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Near-Nozzle Instabilities in Gasoline Direct Injection Sprays

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Abstract

Nozzle flow of multi-hole GDi injectors can lead to undesirable and uncontrolled spray instabilities. In this study, two different injectors were utilised in order to observe the near-nozzle spray using high magnification optics and a high speed camera; a symmetrical multi-hole injector and an asymmetric, stepped nozzle injector. It was found that the symmetric injector exhibited a number of different spray instabilities, including flapping of the spray cone from an individual nozzle, flapping across all nozzles and rapid flapping along a single spray axis. The typical time scale of the phenomena was in the order of a hundredth of a millisecond. On the other hand, the stepped nozzle injector was found to exhibit fewer spray structures associated with spray instability. The results also suggest the nozzle step plays an important role in the primary breakup of the spray and that most of this breakup occurs before the exit of the step.

Introduction

Since GDi was reintroduced to the mass market in 1996 with the advent of the Mitsubishi 4G93 it has demonstrated its potential advantages over the conventional PFI engine configuration. The main benefit of GDi is that it allows an engine to operate with the throttle plate fully open during part load operation by controlling the engine output through mixture control rather than induction throttling, as with a diesel engine **[6, 14]** . This is achieved by creating a stratified heterogeneous mixture so that while the overall induction mixture is lean, the region in the vicinity of the spark plug is close to stoichiometric ratio and combustible. To create this heterogeneous mixture the fuel needs to be injected directly into the combustion chamber. To run in stratified mode the fuel is injected late in the compression stroke so that the combustible fuel-air mixture remains in the region of the spark plug and is not transported throughout the rest of the combustion chamber by mass air motion present in the cylinder, such as swirl and tumble **[13, 16]**. This is in contrast to high load operation where the fuel is injected during the induction stroke so as to achieve high mixing and create a uniform homogeneous fuel-air mixture in the combustion chamber, as achieved by PFI **[14]**. However, injecting fuel directly into the combustion chamber poses two serious problems that need to be overcome. Firstly in both stratified late injection and pre-mixed early injection strategies the fuel has significantly less time to evaporate than it would in PFI where the fuel is usually injected onto the back of a hot intake valve before the air is even drawn into the cylinder. This is overcome by increasing the atomisation level of the fuel droplets leaving the injector by raising the rail pressure of the fuel to significantly higher levels that found in a PFI system; typically around 200 bar in modern GDi systems **[15, 17, 20]**. The other problem that needs to be addressed focuses on the stratified range of operation and is a result of the need to create an ignitable mixture directly in the region of the spark plug. So as to have a mixture that is reliably in the same region at the SOC, the injector needs to be able to produce a very stable and predictable spray.

Inside the injection nozzle and just after the exit of the nozzle the fuel first undergoes primary breakup where instabilities in the liquid core cause it to break up into large droplets and ligaments. These large droplets and ligaments then immediately undergo a secondary breakup process **[3, 12, 24]**. By promoting rapid primary and secondary breakup, the whole process is accelerated. It is generally accepted that cavitation structures present within the injection nozzle result in more rapid and complete primary breakup of the fuel so that secondary breakup can further reduce the size of the droplets and ligaments. However despite the benefits to atomisation of the fuel that cavitation can provide, it can have the unwanted effect of causing instabilities in the spray. This is a result of the different types of cavitation that can occur within a GDi injector. The two types concerned with in this paper are geometric and string cavitation. Geometric cavitation is the result of the working fluid being forced around a sharp feature or corner, such as the entrance of nozzle hole from the sac volume**[5, 7, 22]**. Studies of large scale and real size optical injectors have shown this to be a relatively stable form of cavitation that promotes atomisation with little increase in the instability of the spray **[4, 19]**. This can take different forms such as film cavitation or supercavitation and once established, especially the former, has been observed to be stable in microsecond timescales **[11]**. However, string cavitation being the result of the low pressure region in the centre of a rotating fluid body, has been observed to be very unstable and can fluctuate within very short time scales **[1, 2, 9]**. Further to this, when a string structure reaches the exit of a nozzle hole, this can cause relatively large changes to spray parameters such as overall cone angle while also manifesting in very localised spray flapping where spray on one side of the main cone can be ejected at an angle much greater than the average cone angle of the rest of the spray. These phenomena are known as spray flapping and can result in both fuel outside of the ignitable region of the spark plug and the ignitable fuel-air region missing the spark plug entirely when operating in stratified mode.

