A Fundamental Study of Liquid Sheet Breakup and its Relationship to GDI Sprays

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Many studies have been conducted to investigate the mechanisms of liquid breakup, however, the majority have concentrated on steady state low pressure conditions. It is felt that little can be applied from these studies to analyse the spray structure produced by high pressure GDI injectors which produce a complex hollow cone spray and have a transient nature due to the cyclic behaviour of an SI engine. This study briefly assesses the spray produced by a GDI pressure-swirl injector in the pressure range 10-50 bar. The fundamental study simplifies the problems by considering a transient liquid sheet and aims to characterise the sheet wave structure and breakup process, examining its relationship to GDI sprays. A specially designed rotary valve has been developed to allow the study of a transient flat liquid sheet. Initial results are summarised, and future work planned for varying nozzle geometries discussed.

1. Introduction

Developments in Gasoline Direct Injection, GDI, technology have enhanced the viability of long term SI engine development. This technology strategy is now under development with all the major automotive manufacturers, with many offering production GDI engines. GDI fuel injection strategies provide power and efficiency improvements, in a similar manner as direct injection common rail diesel engines, due to superior fuel metering, in-cylinder mixture preparation and the ability to run throttle-less and under different combustion modes depending on the engine load. Although significant improvements in performance and economy have been demonstrated, work is still required to optimise the GDI strategies as regards emissions. Matching the fuel break up and atomization timescales to those of the charge motion occurring in the engine is essential.

The overall goal of this study is to understand the near nozzle spray structure generated by GDI pressure swirl injectors. Although fundamental studies [1, 2, 3] have investigated the mechanisms of liquid break up at a fundamental level, the majority of these have concentrated on idealised two-dimensional nozzles under steady flow conditions at pressures an order of magnitude lower than those found with GDI injection systems. Due to the cyclic behaviour of an SI engine the spray produced by a GDI injector has a highly transient nature with maximum injection times of up to 5 milliseconds every 125ms, for an engine speed of 1000rpm. Little work has been conducted to investigate the break up of transient liquid sheets.

To help simplify a typical GDI spray, a swirling, three dimensional liquid cone with sheet thinning effects, an analysis of a flat transient liquid sheet has been pursued. This study omits the sheet stretching and swirl effects that are present with the pressure swirl injector. A rotary slit valve of 20 x 1mm has been designed to operate under the same fuel delivery conditions as the GDI injector to allow a detailed comparison between transient flat and conical liquid sheets to be conducted. Future work aims to study nozzles of varying geometries to analyse the effect of sheet thickness and divergence on the development and breakup of surface waves. This study investigates the sheet breakup phenomena associated with a GDI pressure swirl injector operating over a range of fuel pressures, and an initial assessment is made of transient two dimensional liquid sheets.

2. Experimental Rig and Test Procedure

A high pressure fuel injection rig, Figure 1, was developed specifically for the study of both the GDI injector and the flat sheet nozzles. The rig was designed around a high pressure Bosch GDI pump with the capability of fuel line pressures of up to 120 bar. The pump, designed to be driven on the end of the engine camshaft, was provided with a direct drive by a Marelli Motori 2.2kW induction motor. A FID1000 inverter drive was incorporated into the system to provide motor speed control from 500 up to 3,000 rpm. An adjustable and stable pressure was attained using a pressure relief valve with interchangeable springs to provide an accurate fuel line pressure range of 3-65 bar. The current work has focused on a fuel pressure range of 10-50 bar specifically to investigate the Mitsubishi GDI injector, which typically operates at a pressure of 50 bar. These tests were conducted under atmospheric conditions although back pressures of up to 3 bar should have little effect on the sheet development [4].

