The structure of propane/LPG sprays from automotive fuel injectors as a function of fuel and ambient pressure by Mie and LIF imaging

by

M.C. Jermy [(1)], A.K. Vuorenkoski[(1)], T.I. Mohamed[(1)], E. Kaparis [(1)], M. Harrison[(1)] and M. Macartney[(2)]

[(1)]DAMSE, School of Engineering

Cranfield University

Cranfield

Beds MK43 0AL

United Kingdom

http://www.cranfield.ac.uk/soe/departments/optical.htm

E-Mail: m.jermy@cranfield.ac.uk

[(2)]Jaymic Ltd, www.jaymic.co.uk

ABSTRACT

When a gasoline engine is converted to propane (LPG, Autogas) there is usually a reduction in power. This loss can be mitigated by careful design of the injection system such that the heat required for evaporation of the LPG is drawn from the intake air and not the intake walls. The air is cooled and densified, resulting in an increase in volumetric efficiency. To do this effectively requires the injector spray pattern to be known. There are many studies on the structure of gasoline sprays, but few of LPG sprays.

In this work we have imaged LPG sprays from a gasoline direct injection (GDI) injector, a port fuel injector, and from long and short pipes usually used to connect a remote LPG metering valve to the injection point in the manifold. Both Mie and LIF imaging have been used. For the LIF, acetone is added to the LPG. Images were taken in an optically accessed pressure chamber at pressures from atmospheric to 20 bar and with fuel line pressures from 10 to 80 bar.

The imaging of the pipe-coupled injection system shows that (1) there is significant but not complete evaporation in the pipe, the amount of evaporation depending on the length and diameter of the pipe, and (2) during its travel down the pipe the injected pulse of fuel spreads out so that the duration of the LPG pulse at the manifold end is, for 300mm pipes, five times the original duration at the injector, and even greater for 600mm pipes such that fuel is always emerging from the pipe. When fuel evaporated in the pipe the latent heat required is taken from the pipe wall and not from the induced air, where it might usefully cool and densify the air, boosting engine torque. The fuel emerges from the pipe in a narrow jet. This may be less conducive to good mixing than the broad spray which emerges from the close coupled system (which has the injection valve mounted directly on the manifold.

The structure of the sprays and the amount of evaporation that occurs before the fuel enters the manifold explains the observed differences in engine torque and in-cylinder mixture temperature observed with the different systems.

The spray structure of the direct injector is similar with gasoline and LPG. The spray structure is more sensitive to changes in fuel or chamber pressure than to the type of fuel. The droplet size may vary with fuel type, resulting in a different spray structure when exposed to the strong in-cylinder air motion of a direct injection engine.

1. INTRODUCTION

LPG (propane, Autogas) is of interest as a low cost, low pollutant emissions alternative fuel for cars and trucks. LPG is cleaner than gasoline in that it tends to produce less particulates, carbon monoxide (CO) and unburnt hydrocarbons (UHC) (Poulton, 1994, Sher, 1998). Gasoline engines have been converted to LPG for 40 years, initially with simple Venturi type LPG vapour-air mixing devices but recently with more sophisticated systems including sequential injection of liquid LPG in the intake port, and direct injection of liquid LPG into the cylinder. Many conversion systems are available but most cause a significant (~10%) reduction in torque relative to the original gasoline or Diesel engine (Watson and Milkins 1982, Caton et al. 1997, Shehata 2001). In some cases this means the engine is no longer fit for purpose, in others the engine will function but the loss of driveability discourages the driver from converting the engine. This loss can be mitigated by careful design of the injection system. If the heat required for evaporation of the LPG is drawn from the intake air and not the intake walls, the air is cooled and densified, resulting in an increase in volumetric efficiency and ~6% increase in power (Jermy et al. 2004).

As with gasoline it is also important to achieve good fuel-air mixing. There are many studies on the structure of gasoline sprays, but few of LPG sprays.

In this work we have imaged LPG sprays from a gasoline direct injection (GDI) injector, a port fuel injector, and from long and short pipes usually used to connect a remote LPG metering valve to the injection point in the manifold. Both Mie and LIF imaging have been used. For the LIF, acetone is added to the LPG. Imaged were taken in an optically accessed pressure chamber at pressures from atmospheric to 20 bar and with fuel line pressures from 10 to 80 bar.

Measurements of engine torque and in-cylinder mixture temperatures in a gasoline engines converted to LPG with each of the three port injection systems are discussed in terms of the spray structure.

2. EXPERIMENTAL METHOD and PROCEDURES

2.1 Injection systems

The port injection LPG systems are sequential port injection systems with one LPG injector for each cylinder, an exhaust oxygen (lambda) sensor and closed loop control of the injection duration. One LPG system (hereafter called the 'close coupled LPG system' or CCLS) has the injectors mounted directly on the intake manifold, within 100mm of the inlet valve. The second LPG system (hereafter called the 'pipe coupled LPG system' or PCLS) was the identical to the CCLS but that the injectors were not mounted directly on the manifold. Instead they were connected to the manifold by flexible hoses 2mm in diameter. The pipes were used so the injectors could be mounted in a more convenient place. The connection on the manifold was in the same place as the CCLS.