In this paper, a high speed video camera has been utilised to observe the near-nozzle spray instabilities caused by two different types of commercially available GDi injectors which feature different exit shapes. The first one is a 'conventional' symmetric-spray GDi injector while the second one features a step-exit nozzle with an asymmetrical spray shape. This geometric feature is affecting the atomisation process of the injected spray and seems to suppress the influence of the internal flow on the near-nozzle instabilities observed with the other injector. The next section of the paper describes the experimental test-rig, followed by presentation of representative spray images; the main conclusions are summarised at the end.

Experimental test-rig

Previous high-speed video studies of the near-nozzle region have all used shadowgraphy technique due to the inherent difficulties of providing enough light for high magnification imaging when using a continuous light source. However, despite the associated difficulties, Mie scattering was chosen as the preferred technique because it provides much clearer details of the spray structure which is important when identifying and following subtle structures within the spray. A Photron SA1.1 high speed camera operating at 100,000 fps was used for image acquisition so as to follow structures within the fast moving spray. The image size for all injection imaging was 192x192 pixels which resulted in a 2.4mm x 2.4mm image. The images were post processed to scale the pixel intensities from 0-255 using Matlab software which also allowed standard deviation images to be calculated during the steady state portion of the injection event. To achieve the required magnification a 135mm Nikon lens was used in conjunction with an in-house designed telescopic extension tube variable from 200mm to 1000mm depending on the configuration used. Continuous white light illumination was provided by an Arri 575W HMI lamp with the beam controlled by custom infra-red removal and three-stage focusing optics. The light was initially collimated using a 200mm diameter primary lens before being focused by a second 200mm diameter lens and a final focus lens of 50mm diameter. Heat removal consisted of a pair of hot-mirrors after the collimating lens followed by a pair of infra red filters between the final two focusing lenses.

The gasoline fuel injection system that provided the injectors with pressurised fuel consisted of a water cooled, two stage pump rig using a low pressure Bosch lift pump followed by a high pressure, three piston pump with a maximum pressure of 180 bar. The injectors were driven using an injector driver controlled by an in-house LabView control and monitoring program that allowed the injection duration and fuel pressure to be set. Two different injectors were chosen for the experiment to represent either end of the current market in terms of technology. Injector 1 was a 6-hole symmetrical multi-hole injector typical of the second generation spray guided injection systems found in the early 2000's was used to provide a bench mark. This is a commonly used injector in the automotive market, has a maximum working pressure of 120 bar, a nozzle hole diameter of 140µm and an L/D of 2.14. Injector 2 was a new 6-hole, asymmetric injector that is typical of the new generation of side-mount injectors with nozzles designed specifically to match a particular combustion chamber. The injector is tailored specifically to the 2.0 ltr TSI VW Golf which is a modern straight four engine utilising both supercharging and turbo charging for low and high rpm operation respectively **[23]**. The side mount configuration is used to reduce impingement of the fuel on the cylinder walls during heterogeneous operation and impingement on the piston crown during late injection when operating in stratified injection mode **[16, 18]**. The main nozzle section has a diameter of 180µm and a length to diameter ratio of unity where as the step has a diameter of 400µm and a varying length depending on the particular hole, though typically around 400-500µm. The injector also has an unusual internal configuration in that the internal upstream flow profile does not reach the needle seat from above, following the path of the needle as with most injectors. If fact it enters the needle seat area from the side, following four evenly spaced channels.

