Flash Boiling Sprays produced by a 6-hole GDI Injector

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Abstract
During certain stages of GDI engine operation there is a high probability of fuel being injected into the cylinder in a superheated state. Upon injection into the cylinder the fuel will then undergo flash boiling which leads to many drastic changes to the spray including changes to the overall morphology and a reduction in mean drop size. Test conditions were chosen to range from a non-flash boiling condition to a flare flashing condition, complete degradation of the spray shape, with intermediate conditions in which the spray was in a partial flashing state. An imaging study showed that as the superheat degree was increased from a non-superheated case through to a flare flashing case there were a number of different spray morphologies exhibited. Under non-flashing conditions there were the original six spray plumes from this injector. As superheat was increased these plumes were shown to widen and eventually interact with one another. With sufficient superheat for flare flashing the spray was shown to collapse towards the core region and form interstitial streams in the gaps between the original spray streams with the original spray stream locations empty of fuel.

Phase Doppler data showed the important role droplet entrainment has on the spray morphology under flashing conditions. Flash boiling produces a large number of small droplets which have very low momentum levels. A feature of these droplets is that they are readily entrained, hence, under flashing conditions the droplets tend towards regions of low pressure such as the spray core region which has a lower pressure. This collapsing process appears to be aided by the recirculating tip vortices on the leading edge of a spray. The after effect of these vortices is shown to be a continued radial velocity component towards the spray core for the remainder of the spray event long after the vortices have passed through the measurement volume. Mean velocity data in both the mains and interstitial streams were compared which revealed that the droplets in the mains streams are more likely to be entrained into the spray core than those in the interstitial streams. This is a possible explanation as to why under flashing conditions fuel exists in the interstitial streams, but not in the mains streams.

Drop size measurements showed that under flash boiling conditions the large droplets within the spray were all broken down into smaller droplets by the flash boiling process. This led to a significant reduction in mean drop size; a ΔD2 reduction of 42% for a superheat degree of 36°C.

1. Introduction

The operation of modern GDI engines, usually low load or with a warm engine, the combination of increased fuel temperature and sub-atmospheric cylinder pressure during injection, can lead to a phenomenon known as flash boiling. Flash boiling occurs when fuel is in a superheated state such that the rate of evaporation is greater than can be supported by the external surface of the fuel. This leads to internal boiling of the fuel, which causes vapour bubbles to form within the fuel. As evaporation continues these bubbles continue to grow until the point at which their volume is so great that they cause the fuel droplet to break-up catastrophically (Kawano 2006) as per Figure 1.

![Fig. 1 Stages of Bubble Growth (Kawano 2006)](image-url)
The resultant daughter droplets will have equal overall momentum to the parent droplet. Flash boiling will occur when the ambient pressure into which the fuel is injected is below the saturation vapour pressure which increases with fuel temperature.

In recent times much experimental and numerical work has gone into the understanding of multi-hole sprays under flash boiling conditions. A multi-hole injector was investigated (Zeng 2012) under various superheat degrees with a summary of the results shown in Figure 2. An 8-hole 90° cone angle injector was used for this investigation, whereas a 6-hole 60° injector was used for the results presented in this paper. As expected with increased levels of flash boiling the vapour quantity is increased and a widening of spray plumes occurs, leading to increased levels of stream to stream interaction. These results suggest that a large degree of superheat was required in order to cause full spray collapse, but even under partial collapse conditions strong vortices appear to be formed on the edge of the spray tip.