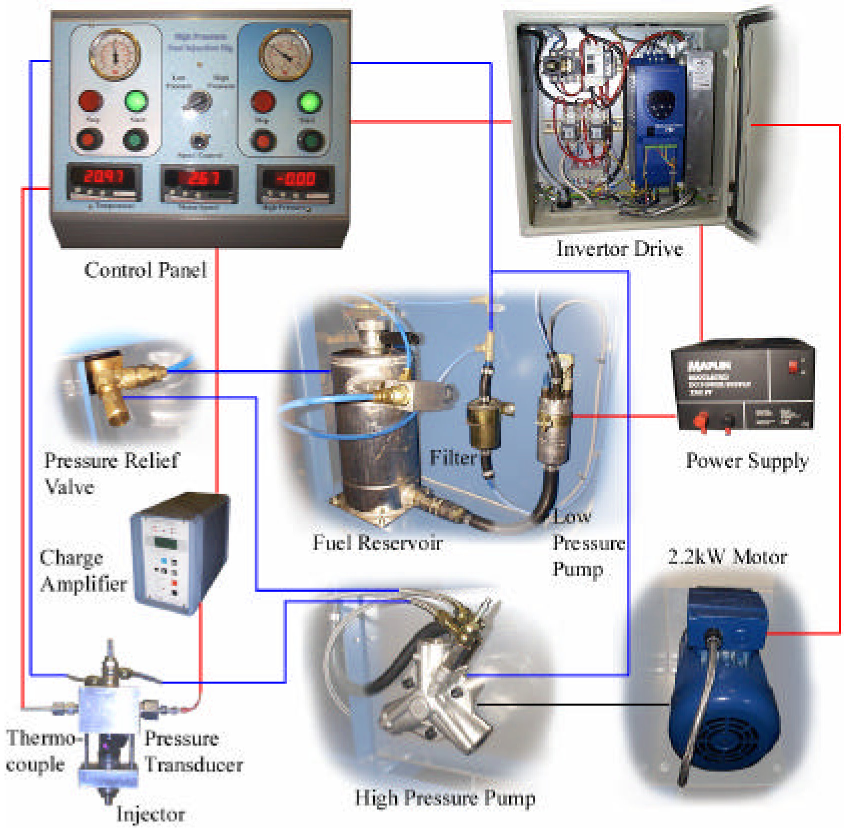

Figure 1. High pressure fuel injection rig

The liquid sheet structures were characterised using a CCD image analysis. To study the GDI spray a PCO fast shutter SensiCam SuperVGA 12 bit camera was used with a Nikon 55mm focal length macro lens to allow close up imaging of the spray. This provided an image size of 19 by 15mm represented by 1280 by 1024 pixels. Whilst studying the hollow cone GDI spray, the camera was angled at 30^o to place the image plane onto the front surface of the spray cone producing a focused image of the liquid sheet. To allow the spray cone to be visualised close to the nozzle orifice the injector nozzle was chamfered, at an angle of 30 degrees, to within 1mm of the orifice. Two EG&G MVS 7020 Xenon flash units were used, one linked to a Fostec fibre optic panel positioned behind the spray, to provide uniform back-lighting, whilst the second, connected to a Fostec fibre optic cable, illuminated the underside of the spray. An electronic trigger, at a frequency of 8Hz, was used to initiate the injector solenoid opening and, through a variable delay unit, to control the camera and the flash. A fuel injection duration of 1.0ms was used for this investigation, delivering approximately 11mg of fuel at 50 bar fuel line pressure.

The rotary valve, designed to produce a flat liquid sheet, Figure 2, consisted of a rotating aluminium bronze cylinder (1) inside a stationary stainless steel cylindrical housing (2). These materials were chosen to minimise friction since the cylinder was precision ground to provide a close running fit of only 4μm clearance around the circumference to minimise fuel leakage. Both (1) and (2) have a single spark eroded slot in the cylindrical walls on a plane through their diameters. Gasoline enters the cylinder chamber from one end of the rotating assembly and is emitted through the 1 x 20mm slot when aligned with the 1 x 30mm slot in the housing. A 1.7Nm AC brushless motor was used to drive the rotary valve through a 10:1 gearbox, providing 16Nm continuous and 30Nm peak torque. The 4A servo drive was programmed to rotate the cylinder once, at a speed of 150rpm, to provide an injection duration of 5.1ms. A range of interchangeable brass nozzles thin the sheet from 1mm to 0.15mm whilst expanding the sheet laterally, with a minimum aspect ratio of 200:1. An optical encoder was positioned on the drive shaft to provide one TTL pulse per revolution, to trigger two CCD cameras and the strobes simultaneously. The use of two cameras allowed front and side imaging of the flat liquid sheet. The TTL pulse was positioned as close to the opening point as possible to minimise any cycle to cycle variations. A signal delay unit was then used to increment the image capture time to allow an assessment of the temporal sheet development.

