaporation effect on the development of the SMD [6].

Last of all, we propose and examine a different hypothesis based on the effect of preferential turbulent dispersion. In typical sprays, the turbulence intensity, defined for instance by the ratio between the RMS drop velocity to the mean velocity can be high, usually up to 50% at 50 mm [7]. The joint probability distribution function for each droplet's size and velocity perpendicular to the plume direction were plotted for the central location in the plume at 30, 40 and 50 mm distance as given in Figure 6. It indicates that smaller particles have a wide range of plume perpendicular velocity (outwards from the spray centreline) close to the injector, while the largest particles - with greater momentum - continue in a more plume-wise direction with low transverse velocities. The smaller droplets are responding to the turbulent entrained airflow time scales much more readily than the large drops, hence the larger droplet size proportion as the distance from the injector increases.
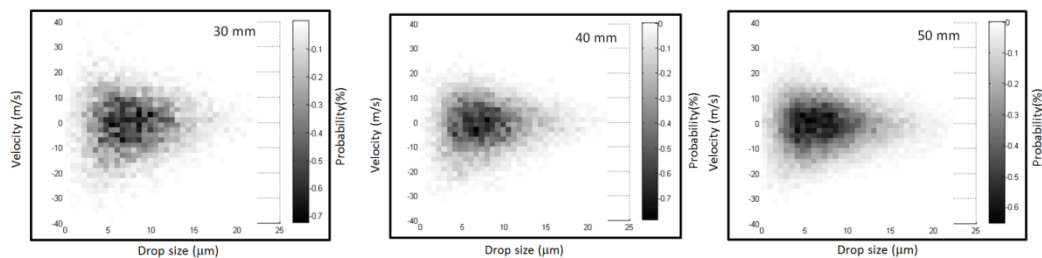
Figure 6. JPDF of Droplet velocity (m/s) vs. Droplet diameter (μm), n-heptane case.

Application to parameters variations

Independently varying the hole design parameters allows a logical investigation of the effect of each on the spray dynamics. In the work presented here, it is applied to of the geometric nozzle variations presented inTable 1, allowing the following aspects to be considered:

1. Hole conicity is varied from divergent to convergent,
2. Hole direction is varied, with angles varied from 20° to 40° relative to the injector axis
3. Hole diameter is varied, until a doubling of the cross sectional area is achieved, at a constant length.

Hole conicity

Example results are given in Figure 7 for hole conicity. One jet is visualised, from a special 3-hole prototype, designed as a compromise between being multi-hole representative, in terms of internal flow, but also avoiding jet-to-jet spray interaction and allowing optical access to each plume. The liquid velocity profile is plotted, as it is a result of the two-way coupling with the surrounding gas. The first defined direction is the axial direction with the main maximum velocity component direction. The second defined direction (1) is radial, perpendicular to the axial direction. The rescaled distance accounts for the cosine(beta) to be comparable to the complementary direction 2. Direction 2 is in the direction tangent to the circumference and perpendicular to the 2 others. The measures are shown at an axial location of 30mm. Three different holes shapes are tested: convergent, divergent, and straight – this last one can be very slightly convergent or divergent, or varying, due to the drilling tolerances by definition.

For all three hole designs, it is demonstrated from the velocity profiles that the spray shape is not round but instead ellipsoidal. The spray is larger in the radial direction 1 and smaller in the pseudo-circumferential direction. Direction 2 is also nominally symmetric. This is not true in direction 1, the case assumed to be the case most affected by the non-symmetric turning induced shear cavitation around the nozzle feed, as already seen for instance in [7]
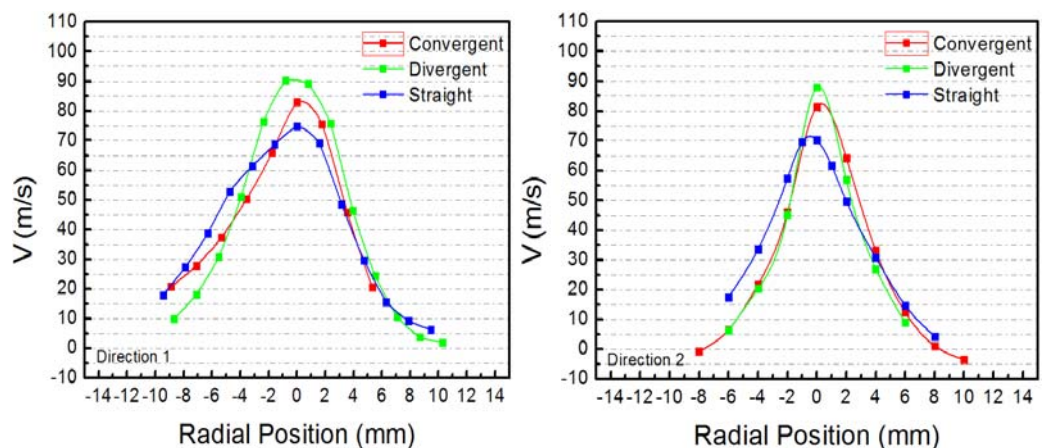

Figure 7. Measures at 30mm distance. Left: along direction 1. Right: along direction 2.