These systems have been installed as both mono-fuel systems and bi-fuel systems capable of switching rapidly between gasoline and LPG and have operated successfully on a 1.0 litre gasoline Nissan Micra engine (Jermy et al. 2004). Like all sequential closed loop systems they gives good transient response and a balanced, near stochiometric air fuel ratio (AFR) over all cylinders resulting in low pollutant emissions.

The LPG is kept liquefied until the injector tip. Since the fuel is injected as a liquid, and evaporates only partially in the manifold, the system gives better volumetric efficiency than a gas injection system. There is an additional benefit from charge cooling. The liquid partly vaporises in the manifold and the vapour expands. Some of the energy required for the latent heat of vaporisation and the PdV work of expansion is supplied by the inducted air (Jermy et al. 2004). Consequently this air is cooled, the mixture density increases and the mass of mixture (and hence total heating value of the mixture) inducted per cycle increases, hence the engine torque increases. A secondary benefit is that knock is less likely in the cooler mixture so the spark can be advanced further, increasing torque. The spark advance due to cooling adds to the advance due to the higher RON of LPG relative to gasoline (Watson and Milkins 1982, Caton et al. 1997, Shehata 2001).

The LPG direct injection system is designed to mimic a system which might be used for injection of the LPG direct into the cylinder of a gasoline direct injection engine, combining the high cycle efficiency of the direct injection engine with the low pollutant emissions of the LPG fuel. It consists of a gasoline direct injection injector and solenoid driver, connected to a reservoir of LPG pressurised with a nitrogen bottle. A dip tube ensures that only liquid fuel form the

bottom of the vessel reaches the injector. The injector was given a current pulse of 1ms total duration from a peak and hold driver. The peak current was 9A and the hold current 3.5A.

The measurements were repeated with commercial gasoline to compare the spray patterns of the two fuels.

The fuels were BP LPG or Total unleaded gasoline bought at UK filling stations. UK LPG is typically 96% LPG and meets BS4250:1997.

2.2 Test rig

The injector (or pipe) was mounted in the Cranfield sprays bomb (Fig. 1), a pressure chamber rated to 25bar with good optical access for measurements of fuel injectors.

For the port injection system measurements, the chamber was kept at atmospheric pressure and purged periodically to clear the accumulated fuel. Fuel pressure was 15 bar and injection duration was 5 ms.

For the direct injection system, the bomb was pressurised to 10, 15 or 20 bar and purged periodically. The nitrogen temperature was 20°C. The fuel pressure was set to 20, 50 or 80 bar. The injector current pulse lasted 1ms. Only Mie images were taken.
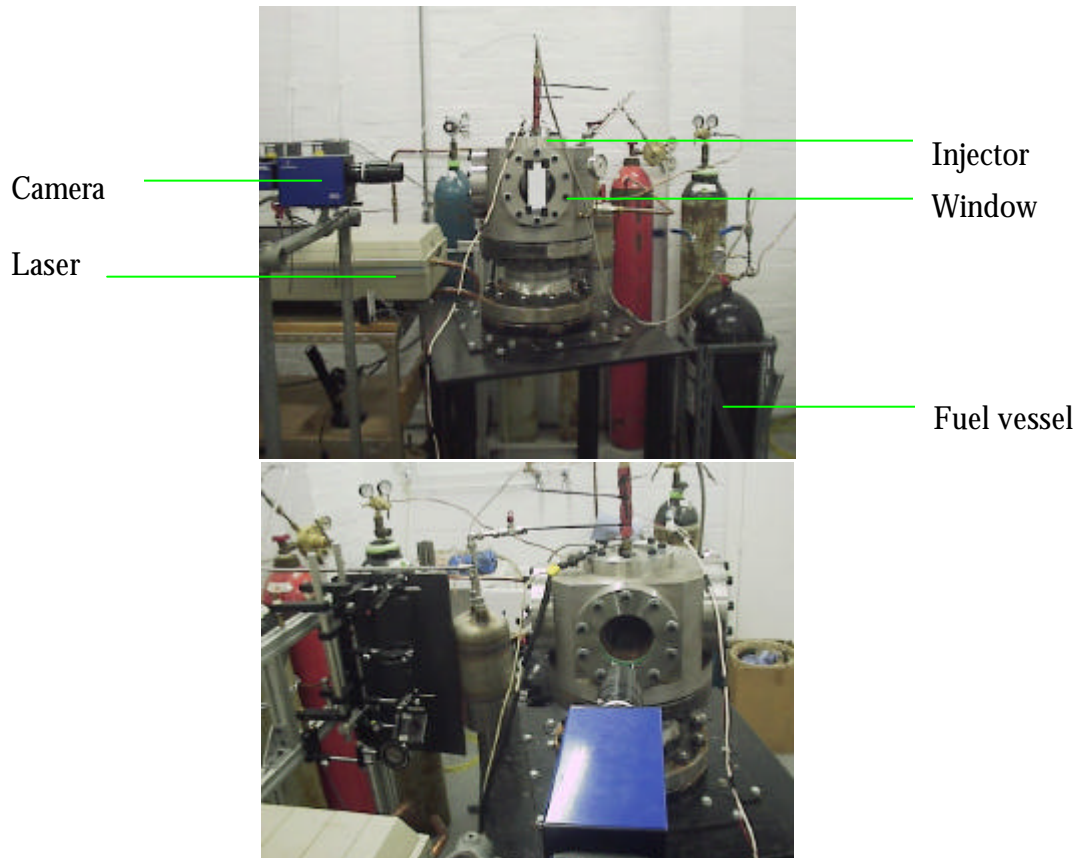