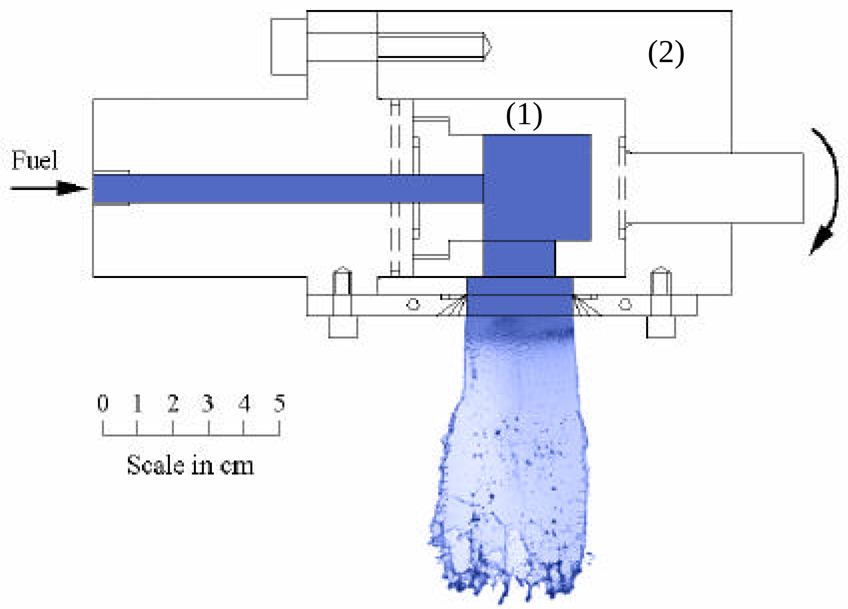

Figure 2. Rotary valve design showing direction of fuel flow

3. Discussion of Results

Droplet velocities and sizes in the near nozzle region of this GDI spray have already been characterised [5, 6]. However, the structure and breakup process has yet to be investigated. The following image analysis was performed at a time of 1.4ms after start of injection. The spray cone at this time was considered to have reached a steady state condition, examples of which are shown in Figure 3. A 1x1mm grid, superimposed on to the image, allowed structural shape, size and position to be quantified. The chamfered nozzle provided an improved field of view in the near nozzle region of 1.3mm. It was possible to identify 4 separate regions within the spray at injection pressures as low as 10 bar, 1) continuous sheet, 2) perforated sheet, 3) filaments, and 4) droplets. As the pressure was increased these regions progressively reduced in size, retreating towards the injector orifice. The complexity of the surface structure also increased with pressure due to the increasing aerodynamic and hydraulic forces accelerating the atomisation process.

