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THE EFFECT OF FLASH BOILING ON BREAK UP AND ATOMIZATION IN GDI SPRAYS

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ABSTRACT

In this work the effect of flash boiling on liquid breakup and atomization is first reviewed and then described in detail for two multistream gasoline direct injectors operating with RON-95 gasoline at 120 bar and 200 bar pressure with a fuel injection duration of 0.8 ms into sub-atmospheric pressures between 1 and 0.1bar and temperatures between 20°C and 100°C. The sprays were injected into the optically accessed chamber whose temperature and pressure were independently controlled. Mie imaging with a single shot CCD camera was applied to obtain images of the sprays under a matrix of the above conditions. In order to investigate the influence of the cone angle on the stream to stream interaction, two different injectors were used, one with a 60 degree and the other with a 90 degree nominal external cone angle.

INTRODUCTION

Flash boiling is the phenomenon that occurs when a liquid is injected into an environment where the ambient pressure is lower than the saturation vapour pressure of the liquid. Flash-boiling atomization exploits a thermodynamic instability to break up a liquid jet. As the heated liquid is accelerated through the injection nozzle its pressure decreases and, if the pressure falls sufficiently below the saturation vapour pressure, rapid boiling of the liquid can result [1].

To optimize the design of gasoline direct injection (GDI) engines it is necessary to understand the fuel spray distribution and vaporization under all engine operating conditions. The spray structure and targeting must be optimized for a controlled distribution and a fast evaporation under a wide range of ambient conditions and injection timings [2]. The heat transfer phenomena occurring in a GDI engine cylinder head can cause the injected fuel to be heated before injection. During the injection process, when the heated fuel reaches a vapour pressure higher than the cylinder pressure, part of it is going to evaporate quickly through flash boiling. This phenomenon was observed in an optical engine by Pitcher et al. [3] and VanDerWege [4]. It was observed that flash boiling affects fuel-air mixing process by modifying the spray characteristics of cone angle, penetration and droplet size. Indeed, these changes in the spray characteristics modify the fuel distribution inside the combustion chamber and hence have a significant influence on the air-fuel mixing and hence mixture preparation.

EXPERIMENTAL SETUP

Two different injectors were used in this study. Both were multistream injectors supplied by Continental, one with a nominal external cone angle of 60° and a static flow rate of 18mm^3/s at 120bar and the other, with a nominal external cone angle of 90°, had a static flow rate of 12mm^3/s at 120bar. The 60° injector was tested at 120 and 200bar and the 90° injector at 120 and 180bar. The difference in upper limits was due to the maximum permissible fuel injection pressure for each injector. The high pressure fuel supply to the injector was achieved by two fuel pumps, the first, a low pressure pump mounted inside the fuel tank which supplied fuel at 3.5bar to the second, an external high pressure pump, which could operate at up to 200bar. The fuel output pressure to the injector was regulated by an adjustable pressure relief valve which returned the fuel spill to the fuel tank.

The injectors were fitted into a constant volume chamber with three windows for optical access. The pressure inside the chamber could be varied from 0.1bar to 10bar. A vacuum pump was used to achieve the sub atmospheric pressure range while a nitrogen cylinder was used to pressurize the chamber up to 10bar. The chamber had two electro-actuated valves, an inlet valve linked to the pressure release valve of a nitrogen cylinder and an outlet valve linked to a vacuum pump which was connected to an exhaust extractor. A pressure sensor was used to monitor the pressure inside the chamber.

The insulated chamber sits on top of a heating plate with a temperature control and an operating range between 20°C and 100°C. Considering the low injection repetition rate of 1Hz and the low fuel quantity injected during the 0.8ms injection duration, nominally 10 and 7 mg per shot for the 60° and 90° injectors respectively, it was assumed that conductive heat transfer through the injector was the main physical process affecting the temperature of the fuel injected into the chamber. Hence injector temperature was equal to the temperature of the chamber. A thermocouple measured the temperature of the gas in the chamber and displayed this information on a control interface and which was also used to determine the required power to the heating plate.

A schematic of the experimental setup is presented in Figure 1, with a picture of the experimental setup shown in Figure 2 while a close-up picture of the pressure chamber can be seen in Figure 3. The fuel injector is positioned at the top of the chamber, firing vertically downwards. A schematic of the injector-camera orientation is shown in Figure 4. It can be seen that although the injector has six holes, only three streams will be seen in side view due to superposition of the streams on the image. Furthermore, the imaged cone angle is not the actual cone angle, as the two outer stream pairs do not lie in the focal plane. A 90° clockwise rotation around the temperature probe axis allowed spray images to be taken from below the injector, i.e. in plan view.

Mie imaging was performed with a 12 bit PCO CCD camera (1280 by 1024 pixels resolution) mounted in front of the optical access of the chamber and a xenon flash panel mounted in front of the opposite optical access. A pulse timing box was used to control the pulse width of the injection signal and the timing of the xenon flash panel and the camera relative to the start of the injection signal. This allowed images to be captured at different stages of the fuel spray development. The collected images are displayed on a PC running PCO CamWare software, which saved the images for post-processing.