Figure 1. Cranfield 25 bar optically accessed sprays bomb

2.2 Imaging system

The plume of fuel emerging from the injector valve (in the case of the direct injection and close coupled systems) or the end of the 2mm diameter pipe (in the case of the pipe coupled systems) was imaged. The plume was illuminated with a 45-60mm high, 0.5mm thick light sheet from the fourth harmonic (266nm) of a Spectra Physics GCR Nd:YAG laser with 100-200mJ/pulse. The plume was imaged with a LaVision SprayMaster 3 camera with image intensifier and 105mm Nikkor UV lens. Two sets of images were taken. Laser Induced Fluorescence (LIF) images were taken of fluorescence emitted a by 8-

10 vol% acetone mixed with the LPG using a Schott WG360 filter. Mie-scatter images were taken without a filter. The LIF is emitted by both droplets and vapour and the signal is proportional to the local mass concentration of fuel independent of physical state. The Mie scatter is only caused by droplets, so the Mie images show the location of the liquid fuel. The Mie signal is proportional to the total droplet surface area in a region.

For the port injection systems (CCLS and PCLS), images were taken at 7-10 different times after the start of the injector current pulse. At each time, 20 images were taken from successive cycles.

For the direction injection system, the laser pulse energy was ≈100mJ for LPG and ≈200mJ for gasoline. The camera settings were f/8, intensifier gate 200ns, intensifier gain 60, camera gain 95. Images were taken at 14 different times after the start of injector current. 20 images were taken at each time setting, from subsequent injection events.

For all systems the images were averaged and corrected for background intensity and light sheet intensity variations with LaVision DaVis 6.2 software.

3. RESULTS AND DISCUSSION

3.1 Port injection systems

The images of the fuel plumes from the port injection systems are shown in Fig. 2. The images are on a false colour scale with hot colours (red, orange, yellow) indicating high intensity i.e. high droplet concentrations and cold (green, blue) indicating low intensity. Note the time of the image is since the first appearance of fuel rather than since beginning of injector current. The PCLS systems have a transport delay between injector opening and fuel appearing at the end of the pipe.

The close coupled injector shows a wide plume of fuel emerging from the injector valve and mixing with the surrounding air. The structure of the LIF and Mie images differs, with the Mie showing a bright central core, and the LIF showing a more even intensity profile. This indicates that the central core contains many droplets, which evaporate as they reach the tip and edges of the plume.

The pipe coupled injectors show a narrow jet of fuel. The Mie and LIF images have similar structure indicating that the distribution of droplets more even than for the close coupled injector. The Mie images are much weaker for both pipe coupled injectors, indicating that the number of droplets remaining at the end of the pipe is much lower than the number emerging from the injection valve: much of the liquid has evaporated in the pipe. The dark region on the centre of the PCLS long LIF images is due to imperfect background subtraction.

During its travel down the pipe the injected pulse of fuel spreads out so that the duration of the LPG pulse at the manifold end is, for 300mm pipes, approximately five times the original duration at the injector, and even greater for 600mm pipes such that fuel is always emerging from the pipe for engine speeds ~1000rpm.

The structure of the CCLS fuel plume changes significantly with time over the first 1.5ms. In contrast after a 0.5ms period during which the basic structure is established, the structure of the jet from the pipe coupled injectors remains approximately constant with time, although the amount of fuel increases and decreases. The concentration along the centreline is not a good fit to the Kleinstein theory for the structure of compressible free jets (Kleinstein, 1964) perhaps because the jet still contains significant mass of droplets whose dynamics differ from that of the gas.

The constant of proportionality relating pixel intensity to colour is chosen for each injector and image type (Mie or LIF) to best display the structure of the image. However the constant is the same for all three sets of Mie images. The PCLS long Mie images are weaker than those of the PCLS short indicating that the longer pipe leads to more evaporation of the fuel before it emerges.