![Graph showing trend lines of spray structural changes and vapor quantity](image)

**Fig. 2 Summary of investigation on flashing alcohol fuels (Zeng 2012)**

Numerical work (Khan 2012) described the role of stream to stream interaction and air entrainment on the downstream spray progression. They suggest that the fuel is drawn into the centre of the spray from the original spray streams and is forced out of this area at a stagnation plane in the spray. This process appears to be experimentally confirmed (Xu 2013), where interstitial streams form under flash boiling conditions in the gaps between the original injection streams due to air motion out from the spray core being blocked in the original spray locations, but not the interstitial stream locations. Previously an investigation was carried out with a comparable 60° multi-hole injector to the one used in this investigation, the XL2 from Continental (Mojtabi 2008). This investigation showed that even under a low degree of superheat (or even negative superheat), as shown in Figure 3 which features gasoline as the test fuel with ambient pressure 0.3 bar and air temperature 60°C, the spray collapse and formation of interstitial streams occurs. A comparison was made between a 60° and a 90° cone angle injector which showed that the sprays from the 90° injector would only collapse under a high degree of superheat, however, the spray collapse is observed for much a much lower degree of superheat for the 60° injector. This shows the importance of stream to stream interaction and the formation of a low pressure region in the spray core on the collapsing behaviour of multi-hole GDI sprays.
2. Experimental methods and test-rigs

Flash boiling sprays have been investigated using shadow and Mie-imaging techniques along with a two component phase Doppler anemometry (PDA) system. The investigation featured a multi-hole XL3 GDI injector from Continental Automotive. The prototype injector, which was made for research purposes, features a 6-hole nozzle with a total cone angle of 60° and 60° circumferentially between the three spray streams. The injector was fuelled with n-heptane with a fuel line pressure of 100 bar. The spray investigations were conducted inside 2 high pressure/high temperature cells which can operate in the range 0.1-10 bar chamber pressure and fuel temperature 20-100°C. The first cell features 80mm quartz windows at 90° and 180° to each other to allow access for shadowgraphy and Mie-imaging. The other cell has windows at 110° for PDA access, with the cell mounted on a 3-component traverse system. Under operation the cell is filled with nitrogen and regularly purged to remove the remnants of previous injections. The fuel is heated by heaters placed within the injector holder and the fuel temperature is measured at the injector tip. Both set-ups, including the pressure cell and the phase Doppler system, are shown in Figure 4. The whole system is controlled with an in-house LabVIEW program.

Imaging studies used a PCO Sensicam Fast Shutter CCD digital camera equipped with a Nikon 55mm focal length lens. For shadowgraphy studies images were backlit by a Fostec 100 by 130 mm flash panel connected to an EG&G Xenon light source. For planar Mie-imaging the same light source was connected to a Fostec fiber-optic planar light delivery source and light was introduced from a 90° angle, from the right hand side as the images are orientated. All images were taken at a time 1100µs after electronic start of injection (AESOI).

The design, construction and application of the two component PDA transmission system to study dense GDI fuel sprays at atmospheric conditions has been well documented (Wigley 2008). The configuration for the 488 and 514 nm laser beam wavelengths at the final focussing lens was: beam diameters of 5 mm, equal beam pair separations of 50 mm, laser powers of 100 and 200 mill-watts per beam with a horizontal polarisation. With a focal length lens of 300 mm this produced coincident measurement volumes of...
diameters of 37 and 39 microns with fringe spacings of 2.94 and 3.10 microns respectively for the two wavelengths. The 514 nm beam pair was in the vertical plane to measure the axial droplet velocity and diameter with the 488 nm beam pair in the orthogonal plane to measure the radial droplet velocity. The Dantec 57X10 receiver was positioned at a scattering angle of 70 degrees. This optical configuration resulted in an effective measurement volume length of 0.1 mm. In-conjunction with the Dantec processor the transmitter and receiver set up produced a droplet velocity bandwidth of -30 to 110 m/s with a drop size measurement range of up to 100 microns.

PDA Measurements were conducted on an axial downstream plane, Z, at 40mm from the injector tip. Radial scans were taken through both the original spray axis and the interstitial stream, which represents an injector rotation of 30°. Each radial scan traversed from the injector axis to the outer edge of the spray stream. The horizontal traverse had a radial step increment, x, of 2.5mm in order to resolve local high velocity gradients across the spray stream.