During this investigation the duration of all injection events was set at 2ms so as to provide a realistic spray duration as might be found within an operational engine that also allows a significant proportion of the spray to be within a steady state, full needle lift phase. Fuel temperature was set to around 20°C though its exact temperature within the injector body was not determined for this investigation. The single component fuel used was 2,2,4 trimethyl-pentane as this has very similar phase change characteristics and viscosity to high octane gasoline typically used by modern passenger vehicles.

Results and Discussion

During the course of the investigation, batches of images for a range of typical GDi working pressures were analysed to record spray instabilities that occurred in both injectors. Events were categorised into two separate types; firstly a phenomenon that will be referred to as spray flapping, and secondly a phenomenon referred to as spray ejection, though both are a flapping type event. Spray flapping was defined as a spray instability that caused an individual spray cone angle to fluctuate significantly, either symmetrically along its axis or resulting in the spray to shift off axis. Included in this is the visible change in instantaneous mass flow rate of an injection nozzle. This was usually found to occur in just one nozzle at a time though some flapping events occurred across multiple nozzles at the same time. The time scales for these events recorded ranged from a minimum of 30µs to a maximum of 150µs though typically the events lasted between 50µs and 100µs. An example of such an event can be seen occurring at the maximum working pressure of 120 bar in the central nozzle of injector 1 in Figure 1. Two features of the spray flapping in this instance can be distinguished. Firstly there is a 'flattening' of the spray evident in Figure 1.c, while from Figure 1.e onwards it can be seen that the central spray cone is shifted to the right. The likely cause of this is film cavitation extending further down the nozzle and blocking part of the hole, hence changing the axis of the spray.

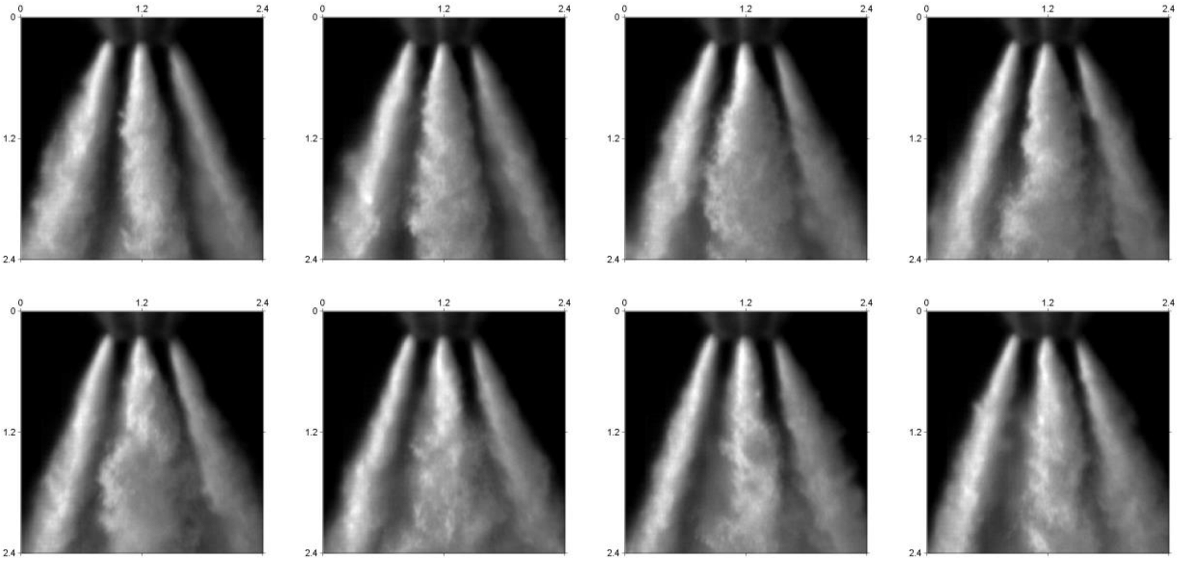

Figure 1.a-h. Spray flapping event occurring in the central nozzle of injector 1 at its maximum working pressure of 120 bar, in time steps of 10µs.

