Impact of Gasoline Direct Injection fuel injector hole geometry on spray characteristics under flash boiling and ambient conditions

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Abstract

The effect of injector nozzle design on the Gasoline Direct Injection (GDI) fuel spray characteristics under atmospheric and flash boiling conditions was investigated using Phase Doppler Anemometry (PDA) measurements. To understand the impact of hole diameter and conicity, experiments were conducted on two bespoke 3-hole injectors in a pressure and temperature controlled constant volume chamber and in the open air. The measurements were taken radially outward from the injector axis to the outer extent of the plume at distances of 15 mm, 25 mm and 40 mm from the injector tip.

Observations of the influence of surrounding gas and temperature conditions and hole design on the injector spray performance were made. Under non-flash boiling conditions, it was found that the injection pressure dictates the length of the spray penetration before collapse occurs, with an increase in pressure resulting in an increase in this length. Comparison of mean velocity and droplet diameter data are also made to understand the performance under flash boiling conditions. Results show that, under flash boiling conditions, the droplet velocity significantly increases while the droplet size reduces. More importantly, it is found that the impact of the flash boiling environment on sprays of different hole geometries is different. Some hole designs offer more resistance against spray collapse. It was found that the mid-sized of the three hole diameters tested here was found to produce a spray that more readily collapsed than that of the smaller or larger hole diameters. In addition, it was found that under flash boiling conditions, the convergent hole had a greater propensity to exhibit spray collapse.

Key words: Phase Doppler Anemometry measurement, Flash boiling, Hole geometry, Spray characteristics, Fuel.

1. Introduction

In recent years, gasoline direct injection (GDI) technology has been widely adopted in spark ignition engines due to its advantages compared to port fuel injection (PFI). It provides the opportunity for faster transients and better cold start response, improved fuel economy and reduced tailpipe emissions [1][2][3]. In order to realise this potential in a GDI engine, understanding and control of the spray characteristics in a complex engine cylinder environment is crucial [4][5][6]. For the fuel to fully mix with air, the injection event of a GDI engine is usually during the intake stroke, where the in-cylinder pressure is sub-atmospheric and the fuel can rapidly reach a temperature of 400 K to 530 K upon injection, [7]. This means that there is a high likelihood of the spray being introduced into an environment that promotes flash boiling. Flash boiling occurs when a liquid is rapidly depressurised sufficiently below its saturation or vapour pressure and becomes superheated, quickly changing state to achieve thermal equilibrium. The saturation pressure of a liquid is a function of its temperature, therefore an increase in the ambient temperature and/or a decrease in the surrounding pressure increases the likelihood of flash boiling occurring when a liquid is injected into a hot and low-pressure environment (e.g. during the intake stroke of internal combustion engine).

The level of fuel superheating during actual operation of a vehicle can be significant. Real gasolines are blends of hundreds of hydrocarbons, with a boiling point range of typically 303-473K, dependent on the exact composition. Kraemer *et al*. [8] computed the occurrence of flash boiling during normalised car testing cycles, based upon representative fuel injection timing, engine cylinder pressure and fuel temperature for a for a mid-range 1360 kg car fitted with a 4 cylinder, 1.4l, 91kW engine. They found that the engine performance was partly influenced by superheating during most of the regulated drive cycles. In the case of the New European Driving Cycle (NEDC) they found an influence on emissions from fuel superheating for 95% of the test duration and, in the case of testing based upon the outline of the, then, forthcoming Real Driving Emissions (RDE) addition to the NEDC, some influence was apparent up to 99% of the test duration.

The occurrence of flash boiling can significantly affect the spray shape and subsequently the performance of a typical automotive multi-hole fuel injector system used in high pressure GDI systems [9][10][11][12][13][14]. An example is given in Figure 1, showing how dramatically an injector's spray morphology is influenced by the conditions of the air region into which it was injected. Some research reports that the smaller droplet breakup and rapid evaporation of fuel undergoing flash boiling would lead to an improved mixing process and a more homogenous air-fuel mixture [13][15][16]. However, it is demonstrated in other studies [10][17] that, when the surrounding pressure and temperature conditions are in the superheated region and far away from the fuel's vapour pressure curve, the multi-jet spray morphology can be significantly influenced by jet-to-jet interaction which can even lead to a full collapse of the jets towards the spray centre, as shown in Figure 1(b). Such a collapse can significantly reduce the spray angle, reducing the usage of available air for mixing and, additionally, can increase the spray penetration, potentially leading to greater levels of piston and combustion chamber wall impingement. Both consequences can potentially generate unacceptably high levels of both particulate and gaseous emissions such as CO and HC. For these reasons, an understanding of the factors affecting the occurrence of spray collapse and its impact under modern Gasoline Direct Injection (GDI) operating conditions is important.

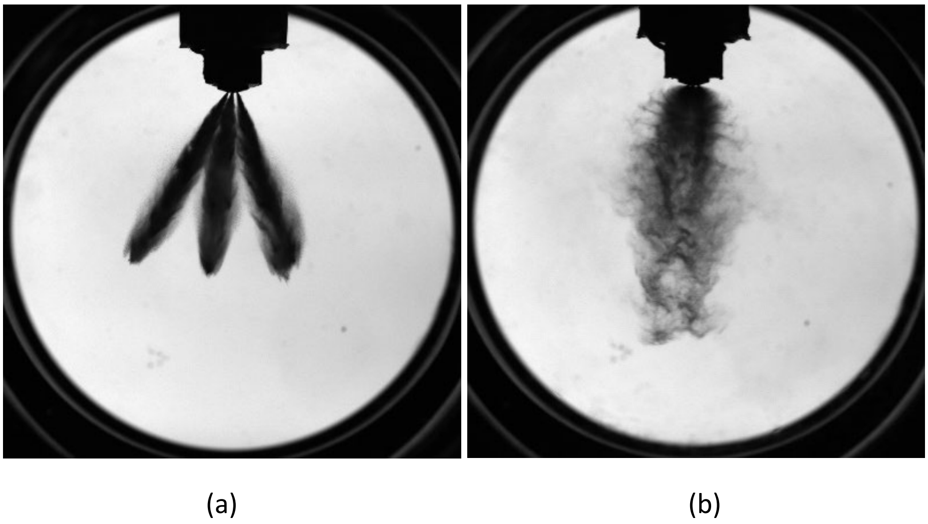


Figure 1 -Spray morphology of a GDI injector at 0.7 ms after start of injection: formed spray (a), collapsed spray under flash boiling condition (b).

The actual process of spray collapse is a complex interaction of a number of factors, such as jet-to-jet proximity, the dynamics of the spray development, air entrainment and vapour release to the surroundings [13][18][19][20]. In addition to the engine operating conditions, the fuel injector design governs many of these processes in part and must be understood and characterised. Previous work has been conducted addressing these issues [21][22][23][24][25] and reported in the literature but there are still many phenomena to be understood. For example, the influence of the fuel injector hole length and diameter, as well as the ratio of the two parameters under flash boiling conditions is still not fully understood. Yildiz *et al.* [26] concluded that there were no measureable effects on the spray from changes in nozzle diameter whilst Vu and Aguilar [27] argued that larger diameters promote a better liquid fuel breakup under flash boiling conditions.