3. Results and Discussion

Spray images and PDA data were acquired at a number of fuel temperature/chamber pressure combinations, as detailed in Figure 5 with their relationship to the saturation vapour pressure curve for n-heptane. The 0.9bar, 23°C test point represents a non-flashing conditions and the 0.1bar, 71°C fully flashing, or flare flashing, conditions. With the intermediate test points representing conditions where were partial flash boiling was expected.

![Graph showing n-heptane boiling point curve with test points](image)

**Fig. 5 Summary of investigation on flashing alcohols fuels**

Shadowgraphy results, Figure 6, show that as superheat degree is increased, from a non-superheated state to a significant level of superheat there are great changes in the morphology of the spray. This is consistent with published data. Even under non-superheated conditions (SD (superheat degree) =-12°C) there is a widening of the spray plumes. With a low level of superheat (SD=12°C) the entrainment of fuel into recirculating tip vortices can be seen along with further widening of the individual spray plumes and partial collapse. For the flare flashing case (SD=36°C) there is complete destruction of the original six spray plumes to form a single central spray. These findings mirror those of many other researchers (Mojtabi 2011), (Xu 2013).

Complimentary planar Mie images, Figure 7, taken at an axial distance, Z, of 40mm from the injector tip (the centre of the chamber) further highlight the differences in spray morphology. The non-superheated case shows a standard spray with the six individual spray plumes. The intermediate superheat level results show various spray morphologies, all featuring the migration of some spray from the original spray streams to other locations, such as widening of spray plumes or the collapse of streams towards the spray core, but not
the disappearance of the original spray streams. With the maximum superheat tested (SD=36°C) the flare flashing spray is exhibited which shows a collapsed spray and the formation of interstitial streams in the gaps between the original spray streams.

Fig. 6 Spray collapse under flashing conditions

To track the formation of these interstitial streams under high levels of superheat, 36°C in this case, planar Mie-images were taken at a number of axial locations from the injector tip, as shown in Figure 8. At a
distance of 5 and 10mm only the mains streams are present. However, by 20mm there is some evidence of both mains and interstitial streams and by 40mm the mains streams have disappeared completely leaving just the interstitial streams and the fuel which has collapsed into the spray core. This shows that in the region of 10-40mm the fuel moves away from the mains streams and into the interstitial streams and spray core. The length of time for fuel droplets to undergo flash boiling has been modelled (Razzaghi 1989) and for fuel to undergo flashing in this region, assuming an exit velocity of 100m/s the time for flashing is in agreement with the model. It can be assumed that at 5 and 10mm downstream the mains streams still exist as the majority of the fuel has not undergone flash boiling, whereas at 40mm downstream most of the fuel has undergone flash boiling and thus formed interstitial streams. This shows that fuel only leaves the mains streams after it has undergone flash boiling.

The images here appear to suggest that fuel is only drawn into the spray core region at a downstream distance of around 20mm, this distance will be superheat dependant, rather than immediately upon nozzle exit as earlier suggested, but with the information available it is entirely plausible that the fuel which collapses may be redistributed and consequently form the interstitial streams.

The formation of a collapsed tulip shaped spray from multi-hole injectors under flashing conditions has been observed for a number of injectors (Mojtabi 2011), (Xu 2013). The plot of discrete droplet radial velocity for only droplets with diameter under 4µm, Figure 9, effectively shows the air motion on the outer edges of the spray over time. The first droplets to reach the measurement volume have a large radial velocity component,
which is consistent with a multi-hole GDI spray. However, shortly after the spray reaches the measurement volume there is a period in which most droplets exhibit significant negative radial velocity, which is due partly to the low pressure region in the spray core, but also due to the effects of the recirculating tip vortices on the spray. For the remainder of the spray duration, the after effects of these tip vortices lead to a continued spray collapse causing the formation of the tulip structure.