Spray ejection, the second type of instability that occurred, was defined as a small ejection of droplets from the main spray cone that did not alter the individual cone angle or structure of the parent spray, as documented by **[11]** and **[21]**. For such an event the droplets are ejected at an angle greater than 7.5° from the main spray and in this study, occur in timescales no more than 20µs, though it was found that the actual ejection from the nozzle occurred in timescales less that 10µs almost exclusively. Figure 2 shows such an ejection event occurring in the left hand nozzle of the Bosch injector at 60 bar rail pressure.

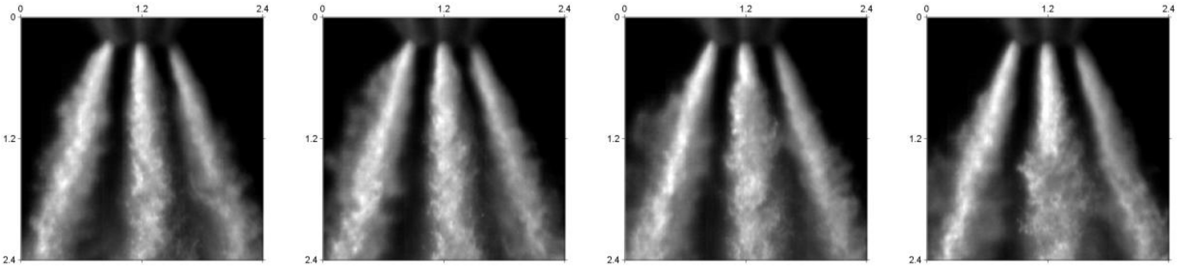

Figure 2.a-d. Spray ejection visible from the left hand nozzle of injector 1 at 60 bar rail pressure and time steps of 10µs.

A more significant, though statistically much less frequent, flapping event can be seen in Figure 4. Here a change in the quantity of fuel can be observed across all visible nozzles and suggests that an internal event has occurred to temporarily choke the nozzles. Despite these usually minor spray flapping events, injector 2 was shown to exhibit good spray stability and uniformity across individual spray cones. Other than dribbling at the EOI, no visible ligaments or large droplets were detected at any of the pressures investigated and the spray is observed as a fine mist of small droplets from the SOI right though the whole injection duration. For this study five different rail pressures were chosen to represent typical injection pressures at which a GDi injector would be operated at during the course of normal engine running. A maximum pressure of 120 bar was used with lower pressures investigated in increments of 20 bar down to a minimum of 40 bar; the lowest pressure that might be used **[23]**. The average number of ejection and flapping events per injection are shown for both injectors in Figure 3. Firstly it can be seen the number of both ejection and flapping events for all pressures was significantly higher for injector 1 than injector 2, save for spray flapping at the maximum pressure of 120 bar. However, it should be noted that the flapping events that occurred in injector 1 were of significantly higher intensity with a greater change in spray cone angles and disruption to the typical conical spray shape than in injector 2. Nearly all of the spray flapping events that occurred in the latter were very minor with very little change in the aforementioned parameters, though often distinguished by a visible change in the normally uniform spray distribution with some locally higher concentration of spray to one side of the cone.