In the case of modelling of flash boiling, additional experimental data is needed to aid understanding of the impact of hole geometry and improve the validity of the simplifications of the phenomenon which are made. Typical models are axisymmetric and based on an extension of two-phase pipe [13][27] or cavitation flows [13] or are semi-empirical [17]; the accuracy of these approaches must be more fully validated. In addition, the simplification of the operating conditions and complexity of the exact fuel composition can affect the model accuracy significantly. Detailed spray measurements close to the injector nozzle exit, under representative operating conditions are therefore required to better understand the flash boiling of fuel sprays and to improve their modelling.

In conclusion, the flash boiling and spray collapse phenomenon of the spray should be better understood due to their importance to GDI engine performance and emissions. In recent years, a significant amount of research has been conducted in order to understand the impact of flash boiling on spray characteristics [9–12,14,28–42]. However, the impact of injector design under flash boiling conditions has been rarely addressed. Therefore, the focus of this paper is on understanding whether geometrical features of the hole design impact the spray behaviour similarly under both atmospheric and flash boiling conditions. The flash boiling phenomenon is investigated using Phase Doppler Anemometry (PDA) measurement on the spray in open air as well as in a pressure vessel, where the initial surrounding environmental conditions can be controlled.

2. Instrumentation and Test Methodology

In this study, Phase Doppler Anemometry (PDA) is used to understand the microscopic spray behaviour of different fuel injector hole features under both atmospheric and flash boiling conditions. This section introduces the PDA measurement technique, the spray characterisation rig, the fuel injector used and the test methodology.

2.1 The Phase Doppler Anemometry technique

The PDA technique is a laser based diagnostic method that provides point measurements of droplet size and velocity in a spray[43]. The system used in this study was a two-velocity component, high power system, developed specifically during previous research to capture measurements in dense automotive fuel sprays, where light obscuration is high. The system layout is illustrated in Figure 2 and described in detail in [44] and [45]. An upgraded signal processor was used here compared to the aforementioned references, since the injection pressure in this study, coupled with the sub-atmospheric back pressure, resulted in peak spray velocities exceeding the measurement range of the previous Dantec 58N50 processor. The Dantec P80 processor was therefore used in preference, with a frequency of 90 MHz as opposed to 45 MHz of the previous system, in turn increasing the vertical direction velocity range upper limit from 108 ms^{-1} to 294 ms^{-1}. Despite the improved signal processing hardware, the data rates experienced could still be low and this necessitated the capture of 120 injection events in order to ensure a sufficient number of fuel droplets were measured to obtain statistically robust validated data.

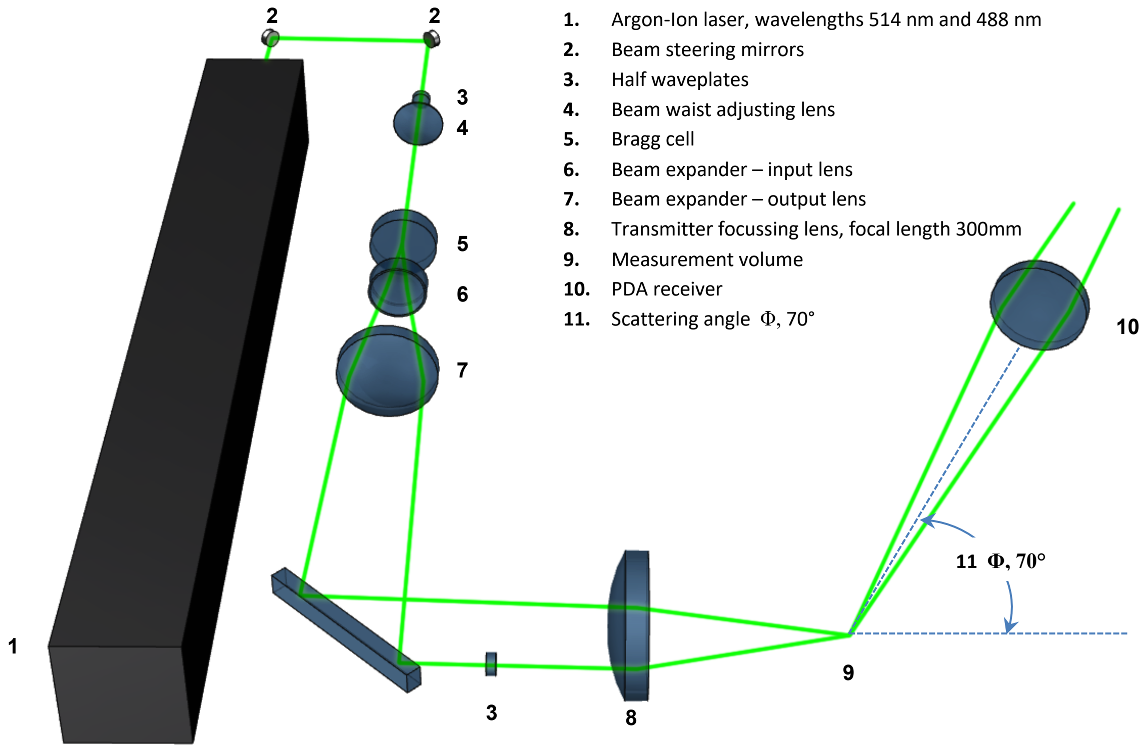


Figure 2 - Schematic diagram of the PDA system used..

Measurements were made along transverse axes at three positions, located at different distances along an axis parallel to the injector's vertical axis, as illustrated in Figure 3(a), these are indicated as red lines across the plume. Measurements made at 15 mm and 25 mm were carried out in the pressure cell under temperature and pressure-controlled conditions; these locations were largely driven by the space restrictions of the pressure vessel in which the measurements were made. At atmospheric back pressure, the droplet velocity was slower but the spray denser than at sub-atmospheric conditions and thus light obscuration from the plume was greater. Because of the level of obscuration, the measurements in atmospheric conditions were therefore made at 40 mm distance from the injector tip, where the spray density was reduced, thus ensuring the quality of the data captured was high. The impact of measurement distance from injector tip on the data quality is discussed more fully in Jiang *et al.* [46], whilst more details of the test configuration will be discussed later in this paper. Once obtained, PDA droplet data was analysed using an in-house Matlab code, producing results of the type illustrated in Figure 3(b), where an example of droplet velocity versus time is shown. The analysis region was chosen to be solely in the steady state period of an injection to exclude the impact of the transients at the start and end of the injection event. This duration is more important because most liquid mass is injected in this period. This method can also avoid the bias towards the unsteady injection period caused by lower PDA data collection rates during the main spray period than the PDA data collection rate in the opening and closing period, where lower spray density increases the data validation fraction. The procedure has been explained into detail in many former publications [47–49] using the same setup and former generation of GDI injectors.