![Graph](image)

**Fig. 9** Raw droplet radial velocity @ Z=40mm x=12.5mm for P=0.1bar T=71°C in interstitial streams

The mean radial velocity profiles for the mains and interstitial streams at a measurement point in the middle of a spray plume, Figure 10, are shown to be very similar for the majority of the spray duration. However, for the period 1-1.5ms there are clear differences. The increased velocity reduction in the mains streams is responsible for the entrainment of droplets away from this region and into the spray core, leaving behind the interstitial streams. It is postulated that immediately after undergoing flash boiling that the fuel from the parent droplet will be in the form of many small daughter droplets which will be easily entrained into the low pressure region in the spray core. With the information available it is impossible to uniquely determine from what the interstitial streams are formed, but based on conclusions thus far about the importance of entrainment on the spray morphology under flashing conditions, it is likely some combination of fuel from the spray core region and flashed fuel directly from the mains streams.

For the level of entrainment of droplets into the spray core to be different between the mains and interstitial streams the spray momentum in the mains stream must be lower than in the interstitial streams. During the period which was shown to be fundamental to the spray collapse, 1-1.5ms for this case, there is a clear difference in axial velocity, Figure 11, between the mains and interstitial streams, with the mains stream displaying significantly lower velocity and thus lower momentum.
One of the key perceived advantages of a flash boiling spray for engine operation is the possibility of producing a spray with a low mean droplet diameter. Many different mean drop sizes taken over the whole spray duration and whole spray area including mains and interstitial streams are shown in Figure 12. This shows that there is a definite correlation between increased superheat degree and reduced mean drop size. Theory states (Kay 2010) that this correlation only exists for values of superheat which are relatively close to zero (~±50°C).
Flash boiling occurs because the external surface area cannot support the evaporation rate required by the superheat of a droplet. Therefore, the droplets which are most likely to undergo flash boiling are the largest as they have the highest volume to surface area ratio. The comparison between histograms of drop size between a non-flashing and a flare flashing spray, Figure 13, shows that for the flashing case there are almost no large droplets (<10µm) recorded, whereas for the non-flashing case there are significant numbers of droplets of this size class. The data for the non-flashing case effectively represents the fuel break-up due to instabilities imparted upon it due to the injector flow and the shear force against the air through which it travels. Therefore, the increased level of fuel break-up for the superheated case can be attributed to the flash boiling phenomena. Another point of note is that smaller droplets are more likely to be entrained, as they have lower momentum, thus the increased importance of entrainment for flashing sprays.
4. Conclusions

This work has helped build into an ever increasing database of knowledge on the behaviour of multi-hole GDI sprays under flash boiling conditions which are found with high fuel temperature and low in-cylinder pressure. An imaging study showed the spray collapse and formation of interstitial streams which have been observed by many other researchers. At measurement conditions in between the non-flashing and fully flashing cases, partial flash boiling of the spray was observed. Features of this included widening of the spray streams leading to increased stream to stream interaction and, when superheat is sufficient, a partial spray collapse. Planar Mie-imaging at a number of axial downstream distances from the injector tip showed the formation of interstitial streams only happened after the fuel had travelled a certain distance downstream. This indicates that the interstitial streams are formed by fuel that has undergone flash boiling. Phase Doppler data show the importance of air entrainment on the spray morphology under flashing conditions. Raw droplet velocity data showed that the small droplets were entrained into recirculating tip vortices and that the aftereffects of these vortices aid the spray collapse. Small differences in the mean velocity profile show there was an increased likelihood of entrainment of droplets into the spray core from the mains streams in comparison to the interstitial streams. Thus, it is assumed that immediately after flash boiling the small droplets produced by flash boiling are entrained away from their position due to pressure gradients within the spray.

Finally, drop size measurements show that for an increase in superheat degree there was an associated reduction in mean drop size. It was shown that under flash boiling conditions there were very low numbers of large droplets (<10µm) in the spray. Small droplets have lower momentum and hence are more likely to be entrained, thus leading towards the previous conclusions on the importance of entrainment on the spray morphology.

One point of note is the importance of the injector cone angle and therefore the stream to stream interactions on the spray morphology under flash boiling conditions.

5. References