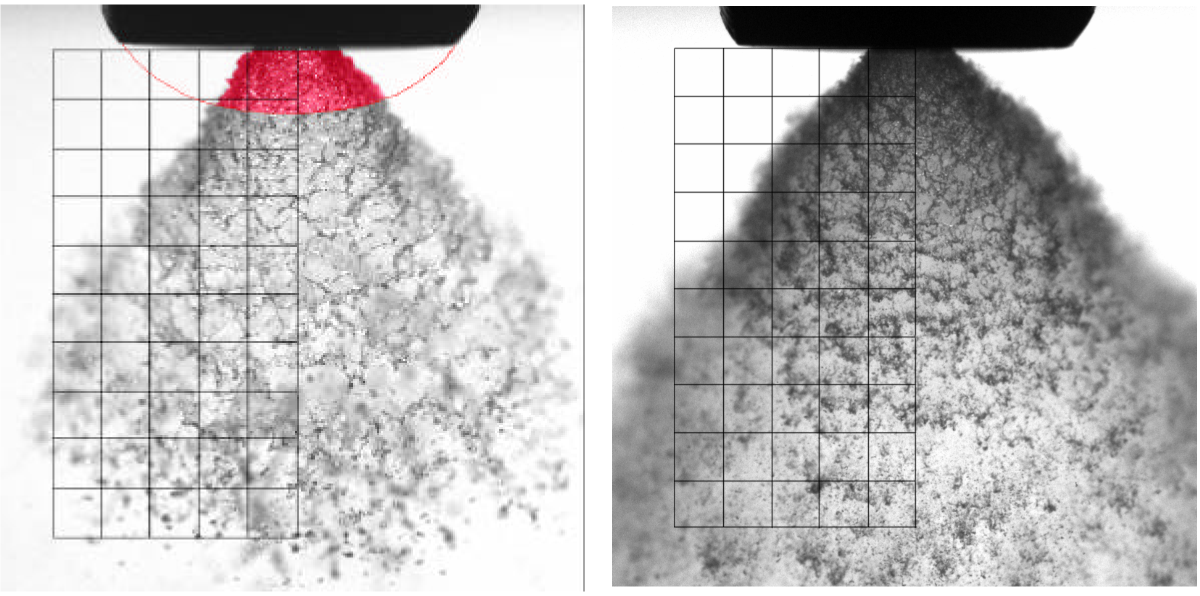

Figure 3. Spray imaging at 10 and 50 bar respectively

An initial assessment has been made of the wave structure simply by counting the waves present in the first 10 mm of the visible spray. The left hand graph in Figure 4 shows how the wave number varies with injection pressure, before and after chamfering the nozzle, series 1 and 2 respectively. The figure clearly shows that in both cases the wave number on the spray surface increases up to an injection pressure of 30 bar. Subsequent pressure increases provided less conclusive results as the complexity of the surface structure was too high for this simple evaluation method. A significant proportion of the wave structure is contained within the initial 2mm of the spray cone, accounting for up to 50% difference between series 1 and 2. Interrogating each millimetre of the spray cone separately provides a clearer picture of the spatial wave structure, the right hand plot in Figure 4. It was found that 25% of the spray wave structure was contained within the first millimetre and over 50% within the first 3mm. The wave frequency was based on the number of waves in a particular region and the measured liquid sheet velocity based on a double exposure image of the same injection. In the near nozzle region, 0 – 4mm, the wave frequency increases, rapidly at first, as fuel pressure is increased but, slowing down above 25 bar before increasing again at 45 bar. It is possible that the changing spray break up structure with injection pressure is responsible for this behaviour, effecting only the liquid sheet region.

The experimental arrangement provided an image resolution of 1 pixel representing 15 x 15µm, which limited the near nozzle analysis for pressures in excess of 30 bar due to an increase in small scale structures. However, the illumination of this near nozzle region has been the most significant limitation.