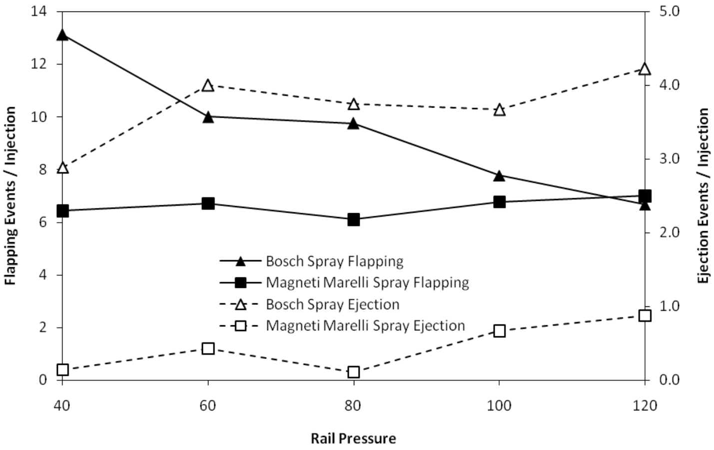

Figure 3. Graph showing the average number of both types of recorded spray instability for each injector.

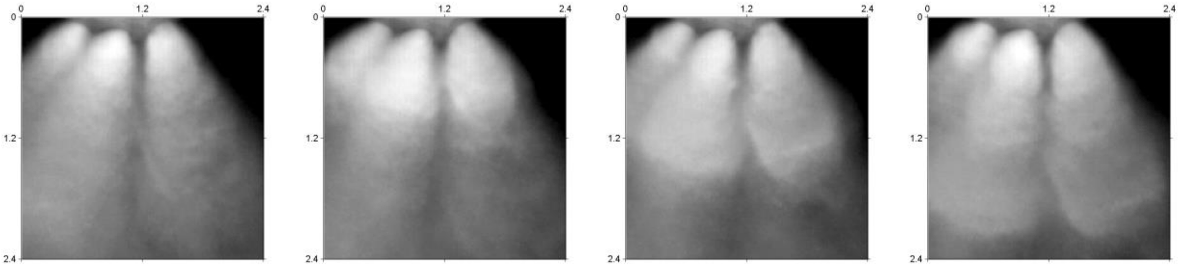

Figure 4.a-d. A rare spray flapping event across all visible nozzles of injector 2 at its lowest likely working pressure of 40 bar, shown in time steps of 10μs.