The wide plume of the close coupled injector suggests that in the engine manifold it will achieve much earlier and more complete mixing of the fuel and air than the pipe coupled system. The lack of liquid fuel in the plume of the pipe-coupled system suggests that much of the fuel has evaporated, leading to low volumetric efficiency due to the space occupied by the vapour state fuel and due to the lack of liquid left to generate charge cooling. This vapourisation in the pipe also leads to a longer period during which fuel emerges from the pipe which can affect mixing.
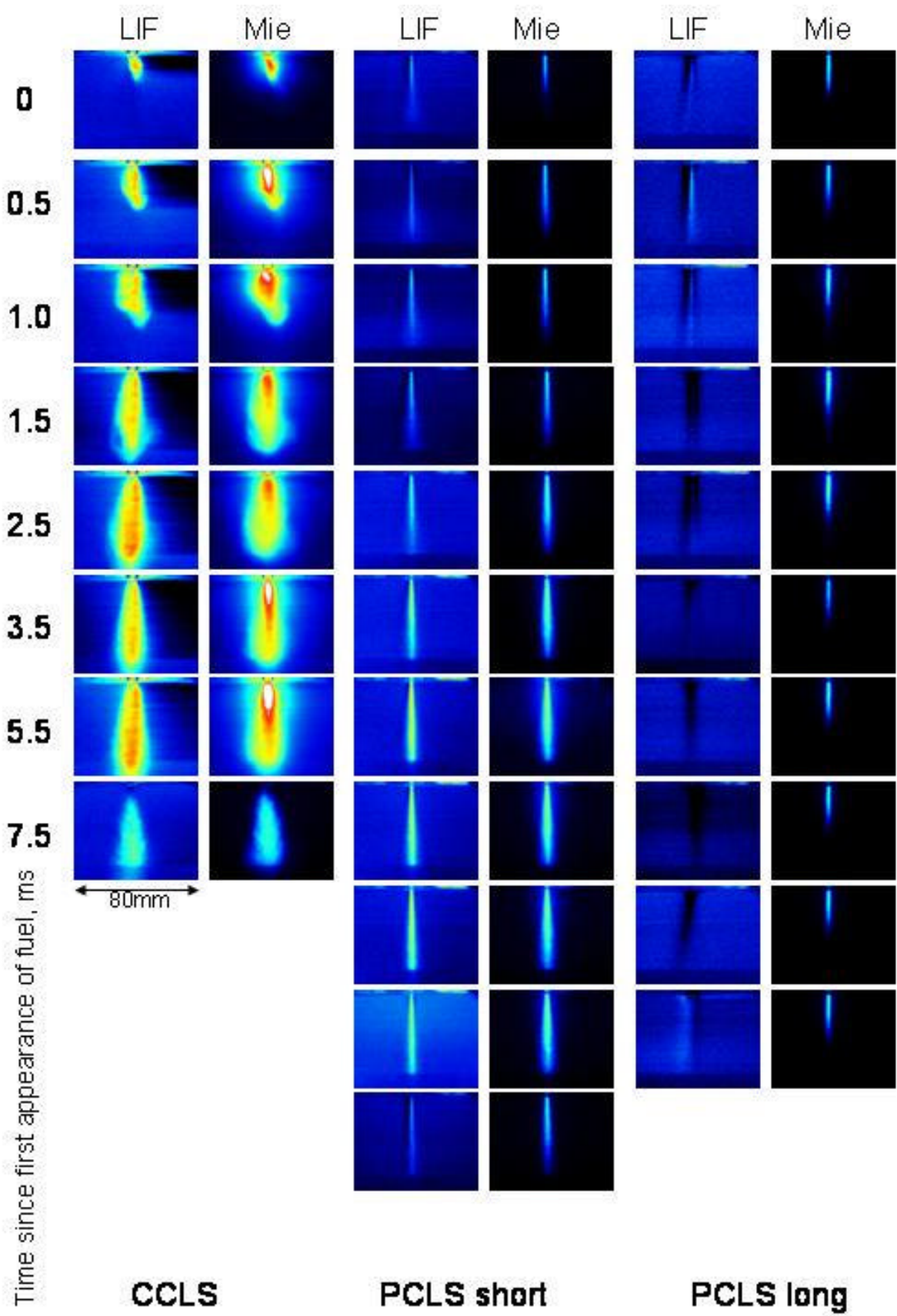
Figure 2. LIF and Mie images of the port injection system fuel plumes

The pipe configuration affects the engine torque. Fig. 3 shows the torque measured at 3000 rpm, wide open throttle with close-coupled injectors, and with pipe-coupled injectors with pipes of length 600 and 300mm length, and 2 and 4mm diameter (Jermy et al. 2004). The figure clearly shows the torque advantage of close coupled injectors. It also shows that the pipe diameter is more important than pipe length. The smaller diameter the pipe, the better the torque, due to the smaller surface area for heat transfer and to the increased velocity of the fuel, leaving less time for heat transfer and vaporisation in the pipe. The shorter the pipe the better the torque.
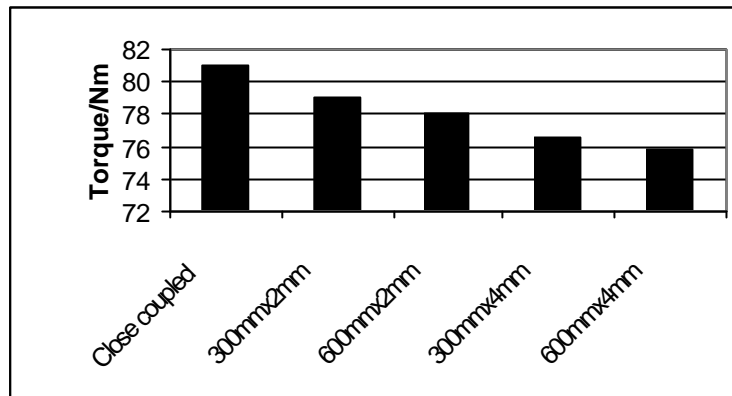

Figure 3. Engine torque with different pipe configurations

To investigate the degree of cooling, the temperature of the mixture in cylinder 1 was measured with a 13μm wire diameter type K thermocouple inserted through a dummy spark plug at 2000rpm (Jermy et al. 2004). The engine was run on the other three cylinders: there was no combustion in cylinder 1. The temperature was logged with a LabView system and the minimum temperature reached in each cycle captured, and averaged over ten cycles. The measurement was repeated with injection on cylinder 1 switched off to give the temperature of a pure air charge without any cooling due to fuel vaporisation. The difference between the minimum cycle temperatures with and without injection is caused by the vaporisation and expansion cooling of the fuel and is given in Table 1.