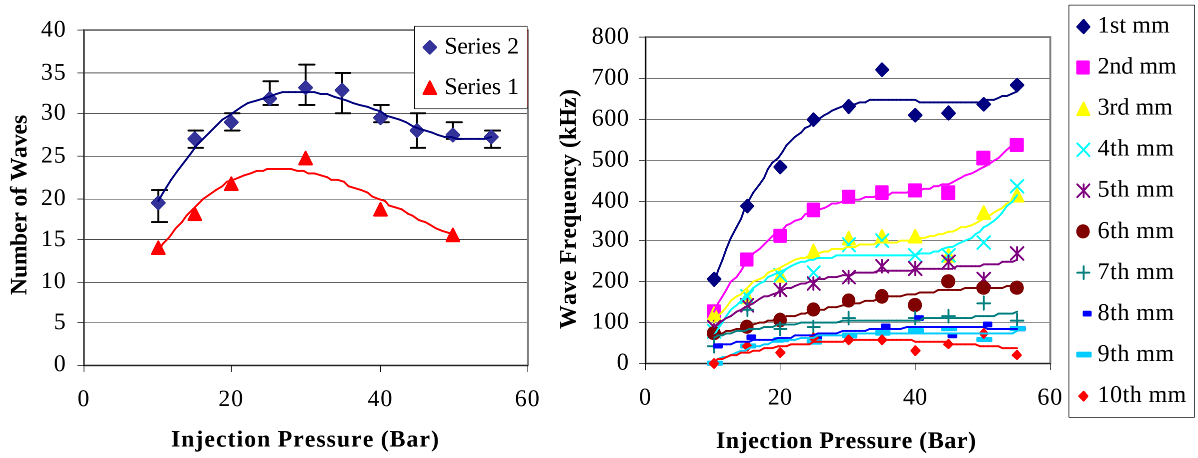

Figure 4. Effect of injection pressure on wave count and wave frequency

Due to the complexities associated with imaging a conical liquid sheet the investigation has endeavoured to simplify the problem by developing a transient flat liquid sheet. The rotary valve has been used to investigate the behaviour of a straight liquid sheet, 30mm x 0.1mm, in the pressure range 10 – 35 bar. To eliminate edge effects, which are not present on a conical sheet, only the central 10mm of the flat liquid sheet images was studied. A datum time was chosen, just prior to the emergence of liquid from the slot, with subsequent image times referenced to this datum in 1ms steps until the end of injection as shown in Figure 5. The 10 x 10mm scale illustrates a field of view of approximately 60 x 100mm, providing pixel resolution of 79µm. During the initial 1ms the emerging liquid fuel sheet is highly turbulent as the high pressure fuel interacts with the static fuel inside the nozzle left from the previous injection. As the spray tip penetrates ligaments and perforations form at the leading edge with the flat liquid sheet following behind. The liquid sheet was considered to be most stable at a time of 5ms, just prior to the valve closing. In the near nozzle region the stable sheet exhibits fine lateral waves, similar to those observed by Hashimoto [7], with a wavelength estimated at 0.3mm. These decay over the first 10mm of the sheet whilst longitudinal waves propagate further downstream and, in some cases, form ligaments.

Double images of the sheet surface and cross-section, shown in Figure 6, illustrate a change in liquid sheet structure with injection pressure. Under an injection pressure of 10 bar, there are two distinct regions, the turbulent spray tip at the leading edge and stable liquid sheet behind. At the higher pressure of 30 bar, the large scale waviness of the sheet viewed from the side disappears as the mass flow and hence sheet velocity increases. As the injection pressure increases it is clear that aerodynamic shear forces play an increasing role in the break up of the liquid sheet. The number of perforations in the sheet increases and the surface wave structures become more complex downstream from 50mm. Although on a different scale, similar behaviour has been observed with the GDI pressure-swirl spray, however further work is required before a direct comparison can be conducted.

It was found that the analysis of a mean sheet image, built up from 5 single shot images at each test condition, were sufficient to provide consistent measurements of sheet penetration and break up length. The analysis of 10 images showed only a maximum variation of 6%. Shot to shot variations at the highest pressures accounted for a maximum of 8% of the total sheet penetration, and measurement errors were +/- 79µm based on image resolution.