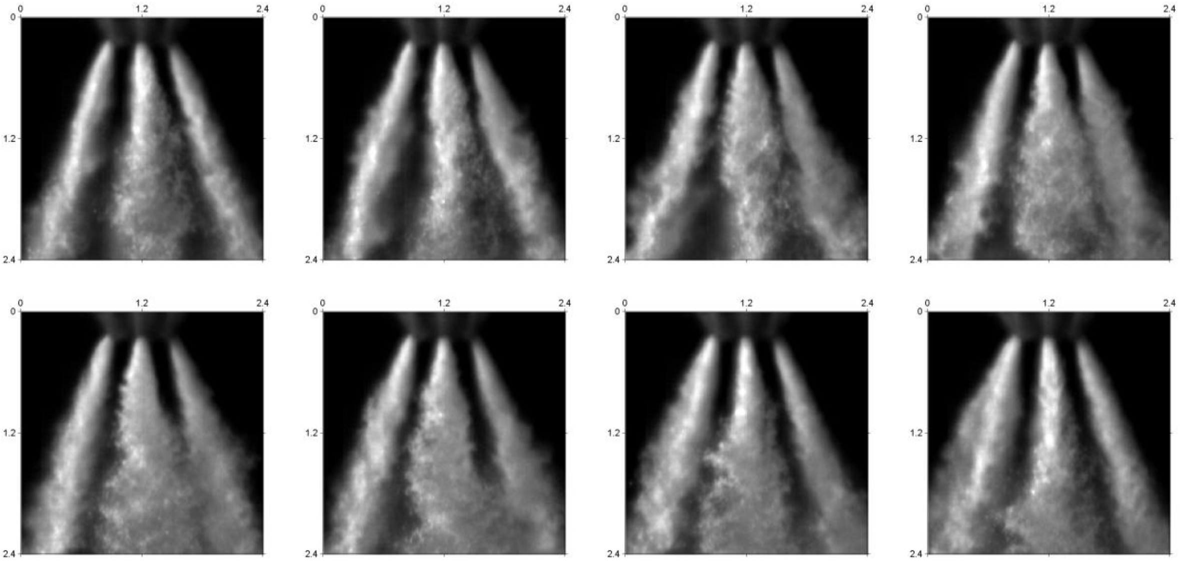

Figure 5.a-h. Spray flapping occurring across all three visible nozzles to different degrees, starting with the central nozzle, in injector 1 when operating at 60 bar rail pressure, shown in time steps of 10μs.

In comparison to the injector 2, injector 1 shows a noticeably less uniform spray with large droplets and ligaments present throughout the spray even during the middle of the injection phase at the maximum working pressure. While no liquid spray core can be visualised using the Mie technique in this experiment, it is likely that at these pressures most of the primary breakup takes place inside or just at the exit of the nozzle hole. However it is clear that a significant amount of the primary breakup of the resulting ligaments and droplets takes place in the near nozzle region, and to some extent, further along the spray path. This is typical behaviour of a cylindrical nozzle and confirmed by other studies in the near nozzle region **[8, 11, 21]** . At the lower end of the range of pressures investigated the spray uniformity of injector 1 decreases further. A flapping event in the central nozzle of injector 1 operating at 60 bar is shown in Figure 5 and the decrease of uniformity of the spray compared to Figure 4 can be observed. Also visible is the effect of the flapping of the central nozzle on the two outer nozzles, particularly in the second half of the images. The cavitation structures inside the nozzle responsible for this phenomenon either occur across all holes simultaneously, though to different extents, or the appearance of the structures in one nozzle induces further flapping effects, slightly delayed, in the other nozzles. **[11]** and **[21]** showed that spray ejection like events, when operating at the low pressures (40 bar and below) required for the single hole optical nozzles used in the investigations, occurred in reasonably long timescales of at least 100μs and the in nozzle imaging suggested that geometric cavitation was the cause. This is reasonable given the stability of geometric cavitation. As shown in Figure 2, the ejection events occurred in much shorter timescales of less than 10μs and as such it is unlikely that the same mechanisms are occurring in the real 6 hole injector. **[10]** and **[2]** have shown that the emergence of string cavitation is a much more rapid process generally and thus it is thought that the extension of a cavitation string to the nozzle exit is the likely cause for these ejection events.

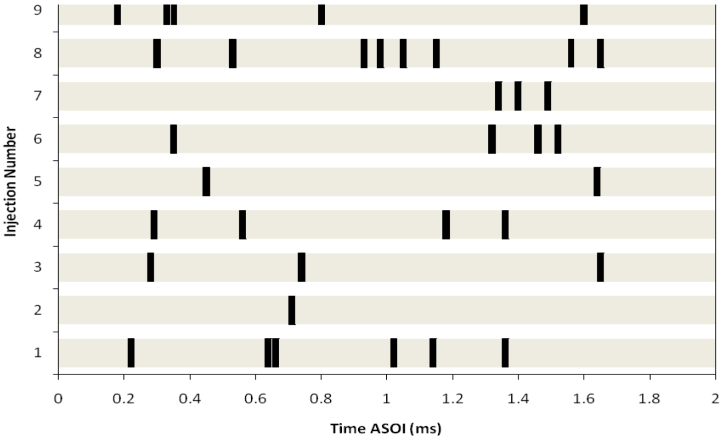

Figure 6. Spray ejection events occurring at 60 bar rail pressure in injector 1.

Recording the ejection events for a batch of 9 sequential injections using nozzle 1 and a rail pressure of 60 bar shows that the events are reasonably randomly distributed throughout an individual injection and the frequency at which they occur during an injection is reasonably widespread, as seen in Figure 6. However, it can be seen that there is some tendency for the events to group together. This could imply that either the same cavitation string is responsible for a group of events, its penetration along the nozzle hole varying, or that the flow field that creates these cavitation strings is able to occur in a reasonably stable fashion for such time periods and is responsible for a number of strings.