Comparing the conicity, the divergent velocity profile is much narrower with a higher peak velocity in both directions A possible scenario is linked to flow detachment at the nozzle inlet linked to a hydraulic flip: the flow in the hole is then not expanding geometrically but the opposite is realised as a reduction in area because of a pronounced vena-contracta effect linked to the detachment and stabilised by the air backflow from the nozzle exit plane. The straight hole has the widest plume, with the most intense cavitation (indicated by negative radial values) but the convergent holes produce a similar peak velocity magnitude as the divergent holes. In this case

the geometrically reduced cross-sectional area accelerates the flow and inlet separation is heavily suppressed, but also the plume profile appears more dispersed in the radial direction.
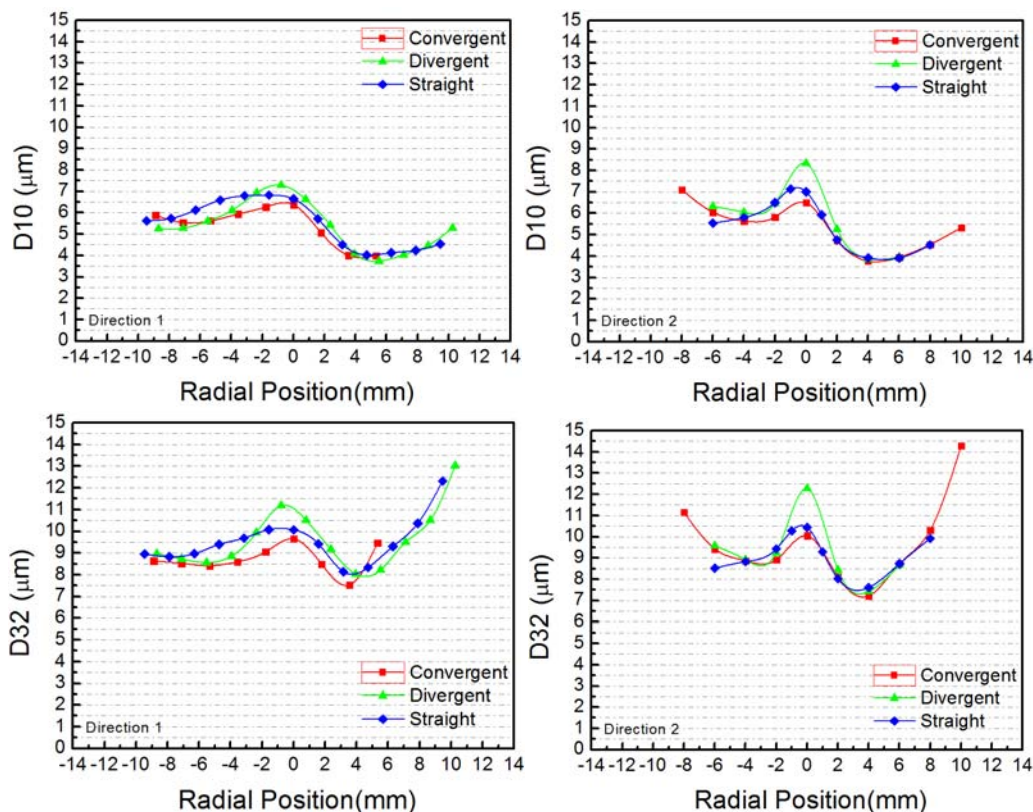

Figure 8. : Measures at 30mm distance. Left: along direction 1. Right: along direction 2.