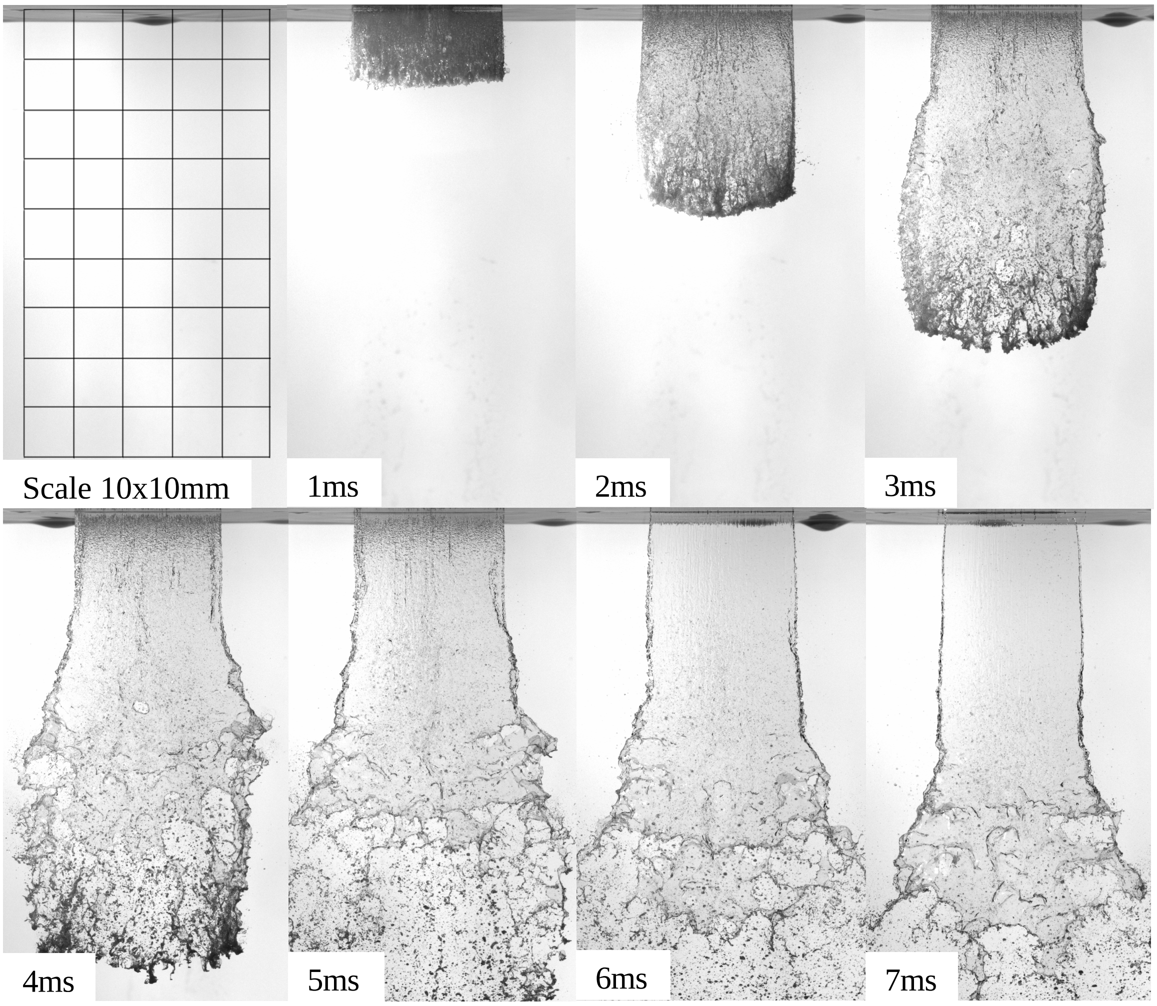

Figure 5. Development of flat liquid sheet under 20 bar injection pressure in 1ms steps