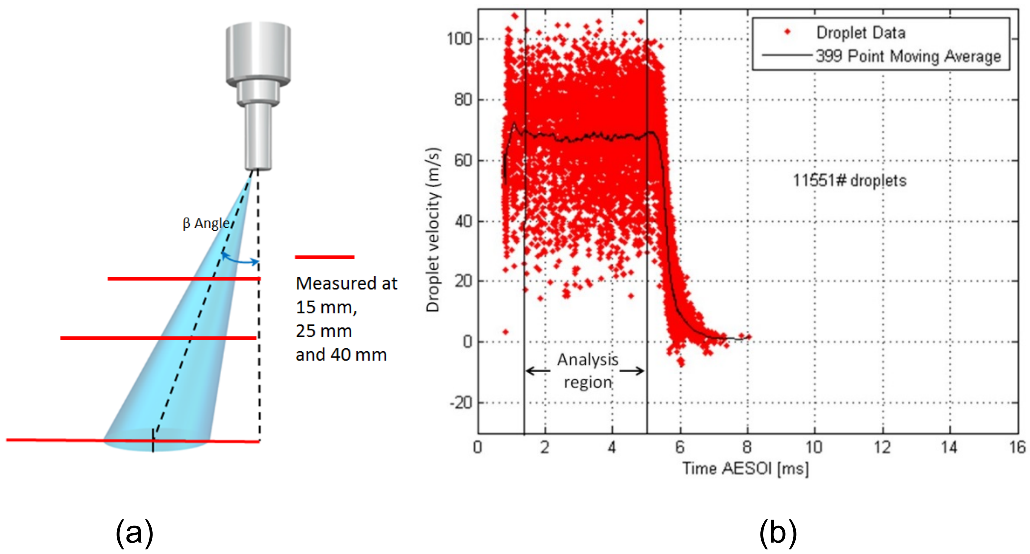


Figure 3 –PDA measurement locations (a) and typical drop velocity time history (b).

2.2 Test Conditions and Injector Configuration

This investigation was conducted using two bespoke research GDI fuel injectors; one with divergent and one with convergent holes, both of which have been the subject of simulation studies, previously reported [50]. Each injector featured three holes circumferentially spaced by 120° about the injector's central axis (see Figure 4). This arrangement of three holes was specifically intended to tailor the injector for optical measurement, by allowing sufficient isolation of plumes for the delivery of laser illumination and imaging. Having fewer injection holes also helped reduce the potential influence of plume-to-plume interaction, minimising the change in an individual injector hole performance under flash boiling conditions. The convergence or divergence of the injector holes tested was quantified by the term Conicity Factor, CF. This term is derived from the hole inlet diameter at the injector sac volume D_i, the hole outlet diameter at the engine cylinder volume, D_a and the hole length, l, as illustrated in Figure 4 and defined as Equation 1.

$$CF = \frac{100(D_i - D_a)}{l}$$ **Equation 1**

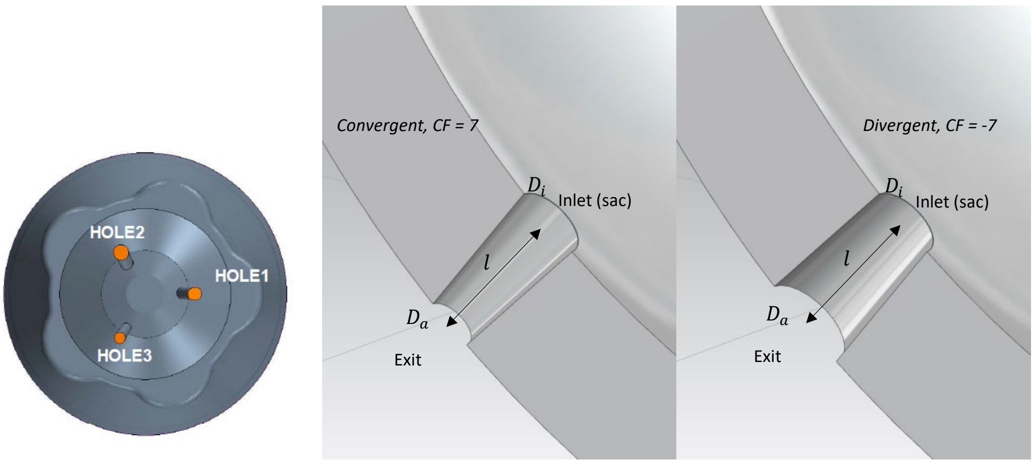


Figure 4 – The bespoke 3 hole research fuel injector used during the tests reported here (left) and an illustration of convergent and divergent holes (right).

A summary of the injector features and other test configurations are presented later in Table 1. The injectors were tested on Loughborough University's spray characterisation rig, which allowed the PDA technique to be applied to the fuel spray. The injectors were configured to spray into an aluminium pressure vessel whose initial temperature and internal pressure were controlled to simulate various engine operating conditions. Quartz windows for optical access allow PDA to be performed on the spray within this vessel. The pressure vessel was controlled by a National Instruments USB controller and its pressure set to the desired level between a nominal vacuum and 1 MPa, either by introducing pressurised nitrogen to raise the pressure or using a vacuum pump to reduce the pressure below the atmospheric level.

2.3 Test fuel

Euro 5 reference gasoline RF-02-08 was used for the tests reported here, which has the evaporation characteristic plotted as a black solid line in Figure 5. The shaded regions illustrate the movement of the evaporation curve when the backpressure increases or decreases. In this study, the back pressure is always equal to or less than 101 kPa so the evaporation line will always be moving within the upper (red) region above the black plotted line.

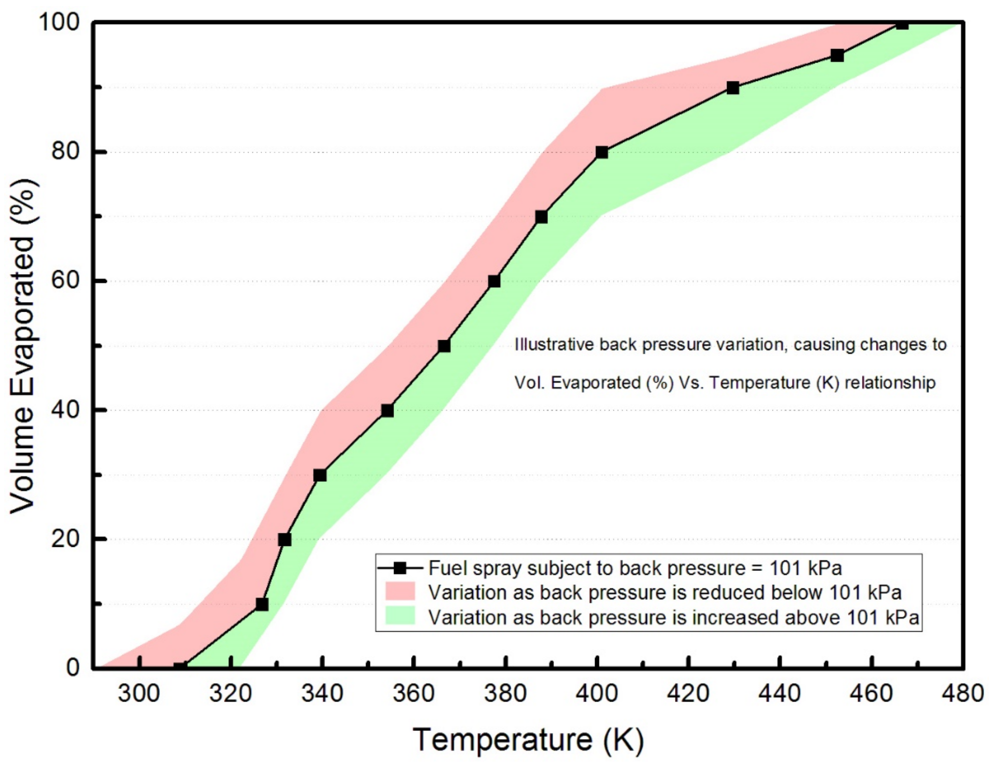


Figure 5 – The evaporation characteristic of RF-02-08 Euro 5 reference gasoline.