The presence of the fuel causes a 14K drop in temperature for the close coupled LPG system due to the evaporation of the LPG. For gasoline the temperature drop is similar, as the gasoline also vaporises. The pipe-coupled LPG system however gains the energy required for vaporisation through the pipe walls rather than from the inducted air: this results in a much smaller 5K drop in mixture temperature.

A simple model of the effect of charge cooling on torque predicted the improvement in torque due to close coupling of the injectors to within 1%, suggesting that charge cooling is the principal mechanism behind the torque advantage of close over pipe coupling (Jermy et al. 2004).

CCLS	-14.3	±	2.4K
PCLS	-4.9	±	2.4K
Gasoline	-13.0	±	2.2K

Table 1.Mixture temperature variations in cylinder with different pipe configurations

3.2 Direct injection system

Fig. 4a-c shows three individual Mie images for comparison. All are taken with fuel at 80 bar, nitrogen in bomb at 15 bar and are at 2.2ms after the injector current begins. The instantaneous image of LPG (Figure 4a) shows the turbulent mixing of the spray with the surrounding gas. The vortices are not visible in the average LPG image (Figure 4b)as they vary from shot to shot and are averaged away.

To scale the image, the ellipse in the top left corner is 1cm long and its top is level with the injector tip.
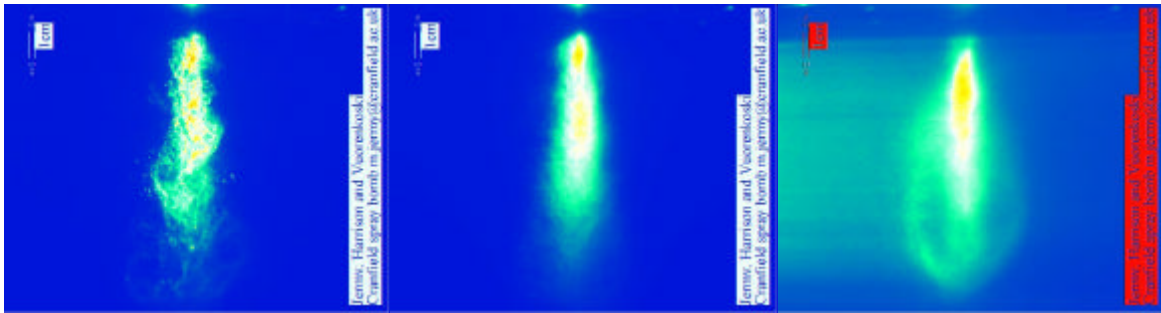
Figure 4.Direct injection system at 80 bar fuel pressure, 15 bar chamber pressure. (a) LPG, instantaneous image, (b) LPG, 20 shot average, (c) gasoline, 20 shot average

The average Gasoline image (Figure 4c) shows a very similar spray structure to LPG. The glow to the left of the spray (on the laser side) is due to the mist of fine droplets which persist from previous injections. This is not seen with LPG as the fine droplets evaporate faster. The gasoline spray appears less symmetric than the LPG. This is because the gasoline absorbs the ultraviolet light as it passes form left to right. LPG also absorbs the light, but more weakly.

The constant of proportionality that relates pixel intensity to colour is differs for the gasoline and the LPG images. The value chosen for each fuel is optimised to make the spray structure most clearly visible in the images.

Figure 5 shows three sequences of Mie images, each at the same fuel pressure but with different chamber pressure. As the chamber pressure increases the spray penetration length decreases and the cone angle increases. The change on length and angle is greater when raining the pressure from 20 to 50 bar than from 50 to 80 bar. The structure of the direct injector spray is similar to that of the CCLS injector (Fig. 2) with a concentrated core and diffuse outer. The spray has reaches its maximum penetration length shortly after the injector current ends at 1ms. After this point the structure remains constant although the concentration at all points decreases with time. Measurable levels of spray persist for ~12ms.

Figure 6 shows three sequences of Mie images at the same chamber pressure but with different fuel pressures. For the same time after start of injection, higher fuel pressure gives a higher penetration length and a narrower cone angle (due perhaps to the longer penetration but the same lateral spread). The differences between 20 and 50 bar are more pronounced than those between 50 and 80 bar.