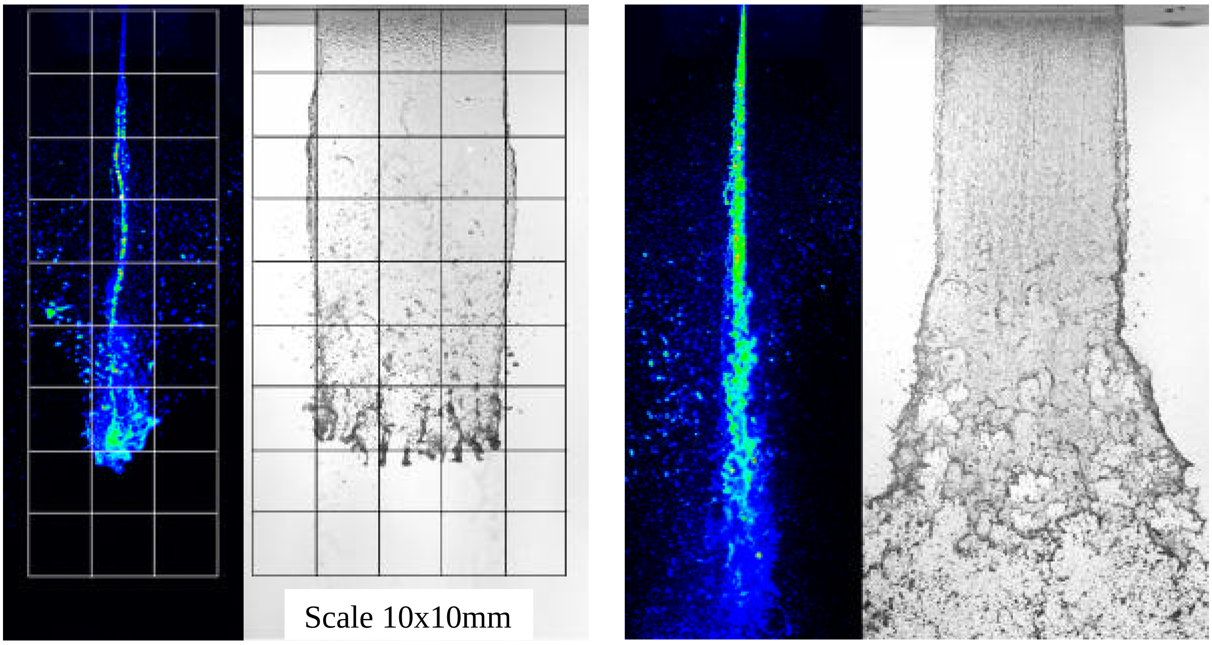

Figure 6. Flat liquid sheet 5ms after SOI at 10 and 30 bar injection pressure

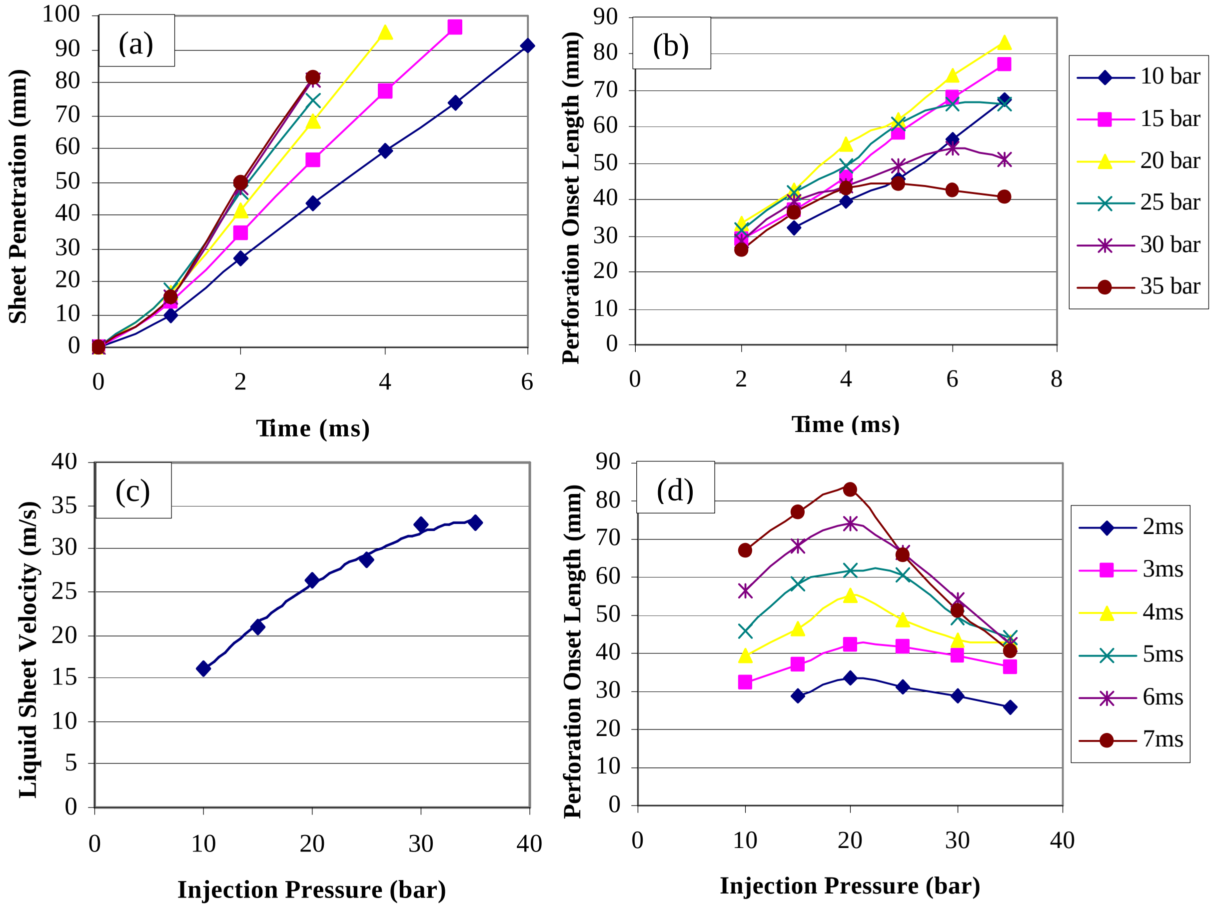

Figure 7. Plots to show temporal sheet penetration and perforation onset length

The temporal sheet penetration follows a well defined linear relationship for all conditions, shown in Figure 7a, and, as expected, increased with increasing injection pressure. For injection pressures up to 20 bar, the onset of perforations in the liquid sheet, 7b, steadily moves downstream as the sheet penetrates further. As the injection pressure is increased above 20 bar the position of these initial perforations reaches a maximum, indicating the break up length of the liquid sheet. The break up length for pressures below 20 bar was not observed, partly because the image size was too small to encompass this point, but primarily because the injection duration was too short to allow a full sheet to develop. The liquid sheet at low injection pressures appears stable with most of the break up occurring in the turbulent leading edge.

The gradients of the sheet penetration plots have been measured to provide estimated liquid sheet velocities which is plotted against injection pressure in Figure 7c. As expected the sheet velocity increases with injection pressure as measured at the cylinder inlet. It is evident that there is a large pressure loss across the nozzle orifice with experimental liquid sheet velocity values only 30–40% of the theoretical value. Future work aims to assess the sheet velocities and surface structure using a PIV technique.

The plots in 7d, showing perforation onset lengths at discrete times, have a 2ms gap in the results as perforations do not develop immediately. All the plots peak at 20 bar and subsequently the perforation onset position reduces for further increases of injection pressure. This indicates that, at 20 bar, aerodynamic shear forces dominate the break up process. The onset of holes in the sheet, retreats towards the nozzle with additional pressure rises; a trend also seen with the GDI spray. Towards the end of injection the perforation onset distance reduces significantly as the pressure rises above 20 bar. This is likely to be caused by a relaxation and thinning of the liquid sheet as the valve closes. It is more apparent at the higher pressures because the nozzle empties the liquid gasoline quicker.