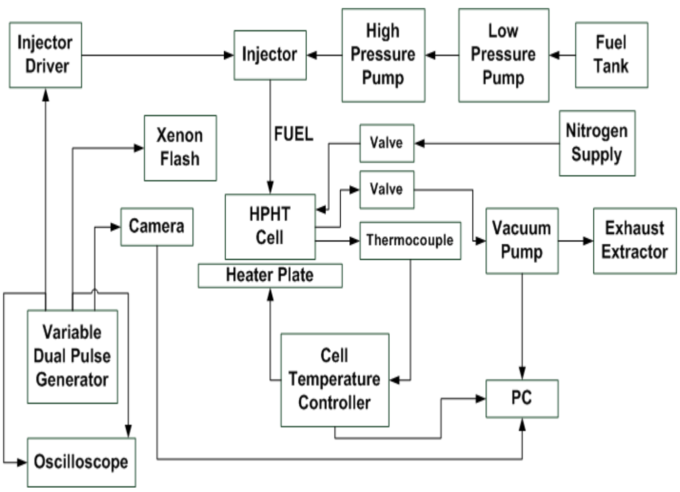


Figure 1 : Setup schematic

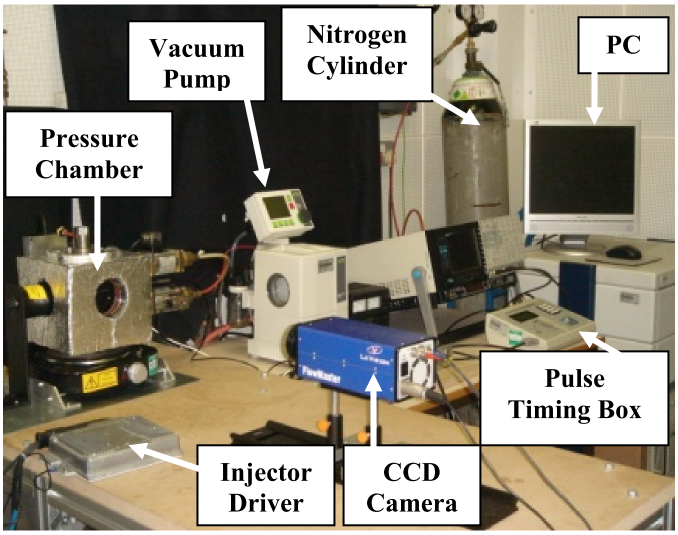


Figure 2 : Experimental setup

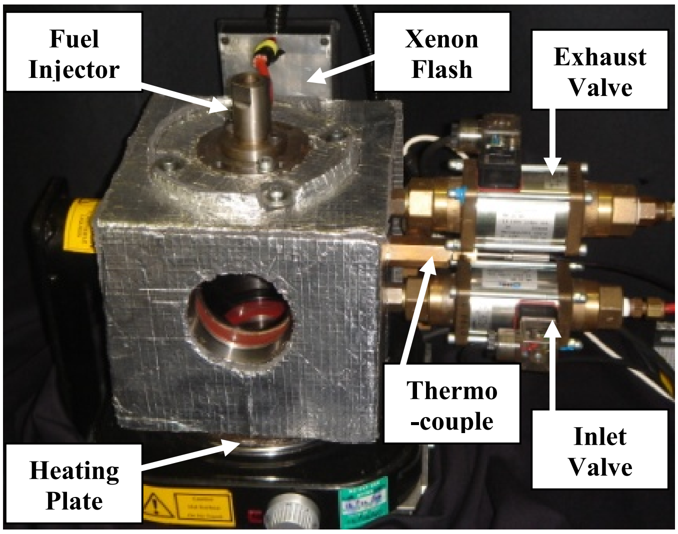


Figure 3 : Pressure Chamber

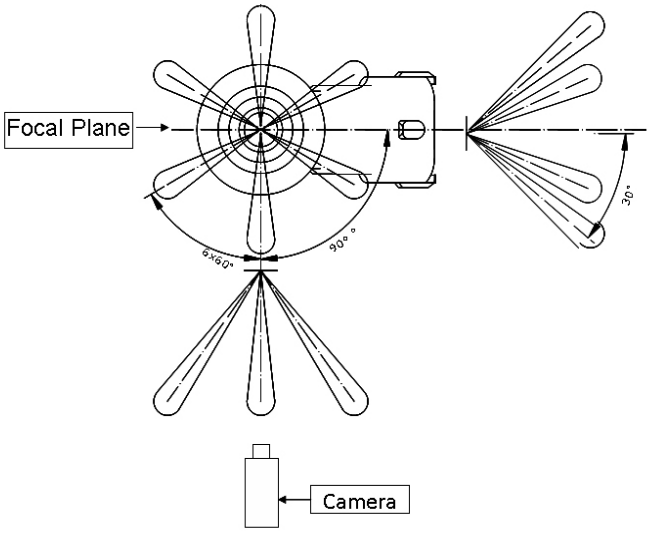


Figure 4 : Injector-camera orientation

FLASH BOILING THEORY

Flash boiling occurs when a sub-cooled liquid is rapidly depressurized to a pressure sufficiently below the saturation pressure of the liquid [5]. The fuel is then defined as superheated. Such a system is in a state of thermodynamic non-equilibrium and thus unstable. The system regains equilibrium by undergoing flash boiling.[6]

Sher et al. [7] summarised current knowledge on the flash boiling mechanism. It was found that there are three stages to flash boiling:

Bubble nucleation is classified into two groups:

- Homogeneous, in which nucleation sites form within the liquid itself, in the absence of any bubble nuclei, with a homogeneous distribution. This process becomes predominant when the liquid pressure is greatly reduced.
- Heterogeneous nucleation occurs when gas and solid phases appear at an interface or a boundary rather than in the liquid. A nucleus can appear in the presence of irregularities on a solid surface (injector inside wall), fine dust or solid particles, and dissolved gases in the liquid.