In injector 1, Figure 3 shows they occur reasonably frequently where as they are a much rarer occurrence in the spray of injector 2. Not only this, as seen in the left hand nozzle of Figure 7, the ejection events occurring in injector 2 are almost always smaller with respect to their ejection angle relative to that of the main spray. However this does not mean that string cavitation, at least the extension of it to the nozzle exit, is less frequent in injector 2. Due to the large step in the nozzle of the injector it is possible that such ejection events are 'captured' by the outer walls of the step and thus contained. It is also thought that the combination of the L/D ratio of 1 and the nozzle step is responsible for the increased atomisation and stability of injector 2, something that will be investigated in further studies. Another point of interest in the sequence in Figure 7 is that the fraction of the step exit that the fuel occupies as it leaves the central nozzle is not complete and in fact fluctuates.

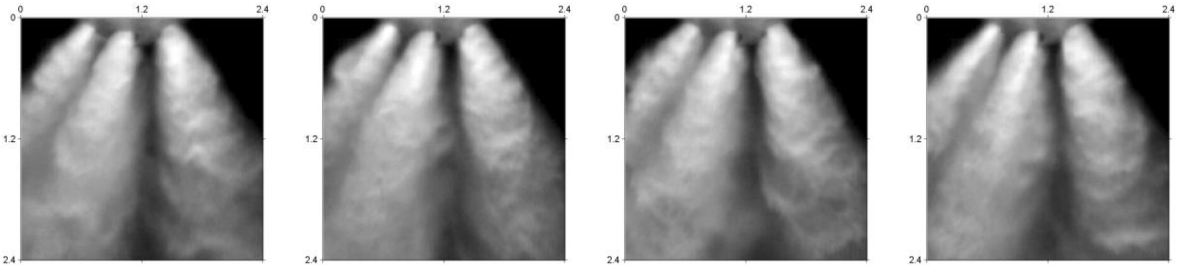

Figure 7.a-d. A small spray ejection occurring in the left hand visible nozzle of injector 2 at 120 bar rail pressure, shown in time steps of 10μs.

To further investigate the effect of rail pressure on the stability of the two injectors, standard deviation images were produced using Matlab software from batches of 90 injections, as shown in Figure 8 with the top row produced from injector 1 and the bottom row from injector 2. Only the main injection phase (i.e. not the needle opening or closing phases) were used for the calculations and all images are scaled by the same factor resulting in a 0-255 colormap of image intensity. Included for interest is a 20 bar rail pressure case, although this is not a condition used in modern multi-hole GDi injectors under working conditions. It is immediately clear that in the centre of the spray cones there is less deviation in the results from injector 2 while both injectors appear to exhibit similar levels of variation in at the peripherals of the spray, partly due to low frequency cone angle fluctuation. It can also be noticed, as expected, for injector 1 that on the whole as rail pressure increases the stability of the spray increases. This data is reflected in Figure 3 where an increase in pressure resulted in fewer average spray flapping events per injection.

The story is different for injector 2 though as on the whole, deviation from mean, especially in the centre of the spray cone, is increased as the pressure rises. The 20 bar case shows very little deviation and the raw data shows that at such low pressures the stability of the spray is very good. Even at pressures as low as 10 bar, injector 2 shows no evidence of ligaments exiting the nozzle step, though the droplet sizes are visibly larger than at higher pressures. This provides evidence that the effect of the step has a dramatic effect in the secondary breakup characteristics of the emerging spray. It is believed that the majority of the secondary breakup of the fuel occurs within the very small region of the nozzle step. To allow this to happen within such a small region and with very little time for air interaction, it is believed that the level of primary atomisation occurring in the short nozzle prior to the step must be substantially greater than injector 1. However at this time it is not known whether it is the unity L/D responsible or an increase in frequency or size of cavitation structures inside the nozzle due to the different flow profile within the injector that are responsible.