2.4 Test configuration

The results presented in this work span a range of ambient temperature and pressures, along with injector geometrical variations, to investigate the droplet size distribution and velocity behaviour under both ambient laboratory conditions as well as pressure and temperature-controlled conditions, which were set to promote flash boiling. Results are taken at a baseline condition of 20 MPa injection pressure, 100 kPa abs back pressure and 298 K cell temperature for three holes of various L/D ratios and both converging and diverging hole conicities. Results in which temperature, injection pressure, back pressure, hole conicity and L/D ratio were varied are then presented, primarily at flash boiling conditions, to compare with the baseline data and allow the influence of these parameters to be compared. The testing reported in this paper was conducted in one of two test configurations; the parameters consistent across both configurations are detailed in Table 1 and those which differed are listed in Table 2.

Table 1 – Common test configuration parameters.

Parameter	Value
Fuel type	Euro 5 Reference Gasoline RF-02-08
Injection pulse width	5 ms
Injection frequency	2 Hz
Number of injections measured	120
Convergent hole CF	7
Divergent hole CF	-7
Hole length/diameter ratios	2.5, 2.1 and 1.75

Table 2 – Test configuration parameters varied across the testing programme.

Parameter	Configuration A	Configuration B
Air temperature	Ambient (~298 K)	~363 K
Back pressure	Atmospheric (~101 kPA)	30, 50 and 100 kPa,
Injection pressure	20 MPa	10 and/or 20 MPa
Fuel temperature	~303 K	~363 K
PDA measurement vertical distance from injector tip	40 mm	15 and/or 25 mm

In each test presented in the results section, PDA measurements were made at a number of locations across the width of the spray plume and were taken from a steady-state portion of the injection event, when the mass flow rate exiting the nozzle is approximately constant.

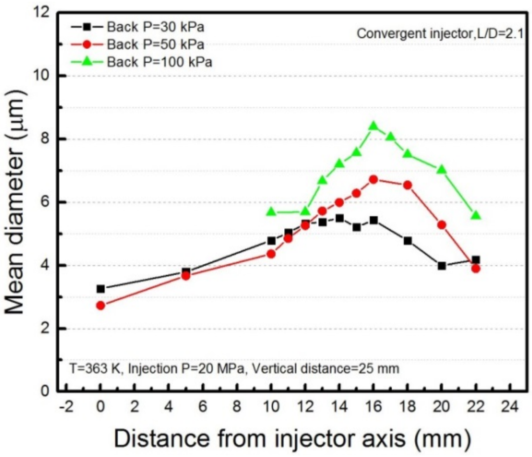
3. Results and discussion

This section presents and describes the droplet size and velocity measurements gathered during testing. The results illustrate investigations into the influence of injector design features and operational parameters upon the spray characteristics produced by a GDI injector. The effect of back pressure on the structure of the injector spray is first reported, which helped define the environmental conditions used in the rest of the study. Following this first section, the effects of several injector design parameters upon spray deformation are considered; hole diameter, conicity and injection pressure.

3.1 The Influence of Back Pressure on Injector Spray Deformation

The flash boiling point of the RF-02-08 Euro 5 reference gasoline used in this study can be estimated by considering the relationship between fuel volume evaporated and temperature, presented previously in Figure 5. The real-world behaviour of a fuel spray, however, is highly dynamic, such that the conditions leading to spray collapse in an engine cannot be entirely predicted based upon the theoretical evaporation characteristics. This study aimed to experimentally investigate the fuel spray behaviour under simulated engine conditions to provide additional understanding and validation data for computer-based modelling tools.

The test was setup with the base configuration as detailed in Table 1 and with the additional specific configuration B of Table 2. Results for the convergent 2.1 L/D ratio hole injecting into a range of back pressures (30, 50 and 100 kPa) at 90°C ambient temperature are presented in Figure 6. Measurements of mean droplet diameter and both horizontal and vertical components of the droplet velocity taken across the fuel plume width are also presented in Figure 6. The plots indicate that a reduction in applied back pressure brought about a reduction in mean droplet size and an increase in both components of mean droplet velocity. The peak velocity magnitude for the 100 kPa, 50 kPa and 30 kPa cases were 96 ms^{-1}, 126 ms^{-1} and 153 ms^{-1} respectively. This increase in velocity is to be expected because of the accompanying decrease in the air density which comes from the reduction in the applied back pressure but the flash boiling itself could also potentially contribute [51][48]. The increase of droplet velocity increases the Weber number of the spray, resulting in the observed greater level of breakup leading to a smaller droplet size, e.g. reducing from 8 to 5 µm at the distance of 16mm from the injector tip as the back pressure is reduced from 100 kPa to 30 kPa.



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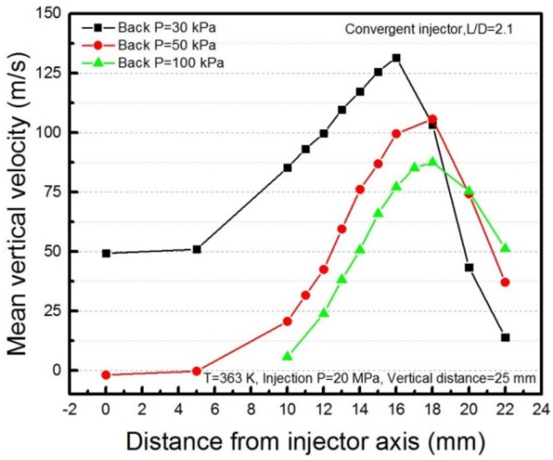

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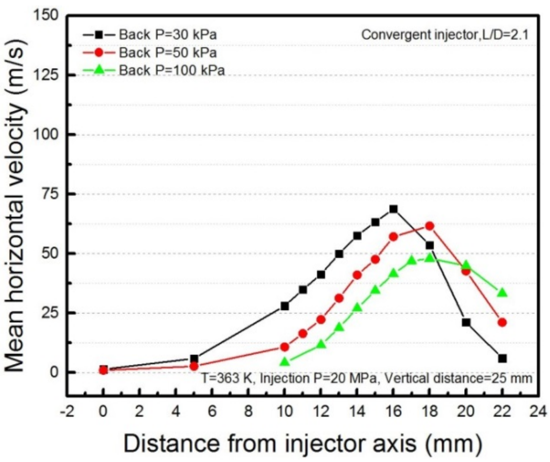


(c)

Figure 6 - Droplet mean diameter (a), mean vertical velocity (b) and mean horizontal velocity (c) for spray at 90°C temperature and subject to different back pressures. The measurements are made at 25 mm from the injector tip.