Figure 7 compares the structure of the spray with gasoline and with LPG, for the same fuel and chamber pressures. The evaporation time is longer with gasoline so more droplets persist from previous injections, giving the 'glow' on the laser (left hand) side. The greater UV absorbance of gasoline gives rise to the shadowing effect seen on the right hand side of the images. The cone angle is perhaps slightly narrower for the LPG than for the gasoline but the difference is not great. The penetration length is similar for the two fuels. The structure of the spray and the penetration length are more sensitive to fuel and chamber pressure than to the fuel type. The greater evaporation rate of the LPG does not affect the structure of the spray greatly in the 12ms since injection.

In these tests the nitrogen in the chamber is quiescent. Differences in droplet sizes between the sprays may lead to differences in spray structure when strong in-cylinder air motion is present, as occurs in direct injection engines.
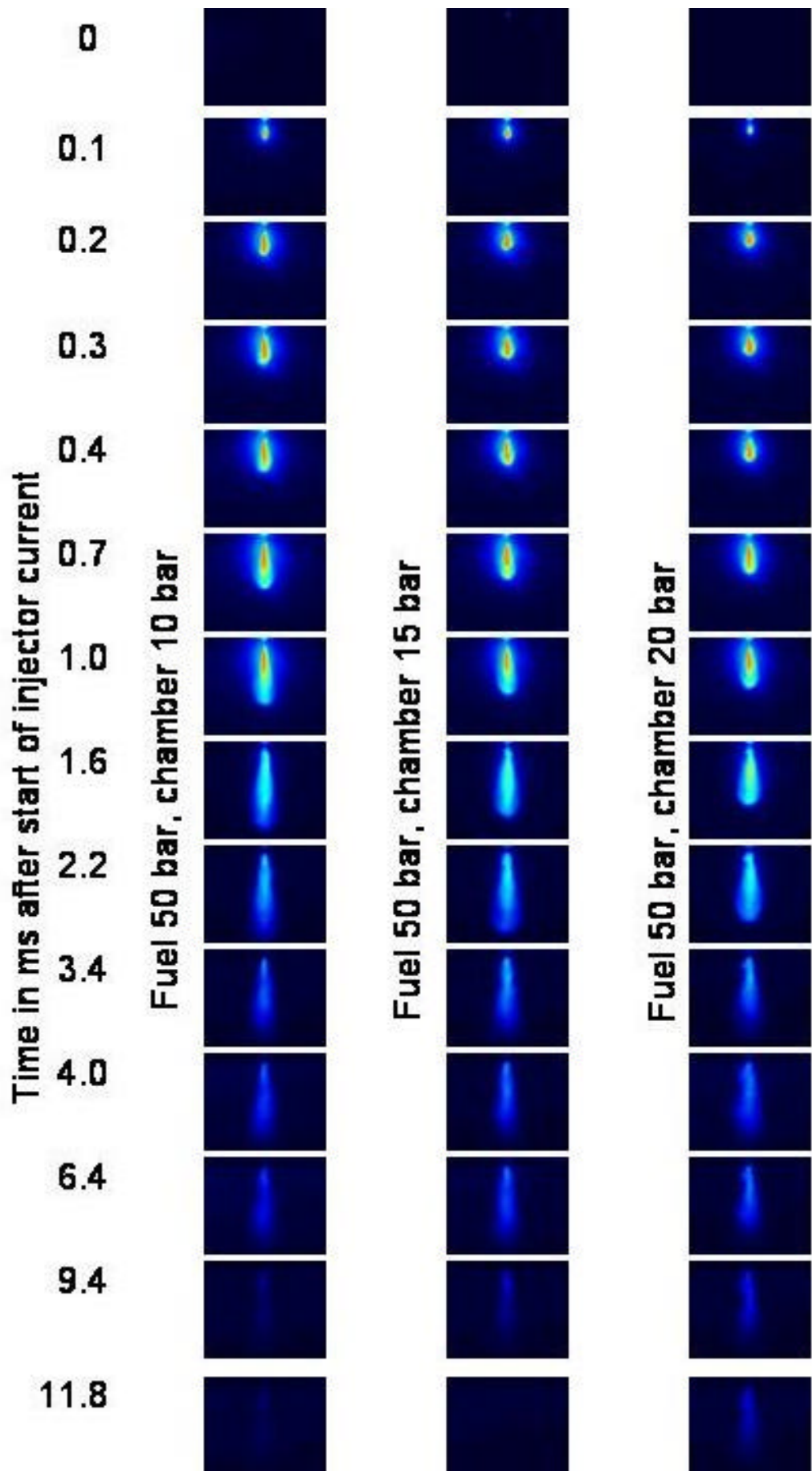
Figure 5. Direct injection spray images showing the effect of chamber pressure
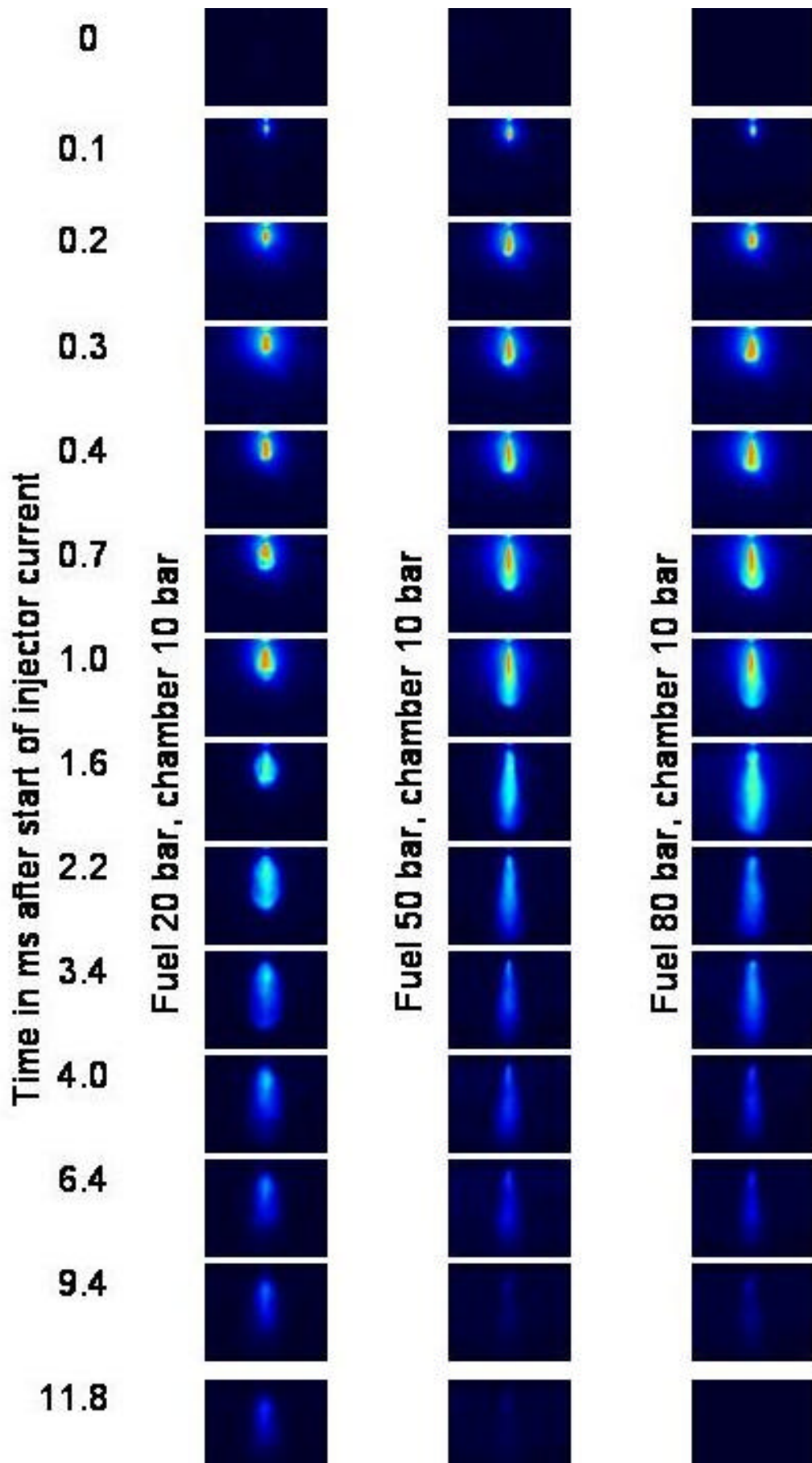
Time in ms after start of injector current