Once the bubble nucleation sites have developed, pressure fluctuations in the fluid can cause the sites to either collapse or grow. The stages of bubble growth were explained by Plesset et al. [8]

- Whilst the bubble is still relatively small, the rate of growth is low and restricted by surface tension of the bubble.
- If the degree of superheat is great enough, the growth rate reaches a maximum as the bubble size increases.
- Liquid surrounding the bubble is cooled due to the transfer of heat energy required for evaporation. The vapour pressure decreases and bubble growth rate is controlled by inertia and thermal diffusion.
- Bubble growth rate further decreases and inertial effects become less important. Growth rate is controlled by thermal diffusion. The bubble interior pressure and temperature approach ambient values and when this happens the growth stops.

Kawano et al. [9] proposed a bubble growth analysis based on the following assumptions:

- The temperature and pressure inside bubbles are uniform and temperature must be identical to the temperature of liquid fuel.
- Bubbles grow spherically.
- The phase change from liquid to vapor occurs continuously due to the growth process of cavitation bubbles inside the nozzle orifice and fuel droplets.
- Marangoni convection in the liquid increases coalescence frequency among the growing bubbles [10].

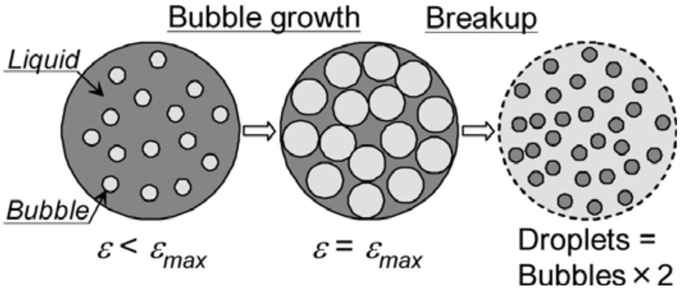


Figure 5 : Break up caused by bubble disruption [9]

The growth of bubbles inside a droplet is limited. This limit is determined by the diameter of the droplet, surface tension, liquid viscosity, the number density of bubble nuclei, and growth rate. The limit of bubble growth rate inside a droplet is described by the void fraction, ε, defined as the volume ratio between the vapor and liquid phases:

$$\varepsilon = \frac{V_{bubble}}{V_{bubble} + V_{liquid}}$$

where V_{bubble} is the volume of bubbles and V_{liquid} is the volume of liquid. Suma and Koizumi observed that break up of a fuel jet occurs at ε ranging from 0.51 to 0.53 [11]. Then, it is assumed that the droplet breaks up into small droplets twice as many as the number of bubbles, as illustrated in Figure 5. As a consequence, both the number and diameter of droplets after break up caused by bubble disruption can be calculated. The momentum of the parent droplet is uniformly distributed among the child droplets. Once the flash boiling process is completed a two-phase flow consisting of both fluid and vapour in equilibrium is obtained.

For a direct injection gasoline engine flash boiling of the injected fuel can occur under part load operation, particularly when operation late inlet valve opening strategies, [12]:

- Fuel in injector is at high temperature (<100°C) due to conductive heat transfer from the cylinder head.
- The downward movement of the piston with the inlet valves closed creates a partial vacuum (down to around 0.1bar)
- The boiling temperature of the fuel at the in-cylinder pressure is below the temperature of the fuel inside the injector.
- Superheated liquid fuel is injected into the cylinder.
- Latent heat cannot be conducted by surface evaporation.
- Rapid and explosive bubble growth occurs inside the droplets and vapourises the fuel.

VanDerWege [4] identified two regimes of flash boiling. Internal flashing occurs when bubbles are formed inside an injector orifice leading to the ejection of a two-phase flow consisting of both liquid and vapour. The spray expands rapidly when exiting the injector. External flashing occurs when the liquid jet is intact as it exits the injector orifice but is then shattered by rapid bubble growth as it moves downstream of the orifice. Work carried out by Gebhard [13] investigated the effects of length to diameter ratio of a steel nozzle using water and found that for l/d < 3, there is no internal flash boiling inside the nozzle. Sato et al. [14] performed a similar study, also using water, and reported that the spray characteristic was not affected by bubble nucleation in nozzle orifice if the orifice length to orifice diameter ratio l/d was less than 7. The injectors used in this study have a ratio l/d < 2.5. However, due to the differences in the type of injector and fuel used we can not assume anything about the occurrence of flash boiling inside the nozzle of the injectors used in our study.

The driving force for the flash boiling phenomenon is the temperature difference between the fuel as it exits the injector nozzle and the fuel's boiling point at the pressure condition the fuel expands into. This can be quantified as the "degree of superheat" and research has shown that atomization of a liquid jet is greatly enhanced when the degree of superheat is great enough to cause flash boiling. Previous work [8] has suggested that flash boiling will affect the spray structure noticeably when the degree of superheat is 20°C or more, however, the exact degree of superheat needed to cause flash boiling is reliant on the surface finish of the injector orifice and the Weber number of the liquid jet. The degree of superheat can also be defined as the difference between ambient pressure and the fluid vapour pressure.