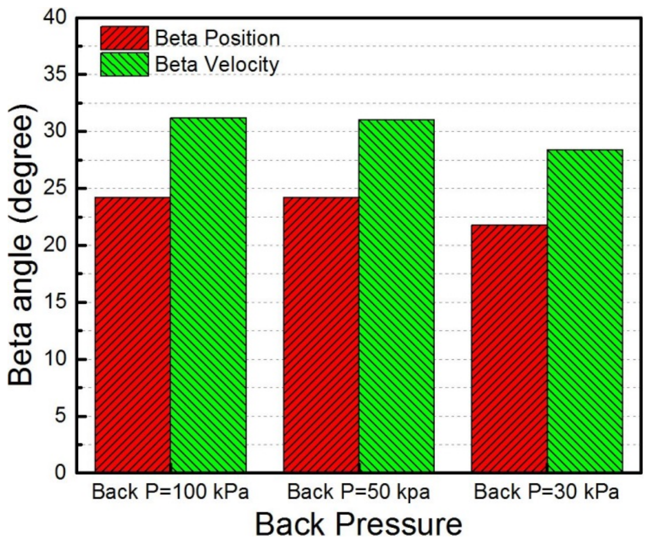


Figure 7 – Angle from the velocity peak position (beta_position) and from the peak velocity direction (beta_velocity) extracted from Figure 6.

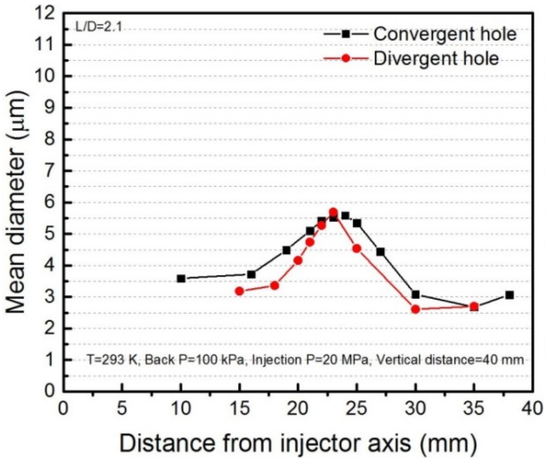
The plume-direction (vertical) average velocity profile across the plume is closely linked with the shape of the plume. Shown in Figure 6b, the peak velocity on the velocity profile is taken to represent the centre location of the plume. As the measurement point of the PDA system moves out of the plume centre to either side of the plume, the average velocity decreases. If the velocity becomes zero, it is thought the measurement point is at or near the boundary of the plume. Thus, the centre and the width of the plume can be extracted from these average plume direction velocity profiles. The velocity profiles in Figure 6 show that the location of both the highest horizontal and vertical velocity components move towards the injector axis as the applied back pressure was decreased, indicating that the spray plume was also deformed towards the injector axis. This is confirmed in Figure 7, where the most significant change in angle per unit back pressure can be seen to have been between 50 kPa and 30 kPa. Additionally, a significantly higher level of vertical velocity is apparent within 10 mm of the injector axis in the 30 kPa case, which also suggests that this case experienced the most significant level of flash boiling. A significantly higher level of vertical velocity is apparent at the 30 kPa (lowest) back pressure case in comparison to the other plots, which would suggest that spray collapse is only apparent at the 30 kPa back pressure and 363 K temperature condition.

In response to the initial observations presented in this section, the remainder of this paper will investigate GDI fuel sprays at both the 30 kPa back pressure, 363 K condition, that are found to lead to significant spray collapse at 20 MPa injection pressure, and also under ambient conditions (293 K temperature, 100 kPa back pressure) where no collapse is seen. Features of injector hole design as well as the injection pressure will be studied by making measurements to understand the impact of the injector configuration on spray behaviour under atmospheric and flash boiling conditions.

3.2 Impact of hole conicity on spray characteristics

It has previously been reported that hole conicity affects the droplet size and velocity distributions measured in a GDI fuel spray, as well as the spray plume width [46]. Since, as with all manufactured parts, the hole is produced within a tolerance, it is important to understand the potential impact of the conicity levels that might arise in manufacture across a range of operating conditions. The test was configured as per the base configuration in Table 1 and with results were gathered under both the configurations of Table 2.

Figure 8(a) compares the mean average droplet diameter across the spray plume for both the convergent and divergent hole profiles under atmospheric conditions, where the divergent hole profile produced the smallest droplet size except for at the centre of the plume, where the droplet size from each hole was comparable. The velocity profiles of the spray, also presented in Figure 8 suggest that the plume of the divergent hole was narrower than the convergent profile hole (Figure 8(b)) and that there was a difference in the angles of the plumes from each injector, indicated by the difference in peak location in Figure 8(c). In addition, the divergent hole produced a higher peak velocity in both measurement directions. It might be expected that the convergent hole would produce the highest exit velocity due to the flow acceleration caused by the area reduction of the hole, so the divergent hole velocity result is unexpected. A possible explanation for this observation is that divergent hole flow was influenced by flow detachment at the nozzle inlet whereby the flow area was not expanding with the geometrical expansion of the hole, but rather a pronounced venacontracta effect, stabilised by the air backflow from the nozzle exit plane, caused the mixed fuel-air flow to accelerate and stay separated from the wall of the nozzle.



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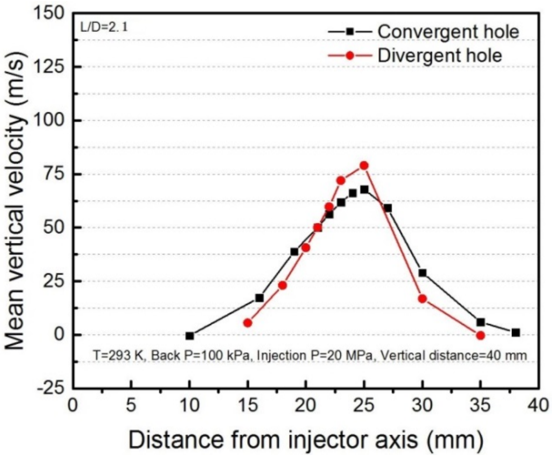

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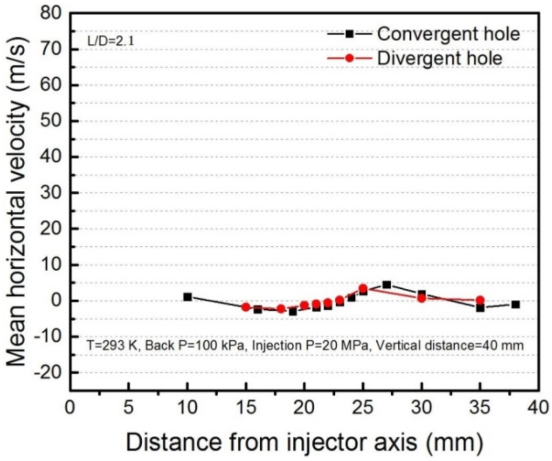
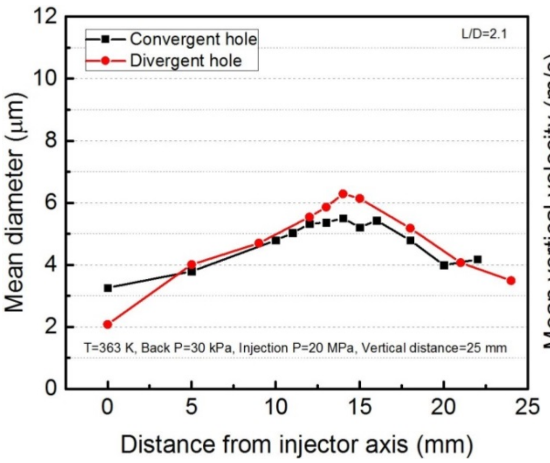