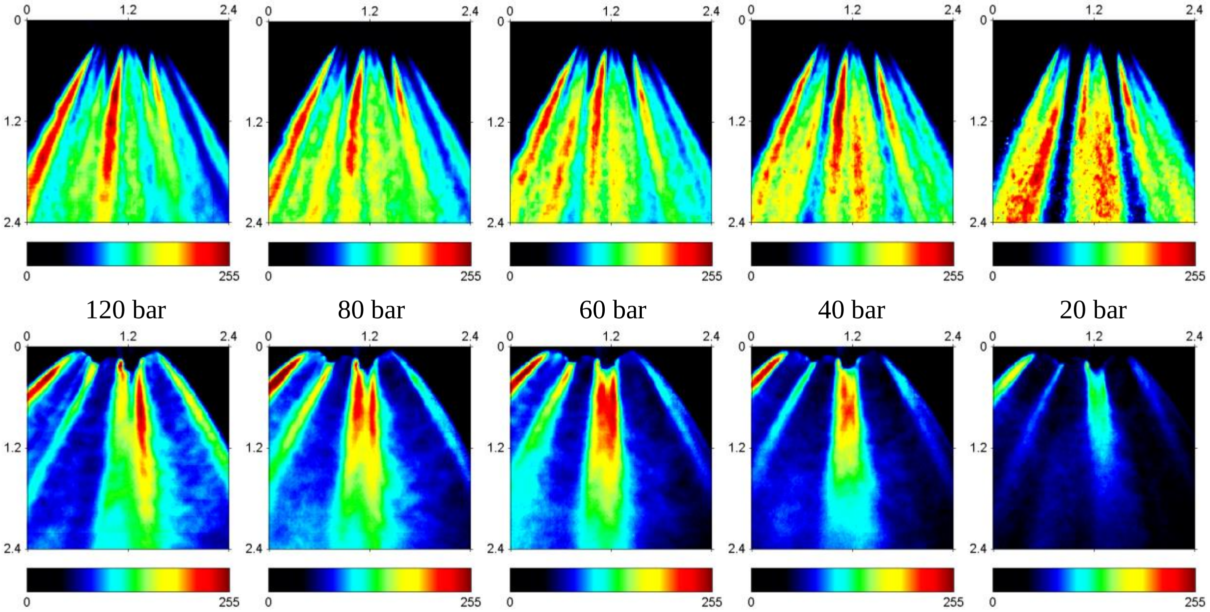

Figure 8.a-j. Standard deviation false colormap images for both injectors at different rail pressures on an image intensity scale of 0-255. Top row is injector 1 and bottom row injector 2.

Conclusions

An investigation into the near-nozzle flapping phenomena in gasoline direct injection sprays was undertaken on two different injectors. The two injectors were operated at a range of pressures typically found during normal operating conditions in a GDi engine; 120, 100, 80, 60 and 40 bar. The number of flapping type instabilities was recorded for each injector during the course of a number of injections and designated into two categories; spray flapping that effects one or more entire spray cones and spray ejection where a small quantity of fuel was ejected from the main spray at an angle greater than 7.5° and had no effect on the rest of the spray structure. The standard deviation images for the spray during the main phase of injection were calculated for each of the investigated pressures, as well as at a lower pressure of 20 bar for reference.

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Nomenclature

GDI - Gasoline Direct Injection
PFI - Port Fuel Injection
PM - Particulate Matter
SOI - Start of Injection
ASOI - After Start of Injection
SOC - Start of Combustion
CCD - Charge Coupled Device
HMI - Hydrargyrum Medium-Arc Iodide
L/D - Length to Diameter Ratio

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