Work carried out by Senda et al [15] involved mixing n-tridecane, which has similar properties to diesel fuel, with a relatively low boiling point additive. When mixing the fuels the vapour-liquid equilibrium in the two-phase region, where both liquid and vapour of both fuel components are present, was taken into account. By controlling the proportion of additive the authors could control the physical processes in the spray such as fuel evaporation and vapour-air mixing. In the two-phase region, illustrated in Figure 6, the vapour of the lower boiling point fuel dominates, with the vapour of the higher boiling point fuel coexisting. The vapour of the higher boiling point fuel would not be present under the same conditions if it was the only component present in the system as this region lies below the fuel's saturated vapour pressure line, shown in Figure 7. This shows that blending a low boiling component fuel with a high boiling component fuel leads to an increase in fuel evaporation and hence multi-component fuels, such as gasoline, are more susceptible to flash boiling than single component fuels.

Benefits of flash boiling are:

- Reduced drop sizes (smaller D_{32} for larger surface area and improved vapourisation)
- Increased cone angles (for better volume repartition)
- Reduced drop velocities (for reduced risk of piston crown impact)

The combination of these benefits results in reduced spray-impingement and gives lower engine-out HC emissions [16].

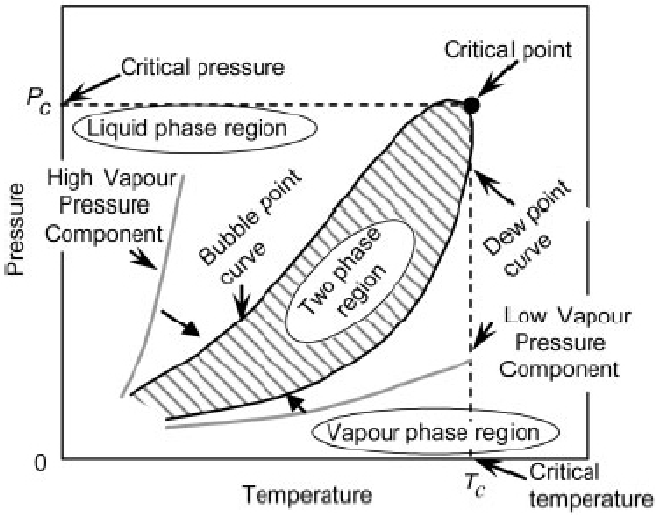


Figure 6: Illustration of two-phase region [15]

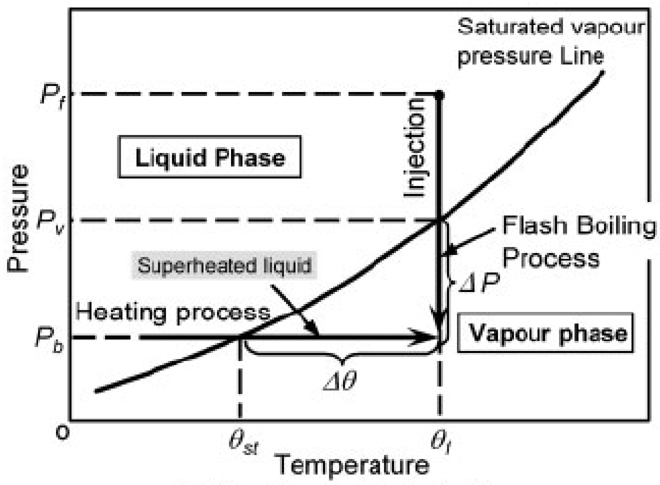


Figure 7 : Flash boiling process [15]

RESULTS

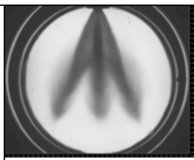
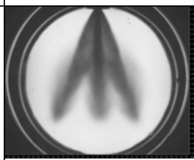
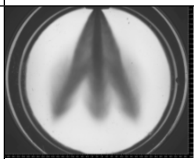
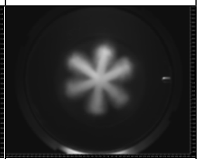
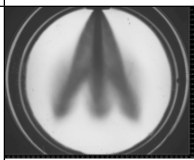
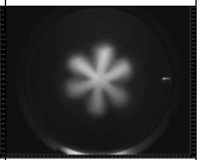
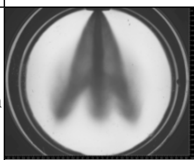
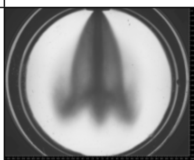
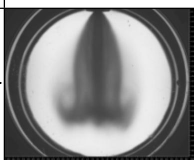
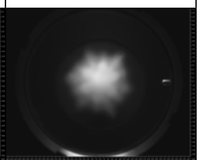
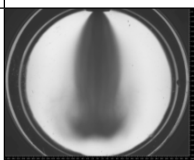
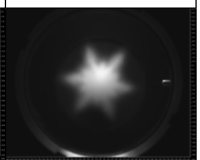
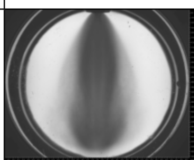
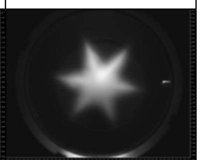
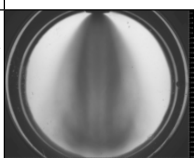
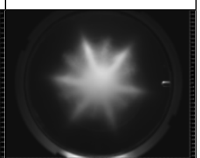
Qualitative Analysis

A qualitative analysis of the images was first undertaken to highlight the significant changes and phenomena visible in the spray images as the degree of superheat is increased. An overview of these changes for the side and plan view spray images are described in Table 1 for the 60° injector. These phenomena are also visible with the 90° injector but, with a greater separation of the streams, the effects of flash boiling on the spray are somewhat reduced.