(c)

Figure 8 - Droplet mean diameter (a), mean vertical velocity (b) and mean horizontal velocity for spray under ambient temperature and pressure measured at 40 mm from the injector tip

In contrast to the previous figure, Figure 9 shows the droplet diameter and velocity characteristics measured for the two hole profiles under flash boiling as opposed to atmospheric conditions. When considering the results presented in Figure 9(a), it can be seen that the droplet size measured for the divergent hole case was larger than for the convergent hole. This observation under flash boiling conditions (30 kPa back pressure, 363 K ambient temperature, 20 MPa injection pressure) presented here is opposite to that for the atmospheric condition, where the droplet size of the divergent hole was generally smaller than the convergent hole. This change in droplet size distribution can likely be attributed to the different hole geometry's resistance to flash boiling, which can be seen to be different. The velocity data under flash boiling conditions clearly indicates this; it can be seen in frames (b) and (c) of Figure 9 that there was a significant difference between the velocity profiles for each hole conicity between 0 mm and 12 mm across the spray; the magnitude of this discrepancy and the fact that it would not be expected to see a significant velocity in the region between 0 mm and 5 mm indicates that there had been collapse of the spray in the case of the convergent hole. The presence of a significant number of droplets in the 0 mm to 5mm region, which allowed the recorded velocity signals to be captured, were brought about by collapse of the spray due to the falling pressure as the flow accelerated through the converging hole to conserve mass flow. Conversely, the pressure recovery experienced by the decelerating flow in the divergent hole helped to prevent the spray from collapsing. The collapse of the spray of the convergent hole led to a significant reduction of the droplet size, thus a lower average droplet size is observed.



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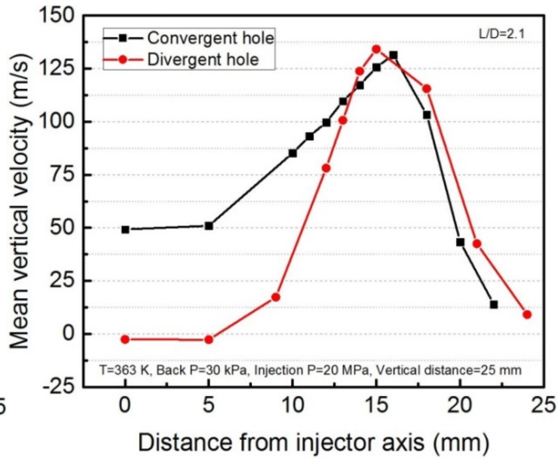

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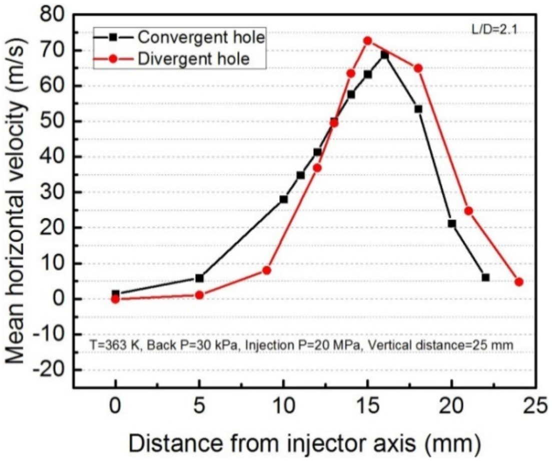
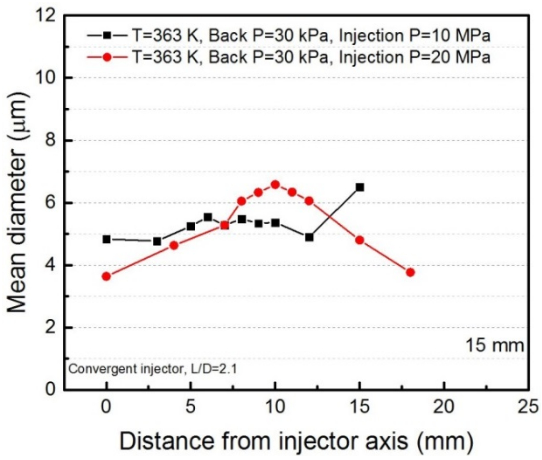


(c)

Figure 9 - Droplet mean diameter (a), mean vertical velocity (b) and mean horizontal velocity for spray under flash boiling conditions measured at 25 mm from the injector tip

3.3 Impact of injection pressure on spray characteristics at different distances

Increasing injection pressure is typically seen as a means of reducing the fuel droplet size in the spray event [52] and a fundamental understanding of the spray that arises at different injection pressures is therefore extremely significant. To this end, an investigation was conducted during this work to study the impact of the injection pressure on spray breakup under flash boiling conditions. The test was configured as per the base configuration in Table 1 and with configuration B of Table 2. Figure 10 and Figure 11 present the PDA measurements made at the two test fuel injection pressures (10 MPa and 20 MPa) and two vertical distances from the injector nozzle tip (15 and 25 mm respectively) under flash boiling conditions of 363 K temperature and 30 kPa back pressure. Figure 10(a) shows that at 15 mm vertical height the average droplet diameter for 20 MPa injection pressure was actually generally higher than that of the 10 MPa injection pressure test. However, Figure 11(a) illustrates the trend changing at 25 mm, such that the droplet diameter during the 20 MPa injection pressure test was lower than that of 10 MPa injection pressure test. The switch between the higher pressure case having the larger droplet size at 15 mm and the smaller at 25 mm was due to differing distances at which the spray started to collapse. Evidence could be seen from Figure 10 (b), which the average velocity for 10 MPa plume at the injector axis is around 50 m/s whereas the average velocity for 20 MPa plume at the injector axis is only 10m/s. This means that the spray plume for 10 MPa case has already collapsed whereas the spray plume for 20 MPa has not at a vertical distance of 15 mm. Thus average droplet size for the 10MPa case is smaller although its injection pressure is lower due to the impact of spray collapse (higher evaporation) on it.