	Fuel 20 bar, chamber 10 bar	Fuel 50 bar, chamber 10 bar	Fuel 80 bar, chamber 10 bar
0			
0.1			
0.2			
0.3			
0.4			
0.7			
1.0			
1.6			
2.2			
3.4			
4.0			
6.4			
9.4			
11.8			

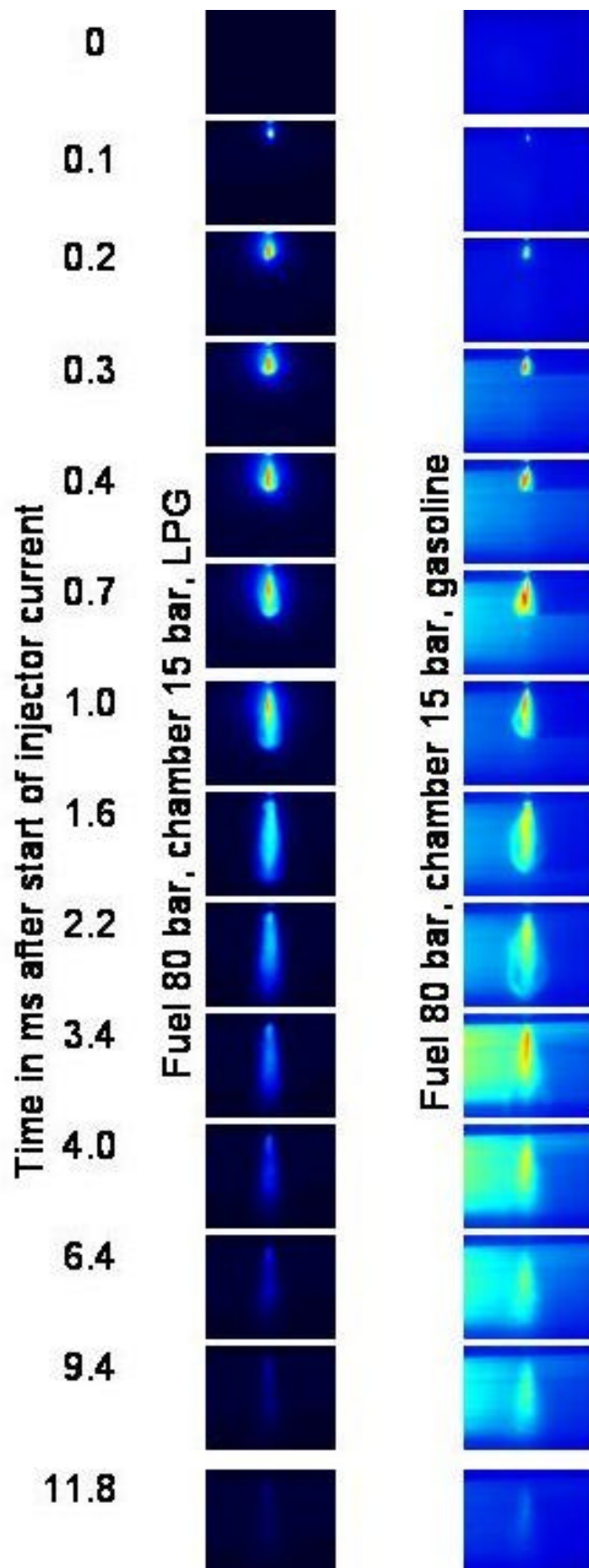*Figure 6. Direct injection spray images showing the effect of fuel pressure*

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Figure 7. Direct injection spray images showing a comparison between gasoline and LPG

3.3 Penetration length of the direct injector sprays

An approximate value for the penetration length was measured from the images. This is the vertical distance from the injector tip to the furthest point that the cyan colour level reaches. The penetration length is plotted in Figure 8. Penetration length varies from ≈34mm at 50 bar to ≈45mm at 80 bar. As expected, penetration increases with fuel pressure, and decreases with chamber pressure, due to the increased aerodynamic resistance of the nitrogen. The differences between LPG and gasoline are within the uncertainty of this quick method of determining penetration.
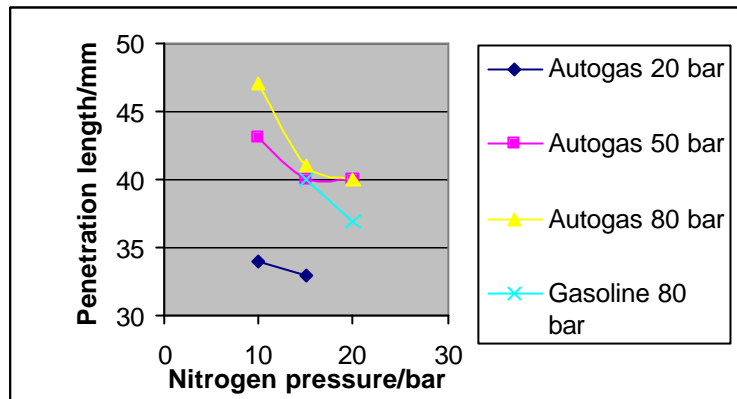

Figure 8. Maximum penetration length of the LPG and gasoline direct injection sprays

4. SUMMARY

The spray from a number of injectors used to convert gasoline engines to LPG have been imaged with Mie and LIF at a range of fuel and chamber pressures. The systems include three different port injection systems and a direct injector.

For those port injection systems which use a pipe to couple a remote injector to the manifold, there is significant evaporation of the LPG before it reaches the manifold. The latent heat required is taken from the pipe wall and not from the induced air, where it might usefully cool and densify the air, boosting engine torque. The amount of evaporation depends on the length and diameter of the pipe. The fuel emerges from the pipe in a narrow jet. This may be less conducive to good mixing than the broad spray which emerges from the close coupled system (which has the injection valve mounted directly on the manifold).

During its travel down the pipe the injected pulse of fuel spreads out so that the duration of the LPG pulse at the manifold end is, for 300mm pipes, approximately five times the original duration at the injector, and even greater for 600mm pipes such that fuel is always emerging from the pipe for engine speeds ~1000rpm.

The close-coupled LPG system achieves lower in cylinder mixture temperatures and better torque than the pipe coupled LPG system by, (1) good mixing, (2) avoiding the loss of volumetric efficiency by keeping the fuel liquid, and by evaporative cooling of the inducted charge, resulting in (3) boosted volumetric efficiency and (4) increased calorific value charge inducted per cycle.

The spray from a gasoline direct injection (GDI) fuel injector was imaged, using both LPG (LPG) and gasoline at fuel and ambient pressures typical of a GDI engine. The spray pattern and penetration are very similar with LPG and gasoline. The spray penetrates 35-45mm into the cold, quiescent gas in the bomb. Under the conditions tested, the spray structure of the gasoline and LPG are very similar. The spray structure is more sensitive to fuel and chamber pressure than fuel type.

The droplet size may vary with fuel type, resulting in a different spray structure when exposed to the strong in-cylinder air motion of a direct injection engine.

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