The main phenomena seen are:

- Collapse of streams towards centre of spray and the creation of a "tulip" envelope.
- Formation of recirculation zones.
- Reduction in spray density.
- Apparent re-orientation of spray streams.

Table 1 : Spray pattern evolution with reduction in cell pressure. 60° injector, 120bar Fuel @ 60°C, 2ms ASOS

0.969bar Individual streams are clearly distinguishable		
0.9bar		
0.8bar		
0.7bar		
0.6bar Up to here only obvious changes are increase in stream penetration, width and interaction with a decrease in spray angle		
0.5bar Spray tip vortices clearly visible and spray is becoming more curved as it collapses inwards. Plan view image shows presence of spray in between streams		
0.4bar Spray takes on "tulip" shape and vortices become even clearer. Plan view image shows interstitial streams developing in between main streams		
0.3bar "Tulip" shape is narrower and penetration is increased. Original streams barely visible as interstitial streams dominate. Appears as if spray has rotated		
0.2bar Spray collapses with central core surrounded by a fine cloud of spray. Spray width increases at the tip. Original streams have disappeared and interstitial streams continue to grow		
0.1bar Spray width increases but density reduces. New streams visible between interstitial streams. Are mainstreams reappearing or is there interaction between interstitial streams?		

The spray development for chamber pressures from 0.969 to 0.3bar at a fixed temperature of 60°C are shown in Table 1. As the pressure is reduced the individual spray streams collapse inwards towards the spray axis. At 0.4bar the side image shows the individual spray streams are indistinguishable and the spray has formed a tulip shape, with recirculation zones around the stream tips. This is very similar to the spray shapes seen by Zhao et al. [17] and Reitz [1] with a pressure-swirl injector when the ambient pressure is increased. As the cell pressure is further reduced, to 0.2bar, the spray width increases and a cloud of fine spray can be seen surrounding the main spray body. The spray width is further increased as ambient pressure is reduced to 0.1bar. At the same time a reduction in spray density is observed, suggesting that an increased proportion of the spray from the injector has vapourised due to flash boiling.

Research on spray formation from pressure-swirl injectors has attempted to explain the reasons behind spray collapse. Work carried out by Delay et al [18] using fluorescent particle image velocimetry showed that interaction between the spray and the surrounding air caused the formation of vortices on the inside and outside of the spray cone. The inner vortex was seen to pull in air from the outside of the cone and this dragged relatively small droplets with it, causing the edge of the spray to curve and eventually collapse. Similar work using the phase Doppler technique was carried out by Allocca et al. [19] and the same phenomenon was observed. A recirculation zone is clearly visible around the spray tip for the 0.5 and 0.4bar images in Table 1. It is likely that the same aerodynamic effects are responsible for the recirculation in each case, and the collapsed stream recirculation is the result of the individual recirculation zones interacting as the streams collapse inwards. The recirculation zones themselves are due to aerodynamic interaction between the fuel spray and the surrounding air. This is the same mechanism responsible for spray collapse, but in this case the outer vortex causes the observed effect [20].

The plan view images for 0.5 to 0.3bar in Table 1 show an apparent rotation of the spray streams about the injector axis. Inspection of the 0.5bar image shows that there is no physical rotation of the spray, rather, additional interstitial streams develop between the main streams and the main streams themselves disperse, as observed by Dahlander [16]. Once the pressure has reached 0.2bar, the original streams are almost invisible and the interstitial streams dominate the spray. As the pressure is further reduced these streams extend in the radial direction and increase in width. It is also noticed at 0.1bar that more streams grow in between the interstitial streams. It is not clear whether these are the original streams reappearing or the development of new streams.

The presence of spray between the main streams is due to the interaction between individual streams as the spray collapses inwards. This interaction, which can be classified by the distance at which the individual streams are joined, increases with increasing superheat, as seen in the side images in Table 1. A further contributory factor to the interaction between streams is, again, the formation of vortices due to aerodynamic interaction between the fuel spray and the surrounding air. Whereas in a pressure-swirl injector toroidal vortices form on the inside and outside of the cone, in a multi-hole injector the vortices form around each spray stream. This leads to interaction between neighbouring streams as the vortices transport droplets from one stream to another. This transfer increases as the level of flash boiling increases. Therefore, the increased visible stream interaction with increased degree of superheat is likely to be due to a combination of the individual streams being bent inwards and the individual streams interacting with one another due to the interaction of the vortices.

Quantitative Analysis

Spray Characteristics - Chamber Pressure

The image processing technique detailed in Figure 8 allows simple quantification of the spray cone angle and axial penetration. The 50% intensity contours have been used to identify the spray boundaries with cone angle measured at 20mm downstream from the nozzle.