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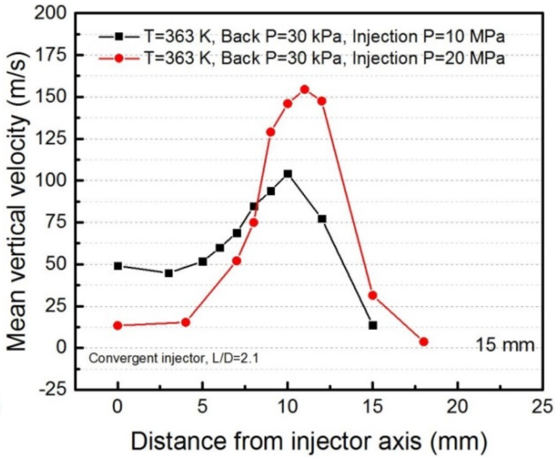

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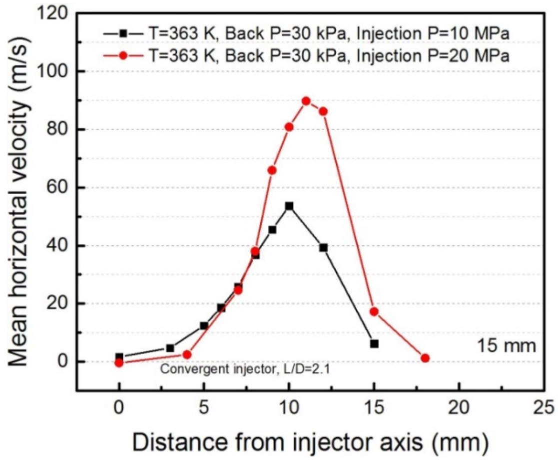

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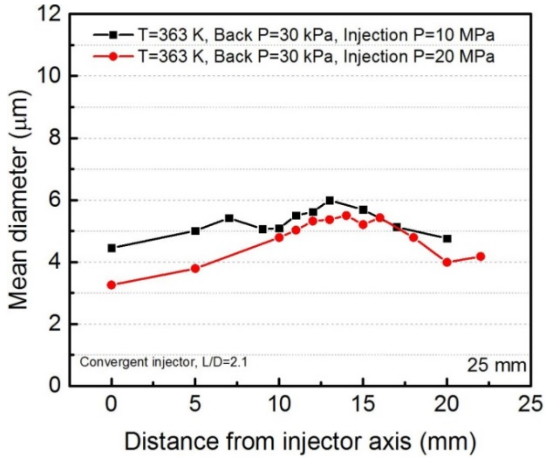
Figure 10 - Spray characteristics of convergent injector measured at a distance of 15 mm



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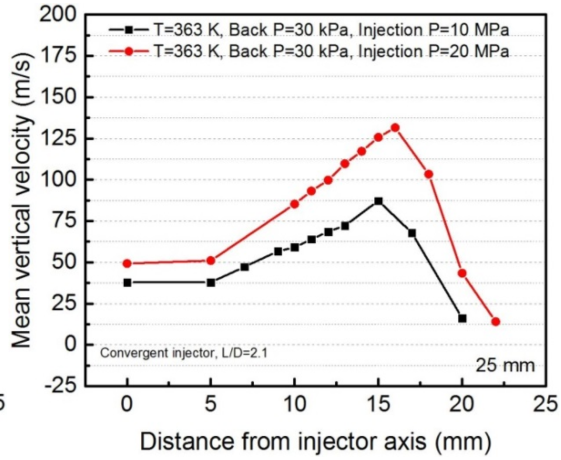

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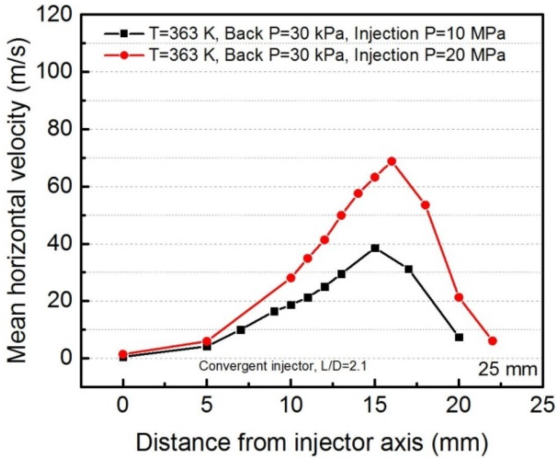


(c)

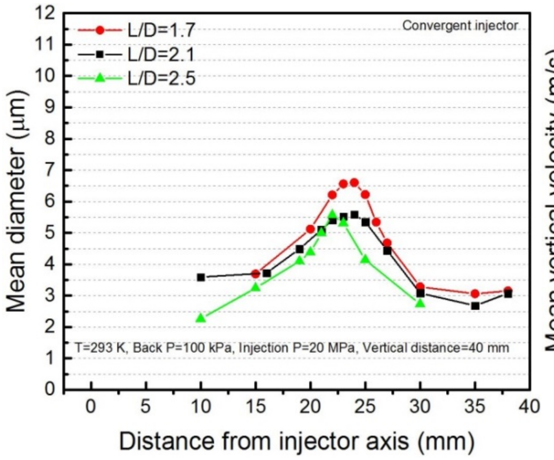
Figure 11 - Spray characteristics of convergent injector measured at a distance of 25 mm

The profile of velocity in the vertical direction taken across the spray is a good indicator of the spray plume shape, as the peripheral measurements of velocity indicate the outer most presence of fuel droplets (necessary to produce a measurement), whilst the velocity peak indicates the plume centre position. From Figure 10(b) it is apparent at a distance of 15 mm from the injector that the 20 MPa injection pressure case has shown less sign of spray collapse as the velocity in the region near to the injector central axis is close to zero. At this same location, the 10 MPa injection pressure case demonstrated distinct signs of spray collapse as there was a significant vertical velocity measured in the region between 0 and 5 mm of Figure 10(b), indicating an inward collapse of the spray. Collapse of the spray for the 10 MPa case led to better break-up of its fuel droplets, thus a lower mean diameter which was seen at 15 mm distance compared to the 20 MPa case. At 25 mm from the tip of the injector nozzle, spray collapse can be observed for both injection pressures (Figure 11(b) and (c)), with there being significant velocity levels in the region of 0 to 5mm for both cases. The plume shapes for the two injection pressures tested can also be seen to be similar, although their magnitude was different. When both sprays entered the region of collapsed spray, the higher injection pressure (20 MPa) was found to result in a smaller mean droplet diameter. Also, at 25 mm vertical distance (during spray collapse) the peak plume direction velocity of the 20 MPa injection pressure case was reduced in comparison to the formed spray at 15 mm, although it did remain greater than the 10 MPa injection pressure case.

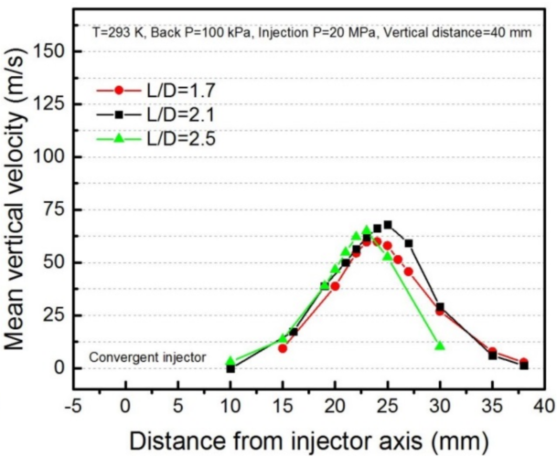
3.4 The influence of hole diameter on injector spray characteristics

The hole diameter of GDI injector is a very important geometrical parameter which significantly affects the spray characteristics (e.g. droplet size, fuel flow rate) and there is a requirement for additional insight and understanding of the relationship between the hole size and the resultant spray, in order to support both modelling and design processes. Three different hole diameters were investigated in this study, using an injector with holes of converging cross-sectional area, under both atmospheric and flash boiling backpressure conditions. The study was configured as the general setup listed in Table 1 and the specific configuration A of Table 2 for the atmospheric tests and configuration B for the flash boiling tests. PDA measurements were again gathered across the spray plumes, capturing droplet size and velocity information.