Effect of the hole direction on the developed spray

Figure 9 shows the PDA measurement methodology: measurement points go through the plume from the longitudinal and transverse directions at 30 mm and 50 mm vertical distance from the nozzle tip. On the right hand side, a picture of the spray plume with the measurement volume, visible as the bright spot within the spray boundary, is shown. This picture is taken via a camera perpendicular to the plume and PDA laser transmitter. It can be seen that the injector is rotated to ensure that the plume is perpendicular to the ground for ease of measurement. The holes are machined at angles of 20°, 30° and 40°, however, the plume direction angles actually measure 13.5°, 25° and 36° (as shown in Figure 10). The arrangement of the three holes means that there is some obscuration of plumes by one another during the PDA measurement which affects the droplet size measurement result. In order to avoid misinterpretation of the result, the analysis is only conducted on the spray velocity field. At a vertical distance of 30 mm, peak average velocities at the plume centre are similar for all plumes (around 80 m/s) At this measurement location, the spray cross section is seen to be ellipsoidal and to differ depending upon the spray beta angle; for small beta angles, the transverse diameter of the plume cross-section is wider than the longitudinal diameter, whereas for larger plume angles, the longitudinal diameter is wider than the transverse diameter. The results clearly exhibit an ellipsoidal spray, with a shape depending on the hole direction.
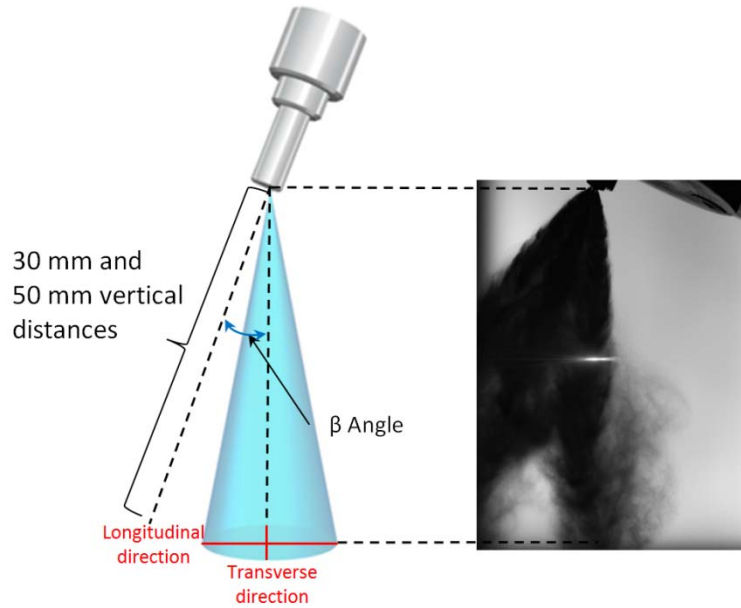
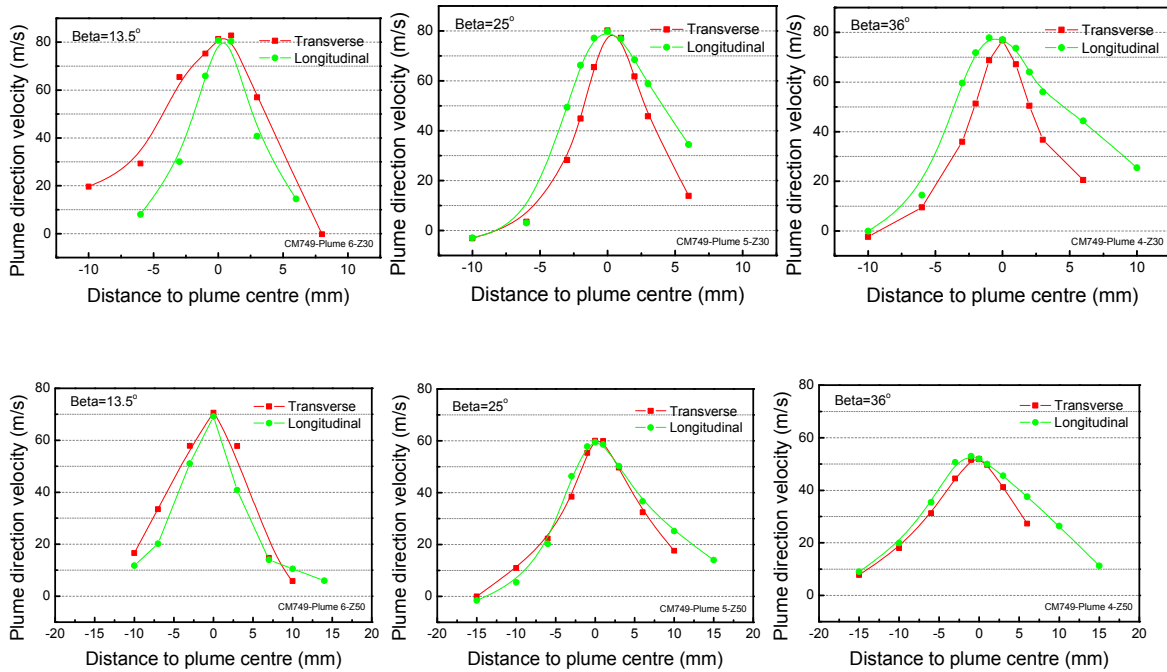**Figure 9:** PDA measurement on a bespoke injector with drilling beta angles of 20°, 30° and 40°

Figure 10. : Measures at 30mm distance (top), 50mm (bottom). Left: along direction 1. Right: along direction 2.