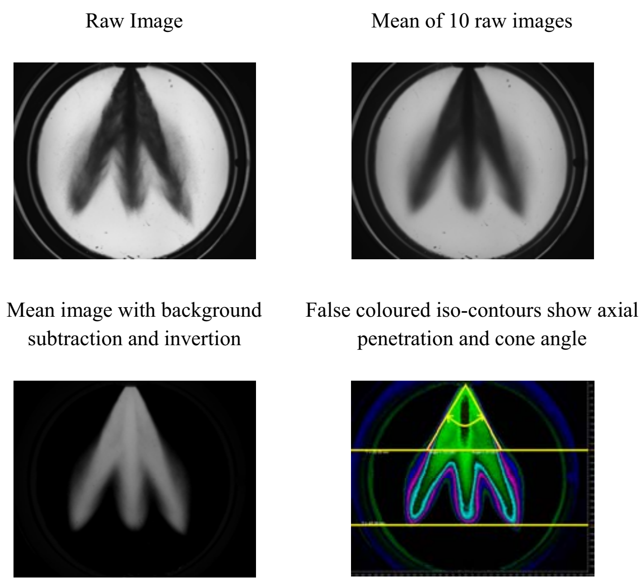


Figure 8 : Image processing technique

Varying the ambient pressure in the chamber alters the fuel's boiling point and, as a result, changes the degree of superheat. This affects the spray penetration, cone angle, and the shape of the spray. It can be seen in Figure 9 that as pressure is reduced and the degree of superheat of the fuel increases it has the effect of increasing the spray angle. These increases are greatest below approximately 0.3bar ambient pressure. Spray width decreases further downstream as the spray collapses inwards on itself, creating a curved spray profile.

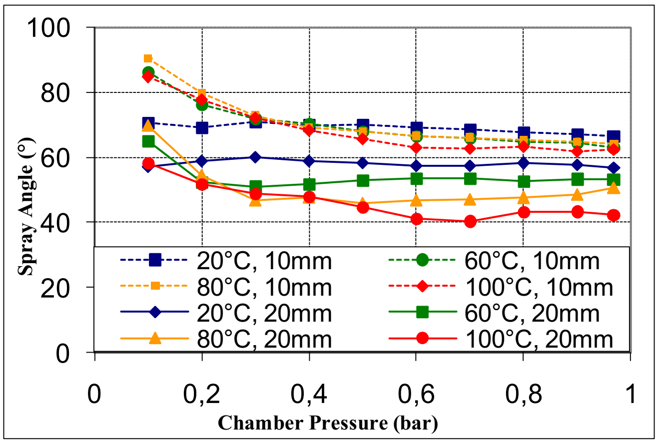


Figure 9 : Spray angle comparison for ambient pressure variation. 60° injector, 120bar Fuel, 2ms ASOS

The spread of spray angles over the temperature range is greatest further from the injector tip, particularly at ambient pressures close to 1.0bar. The spray angle for 20°C fuel temperature is relatively stable compared to the other fuel temperatures as pressure is decreased, and in fact decreases only slightly from 0.3 to 0.1bar at 20mm downstream, which appears to be the opposite behaviour to the general trend. Spray angles are lower for higher fuel temperatures.

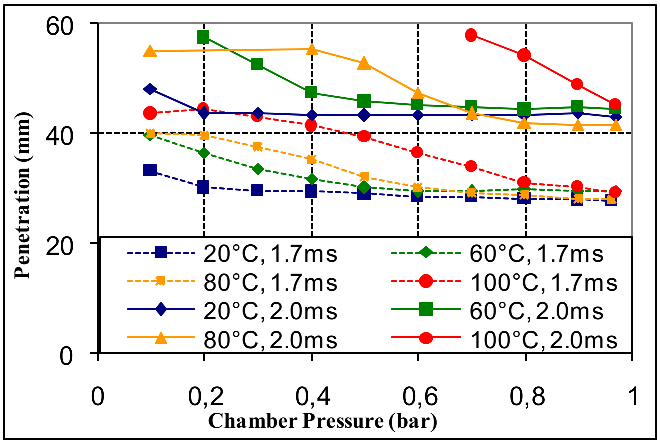


Figure 10 : Penetration comparison for ambient pressure variation. 60° injector, 120bar Fuel, 2ms ASOS

The penetration data displayed in Figure 10 show an increase in penetration as ambient pressure is decreased mainly due to the reduced air density causing less aerodynamic resistance to the spray. The higher the temperature of the spray then the greater the penetration as pressure is reduced. This is particularly noticeable at 2.0ms ASOS, where it can be seen that the 100°C spray begins to increase in penetration immediately as pressure is reduced, whilst the 20°C spray remains relatively unchanged until the chamber pressure is reduced to 0.2bar. The penetration for 60°C and 100°C fuel temperatures extended beyond the viewing window of the chamber as pressure was reduced.