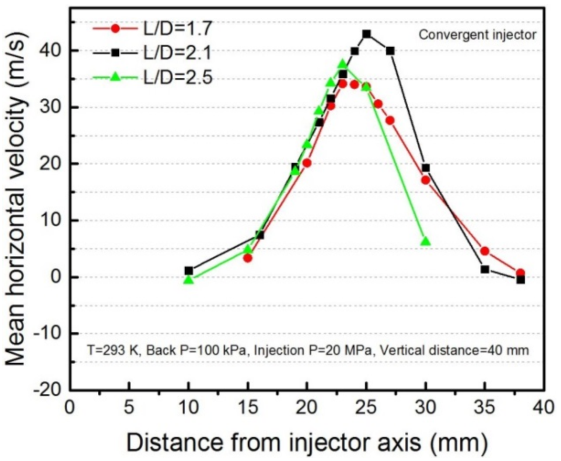
The processed PDA results from the investigation are presented in Figure 12, showing the mean droplet diameter and mean velocities at 40 mm vertical distance from the nozzle in the vertical direction across the spray plumes of the three injector holes under atmospheric backpressure, 293 K air temperature. It is apparent that under atmospheric conditions a smaller length to diameter ratio (larger hole diameter) led to a higher mean droplet size. This observation is consistent with findings in the literature [53].



(a)



(b)

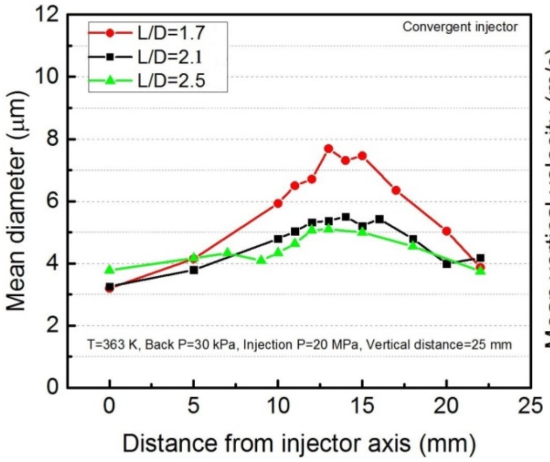


(c)

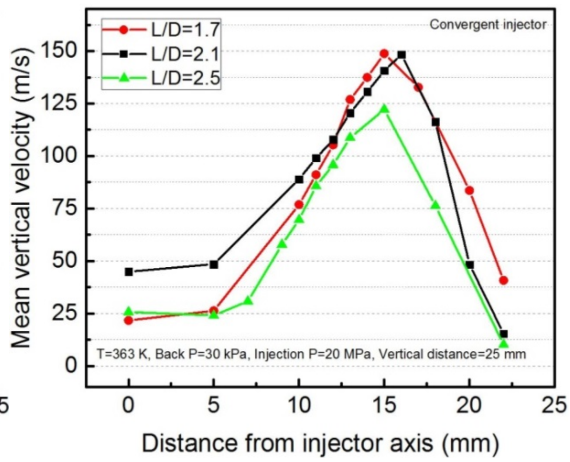
Figure 12 - Droplet mean diameter (a), mean vertical velocity (b) and mean horizontal velocity for spray under ambient temperature and pressure measured at 40 mm from injector tip

Figure 13 shows the spray measurements made across the spray plumes under flash boiling conditions, at a distance of 25 mm from the injector tip. The PDA measurements were made at this position closer to the injector nozzle tip during this test because of the restrictions of the pressure cell used to seal the spray environment. Under the flash boiling conditions, it can be seen from this data that a larger hole diameter again led to a larger average droplet diameter, as observed at ambient conditions in Figure 12.

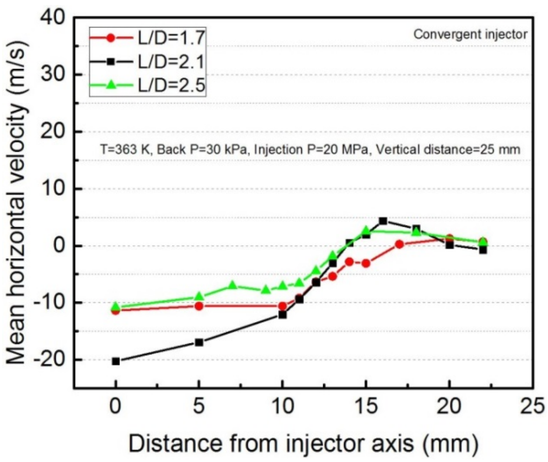
It can be seen that from Figure 13 (b) and (c) that all three sprays experienced flash boiling and spray collapse at the measurement location 25 mm downstream of the injector tip, evident from the marked deviation in the vertical velocity signals measured at the spray fringes (between 0 and 5 mm). The L/D ratio of 2 exhibited a velocity that is markedly greater than for the other two conditions between 0 to approximately 5 mm distance across the spray region. This might tend to suggest a non-linear relationship between hole L/D ratio and resistance to spray collapse and that the optimum for resistance to collapse for this fuel, injection pressure and set of ambient conditions might lie within the tested range. Likewise, the magnitude of the horizontal velocity component between 0 and 5 mm was greatest for the 2.1 L/D case, indicating this was the region of the most significant inward motion of droplets towards the injector axis.



(a)



(b)



(c)

Figure 13 - Droplet mean diameter (a), mean vertical velocity (b) and mean horizontal velocity for spray under flash boiling conditions measured at 25 mm from the injector tip

4. Conclusions

In this study, PDA measurements were performed on two 3-hole GDI injectors with different hole diameters and cross-sectional profiles under both atmospheric and flash boiling conditions. The effects of injector design features and injection pressure on spray morphology, droplet size and velocity were investigated. Comparisons of the spray behaviour under atmospheric and flash boiling conditions were made in order to gain a deeper understanding of flash boiling phenomena. The following conclusions were drawn in this investigation:

1. The collected data showed that the spray did not collapse immediately upon exiting the injector holes at the flash boiling conditions tested. In addition, the distance travelled by the spray prior to collapse was increased by increasing the injection pressure.
2. Some of the hole design features were shown to offer greater resistance towards spray collapse than the others when flash boiling. This could lead to changes of orders of spray plume width, droplet size and droplet velocity when shifting from atmospheric conditions to flash boiling conditions. These were as follows:
    a. The middle-sized hole of the three diameters tested exhibited the most apparent spray collapse under flash boiling conditions.
    b. The divergent hole offered a greater resistance against spray collapse than the convergent hole, with its droplet size affected less by changes in the surrounding conditions, whilst the convergent hole droplet size reduces significantly under flash boiling conditions, creating greater levels of spray collapse.
    c. The largest hole diameter created the largest droplets of the three holes and this was maintained as the surrounding conditions were changed to flash boiling conditions. The larger droplet size resulted in a lower level of droplet breakup in comparison to the smaller diameter holes, because of the lower fluid velocity of the large hole. This helped to maintain the spray plume morphology and prevent collapse.

Acknowledgements

The authors would like to acknowledge the financial support of the Advanced Propulsion Centre (APC) for this work which was undertaken as part of TSB/APC project number 113130. The authors also wish to acknowledge Ford Motor Company for their technical support of the work.

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