4. Conclusions

A rotary valve has been developed to allow the study of two dimensional transient liquid sheets for the purpose of gaining an improved understanding of the more complex hollow cone spray produced by a GDI pressure-swirl injector. Early analyses of both the Mitsubishi hollow cone spray and transient flat liquid sheet have been carried out with the future view of conducting a detailed comparison of the two sprays.

Operating with an injection pressure of 10 bar, 4 separate regions were identified on the hollow cone spray, 1) continuous sheet, 2) perforated sheet, 3) filaments, and 4) droplets. These regions reduced in size, retreating towards the nozzle as the injection pressure was increased, whilst the surface structure increased in complexity.

The rotary valve nozzle was configured to produce a straight flat liquid sheet of dimensions 30mm x 0.15mm, with only the central 10mm analysed to avoid liquid edge effects. A perforation onset distance was measured for an injection pressure range of 10 – 35 bar. Liquid sheet break up lengths were only observed at pressures exceeding 20 bar, mainly because the short injection duration did not allow full sheet development at the low pressures. Based on these results it was evident that aerodynamic forces start to dominate the break up process at pressures higher than 20 bar.

Further work is planned which will involve a PIV analysis of the surface waves on the transient liquid sheet [8]. This will determine their velocities and wave frequency as a function of pressure as the spray develops throughout the injection process. Various nozzle designs will be studied to investigate the effect of liquid sheet thickness and sheet stretching, thought to be a contributing factor in the development of perforations.

5. References

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