Spray Characteristics - Chamber Temperature

Increasing the temperature of the fuel is another way of increasing the degree of superheat of the fuel as it is injected into the chamber. The trends for changes in spray angle and penetration due to temperature are shown in Figures 11 and 12. Data for spray angle, Figure 11, are not shown between 0.9 and 0.6bar as there is very little change. The trends, as temperature is increased, vary for different ambient pressures. The spray angle increases with temperature for low ambient pressures but decreases with temperature for higher ambient pressures. In all cases, the spread of spray angles over the pressure range increased at higher temperatures, suggesting that spray was affected to a greater extent at the extremes of pressure. Also, the spray width reduced further from the injector tip, showing that the spray boundary was curved as it collapsed inwards. Spray angle was greater for lower pressures at all conditions but with two exceptions. At 0.96bar ambient pressure and 20mm downstream, the decrease in angle with increase in fuel temperature was lower than that for 0.5bar between 60 and 80°C, resulting in the higher pressure condition having a greater spray angle. This trend changed at 100°C and the 0.96bar conditions followed the general trend of reduced spray angle at higher ambient pressure.

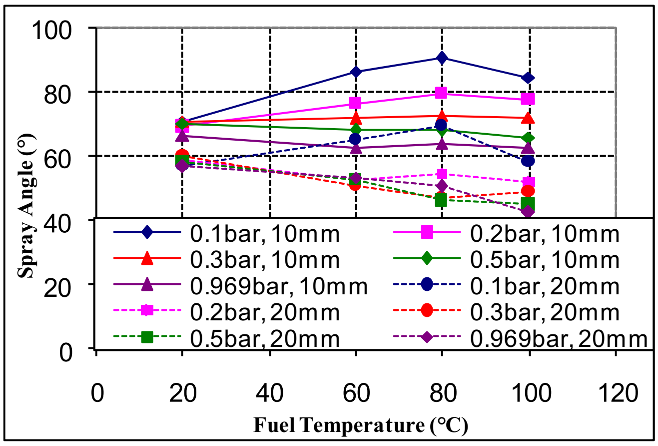


Figure 11 : Spray angle comparison for fuel temperature variation. 60° injector, 120bar Fuel, 2ms ASOS

Spray penetration data are shown in Figure 12. The general trend is for increased penetration as fuel temperature is increased and the spread of penetration values also increases with temperature. There are, however, several exceptions to this general rule. There was a decrease in penetration between 60°C and 80°C before an increase between 80°C and 100°C for pressure conditions from 0.7 to 0.96bar.

Due to the limited diameter of the viewing window the spray tip was out of range for the lowest chamber pressure conditions. This was due to the original choice of a 2ms ASOS image time and a much reduced aerodynamic drag on the spray causing maximum penetration. An interesting point is that the penetration for 0.1bar went off the scale at 60°C, returned at 80°C and then left again at 100°C whereas for the other pressure conditions there was no return once the spray tip was out of range.

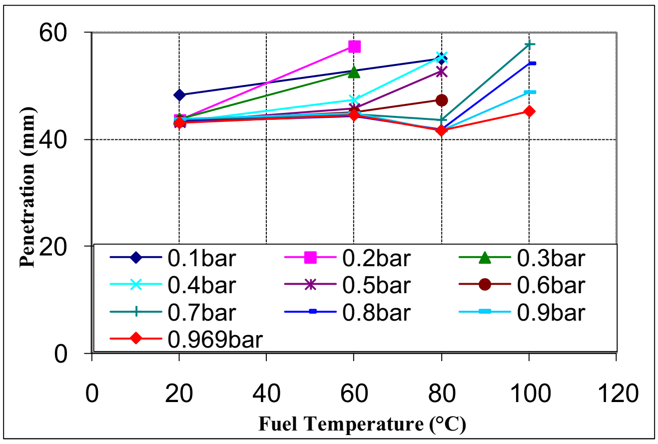


Figure 12: Penetration comparison for fuel temperature variation. 60° injector, 120bar Fuel, 2ms ASOS

The increase in penetration with increased temperature is most likely a result of the change in shape of the spray. As temperature is increased, the intensity of flash boiling increases and causes the fuel spray to collapse. This collapsed spray has only one stream and, as such, has a reduced aerodynamic drag relative to spray with six individual streams.

Spray Characteristics - Fuel Pressure

Higher fuel pressures increase the spray velocity as it exits the injector nozzle which affects droplet break up and atomization by altering the Weber number.

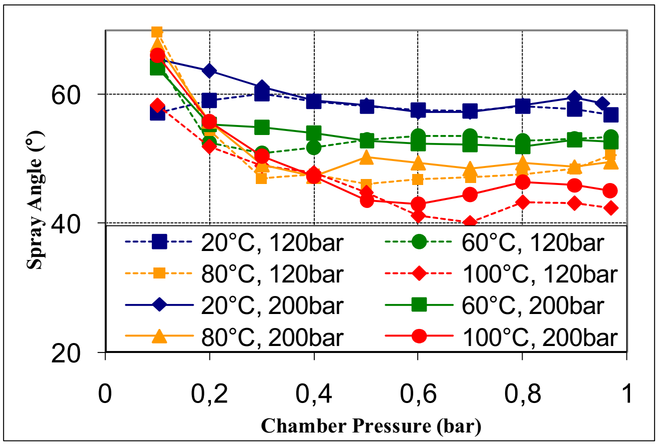


Figure 13 : Spray angle comparison for fuel pressure variation. 60° injector, 2ms ASOS, 20mm downstream

Spray angle data, Figure 13, show that in general, higher fuel pressures give increased spray angles. This is likely to be due to the increased pressure differential between the fuel and the atmosphere causing increased break up and atomization generating smaller droplets which are more susceptible to the aerodynamic conditions in the chamber. The trends for both fuel pressures are similar but this similarity is reduced at lower ambient pressures, for example, the 20°C-120bar data show a reduction in spray angle between 0.3 and 0.1bar whereas the general trend is for an increase.