The development of the plume further downstream is now studied using the same profiles plotted at a distance of 50mm. Here the cross-sections of all plumes tend to have become more circular in nature, as an expected result of the turbulent mixing and reorganisation. The peak velocities at the plume centreline differ significantly for each plume as a result of the Beta angle change. The peak velocity decreases with an increase in beta angle, from 70m/s to 50 m/s. The larger beta-angle corresponds to the wider spray plume, this corresponds logically since the there will be strong correlation between drop and momentum diffusion perpendicular to the plume centre line. The two other plumes exhibit similar spray angle (similar spray profile except at the tip).

Effect of the hole diameter on the developed spray

Nozzle length to diameter ratio is one of the most important parameters which affects fuel injector spray characteristics. Figure 11 shows the comparison of droplet diameter and droplet velocity for nozzle holes with different hole diameter under atmospheric backpressure and 30°C ambient temperature at 40 mm vertical distance to the nozzle. By keeping the hole length the same while varying the hole diameter of a three hole injector, different length to diameter ratios are compared. It could be seen from Figure 11 (a) that generally bigger hole diameter (smaller L/D ratio) leads to higher droplet size. This observation is consistent with findings in other

literature [8]. The plume direction velocity profiles does not show a very clear trend between the magnitude of velocity and the hole diameter. However, it seems that the plume width of smaller hole diameter is narrower.
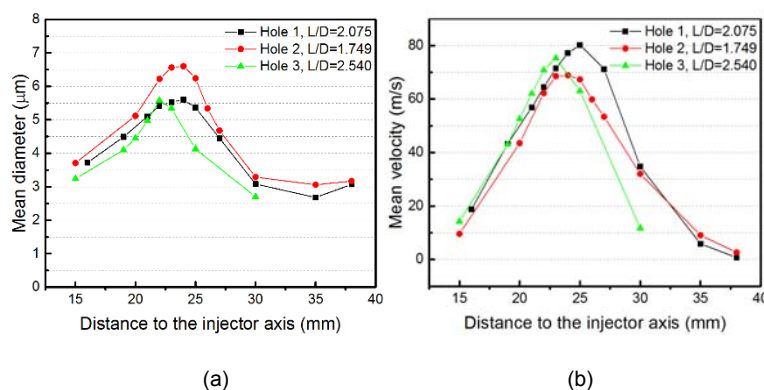

(a)   (b)

Figure 11: Droplet mean diameter (a), mean plume direction velocity (b) for different L/D ratios under atmospheric backpressure

Conclusions

In this study, 2D PDA measurements were performed on several bespoke research injectors, representative of Euro 6 GDI injectors, in order to understand effects of the injector designs (i.e. hole conicity, hole direction, hole diameter). The following conclusions were drawn:

1. The measurement made along the plume centre suggests the increase in the proportion of larger droplets with distance from the injector is due to different levels of turbulent diffusion for different droplet sizes: smaller droplets move away from the plume centre more preferentially through turbulent diffusion.

2. The divergent injector produces the highest spray direction velocity, longest penetration length and largest mean droplet size

3. Overall, the divergent injector design is considered poor for the above factors. It appears that a combination of straight and convergent hole profile would be the optimal injector design

4.   Plumes with larger beta angle tend to be wider.

5. The plume cross-sections for all plumes are ellipsoidal at the early stage of penetration. For different plumes, the aspect ratios are different. However, despite of the difference, the ellipsoidal shapes tend towards circular for all plumes as they penetrate to 50 mm.

6. Larger hole diameter leads to high droplet size and narrower plume under atmospheric conditions.

Nomenclature
PDA   Phase Doppler Anemometry
L/D   Length to Diameter ratio
LDA   Laser Doppler anemometry
GDI   Gasoline Direction Injection
D10   Mean droplet diameter
D32   Sauter Mean Diameter
SMD   Sauter Mean Diameter

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