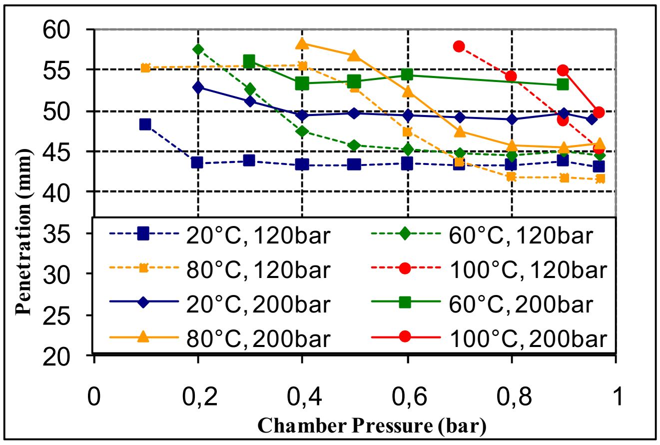


Figure 14 : Penetration comparison for fuel pressure variation. 60° injector, 2ms ASOS

Fuel penetration data are shown in Figure 14. Higher fuel supply pressures give increased penetration due to the increase in velocity of the fuel droplets as they leave the injector. Once again the trends are very similar regardless of fuel pressure.

Injector Comparison

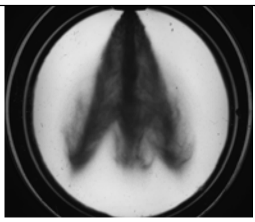
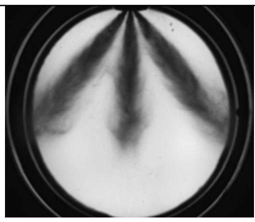
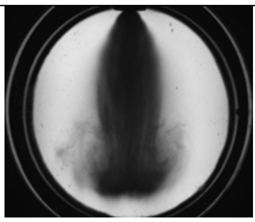
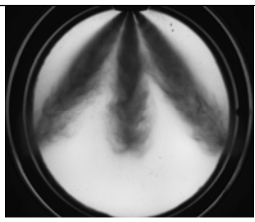
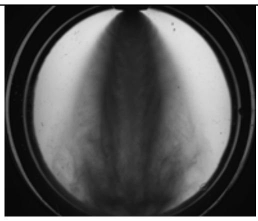
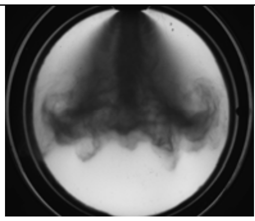
	60° injector	**90° injector**
0.6bar		
0.3bar		
0.1bar		

Table 2 : Spray pattern evolution. Injector comparison, 120bar Fuel @ 60°C, 2ms ASOS

To investigate whether a change in nozzle geometry and spray pattern would lead to a variation in spray characteristics two injectors were tested, one with a nominal cone angle of 60° and the other with a nominal cone angle of 90°. As expected, it can be observed in Table 2 that the 90° injector, with its increased cone angle, has a reduced axial penetration relative to the 60° injector. For the images shown at 0.3bar, the 60° injector spray is fully collapsed whereas for the 90° injector spray streams are just beginning to turn inwards. This suggests that the spray from the 60° injector is collapsing earlier than the 90° injector as the chamber pressure is decreased. This is due to the fact that as the spray streams for the 60° injector are closer together they interact more with each other and start collapsing with a lower degree of superheat. In Table 2, it can also be noticed that, as the chamber pressure is reduced further, the variation in penetration for the 90° injector spray is smaller than for the 60° injector. As a consequence the tulip shape is wider for the 90° injector. These observations have also been made as the fuel temperature is increased. This suggests that for injectors with large spray stream angles the fuel spray penetration is more robust to increases in the degree of superheat.

CONCLUSION

The flash boiling effects on spray evolution has been described for two multistream gasoline direct injectors operating with RON-95 gasoline at 120 bar and 200 bar pressure with fuel injection into sub- atmospheric pressures between 1 and 0.1bar and temperatures between 20°C and 100°C.

The general trend is that as the degree of superheat is increased, through either fuel temperature increase or ambient pressure decrease, the individual spray streams collapse inwards towards the injector axis, thereby reducing the diameter of the spray footprint. Once fully collapsed, the individual streams are no longer visible, but, as the degree of superheat is further increased interstitial streams become visible between the main stream locations. These then grow away from the injector axis in the radial direction, resulting in the diameter of the spray footprint increasing. These trends were also visible over the range of temperatures studied at a fixed pressure. This suggests that the mechanisms behind the spray changes relies on a combination of both temperature and pressure as regards boiling point of the fuel.

The dependence of the flash boiling on both temperature and pressure for a multi-component fuel is highly complex. However, this level of complexity is likely to increase as gasoline-alcohol blends become more common place in fuel spray studies. In the mean time an analysis of sprays with single component fuels with a range of boiling points representative of the range found for gasoline is underway.

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