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Characterisation of the Soot Formation Processes in a High Pressure Combusting Diesel Fuel Spray

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ABSTRACT

As part of an ongoing investigation, the influence of In Cylinder Pressure (ICP) and fuel injection pressure on the soot formation processes in a diesel fuel spray were studied. The work was performed using a rapid compression machine at ambient conditions representative of a modern High Speed Direct Injection diesel engine, and with fuel injection more representative of full load. Future tests will aim to consider the effects of pilot injections and EGR rates. The qualitative soot concentration was determined using the Laser Induced Incandescence (LII) technique both spatially and temporally at a range of test conditions. Peak soot concentration values were determined, from which a good correlation between soot concentration and injection pressure was observed. The peak soot concentration was found to correlate well with the velocity of the injected fuel jet. Charge air pressure was observed to have minimal effect on the peak soot concentration indicating insensitivity to ignition delay and spray break-up length. Injection pressure was also observed to strongly influence the early soot formation process. Soot was found to form earlier closer to the injector at high injection pressures. It was proposed that air-fuel mixing promoted by better atomisation of the spray at high injection pressures results in early pyrolysis of the fuel and the formation of soot.

INTRODUCTION

The direct injection diesel engine remains the most efficient, economic power-plant available for transportation applications, particularly when applied as part of a ‘hybrid’ powertrain [1,2]. Increases in fuel price and concerns over greenhouse gas emissions are likely to lead to increased adoption of a diesel engine based powertrain for future cars and commercial vehicles [3]. However, concerns over the environmental impact of diesel particulate emissions have led to ever stringent legislative control over tailpipe emissions in most parts of the world [4,5]. To date, improvements in fuel injection technology [6], combustion system design and turbo-charging [7] have enabled the design of clean, economical engines at acceptable cost to the consumer [6].

Future emissions legislation, particularly in North America is likely to require further improvements in engine out particulate emissions. Further improvements in turbo-charging and fuel injection technology may yield some benefit, but more sophisticated techniques are likely to be required [8], probably combined with a particulate control after-treatment system [9]. Better understanding of the in-cylinder soot formation process that lead to particulate emissions may allow improved design of the combustion system and lower engine out tail-pipe emissions [10]. Improvements in engine out emissions may realise improvements in an engine / after-treatment package in terms of both system cost and vehicle fuel consumption [11]. This complex soot formation processes is still not fully understood and further investigation is needed to provide the required understanding that could lead to the next level of improvements in combustion system design.

The diesel combustion process was conceptually described by Dec [12]. The conceptual model proposed by Dec suggests soot formation starts prior to auto-ignition in the rich vapour plume ahead of the liquid spray. Small soot particles formed in the dense fuel rich plume grow and migrate down the fuel jet towards the head of the spray where some particles are drawn out towards the diffusion flame formed round the head of the spray where they are burnt. Others particles are trapped within the head vortex where further agglomeration can occur resulting in larger particles. The work by Dec was performed in a single cylinder optical engine at test conditions using a relatively low pressure (86 MPa) fuel system by modern standards, however, the model offers a comprehensive description of the spray formation, combustion and emissions formation processes.

The application of high fuel injection pressure, small nozzle orifice size and air motion to effectively control particulate emissions is well established within the automotive industry.[13,14]. The established view is that good mixing of the fuel with the charge air is required to promote soot oxidation and hence low particulate emissions [14]. Recent work by Siebers [15] utilised a constant volume optical bomb and a high pressure (190 MPa) common rail fuel system to study the auto-ignition and soot formation processes. The effect of injection pressure and nozzle orifice diameter were studied. A correlation between fuel jet velocity and peak soot volume fraction was found. The authors proposed that the decreased residence time of the fuel in the combustion region of the jet resulted in less time for the fuel to pyrolise before combustion and hence less soot. Mixing and residence time have therefore both been put forwards as mechanisms for the reduction of particulate emissions observed with increased fuel injection pressure.

The work described in the paper is part of an ongoing collaborative project between Ricardo and the University of Brighton to understand the combustion processes in the diesel engine. The work centres around a high pressure and temperature rapid compression machine [16] installed at the University of Brighton. Extensive spray characterisation work [17] has been completed and work on the combustion processes is now in progress. The influence of fuel injection pressure and charge air pressure on the soot formation process was studied, using the LII technique. Post processing of the LII images has enabled the relative soot density to be determined both spatially and temporally. Summation of the soot density across the image has enabled cross correlation of the measured soot in the fuel spray with injection pressure and the in-cylinder pressure (ICP) during the evolution of the fuel spray, auto-ignition and diffusion flame.

EXPERIMENTAL APPARATUS

SPRAY RIG

A high-pressure spray rig was installed at the University of Brighton in 1999. This facility has allowed the behaviour of a diesel spray to be studied under representative, controlled conditions. A Rapid Compression Machine is used to generate near quiescent high pressure and temperature air into which fuel can be injected. In-cylinder pressures and temperatures up to 12 MPa and 750 K respectively can be achieved, by preconditioning the boost air supply to the rig. An optical chamber gives good visual access to the full spray allowing the application of a wide range of optical techniques to be applied. The design of this facility has been described in detail in previous publications [16,18].

A second generation Bosch common rail system [19] was used for this work, with a maximum rail pressure capability of 160 MPa. The fuel pump was powered by an electric motor running at 1400 rev/min ensuring a stable rail pressure with minimal fluctuation. The rail and delivery pipe were both instrumented with a 4067 Kistler pressure transducer to monitor transient variations in the fuel rail and injector pressures. The pipe from the rail to the injector was kept short, representative of the length typically used in a production passenger car installation. A custom controller was developed [20] to enable independent control of injection timing, duration and rail pressure.

LII SYSTEM

The laser used was a pulsed Nd:YAG laser, capable of delivering pulses of 300 mJ at a frequency of 10 Hz and a wavelength of 532 nm. The system was described in detail by Crua [21,22] and was set up as follows:

Final pulse energy[1]	280 mJ
Sheet Thickness	0.75 mm
Sheet height[2]	57 mm

[1] After losses though optical path

[2] Limit of window optical access

An intensified CCD camera with a 12 bit resolution was used to acquire a monochromatic LII image. The images were 1280 by 1024 pixels in size with a measured resolution of 73 μm^2 per pixel. An image doubling extension was fitted onto the camera lens to duplicate the view of the combusting sprays. Two views of the spray were recorded on one single image, with different optical filtering applied to each half image (figure 1).

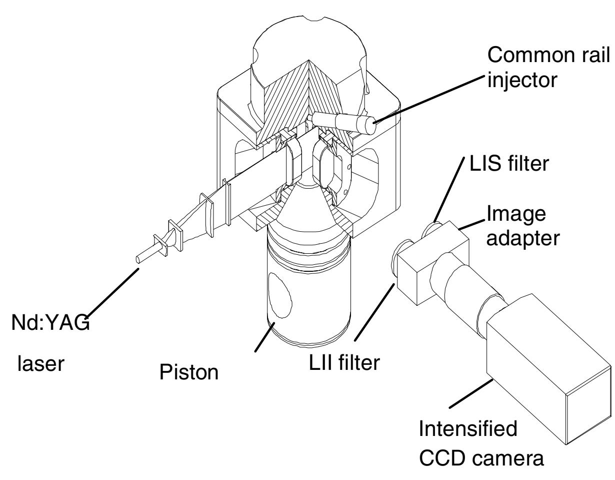

Figure 1: Experimental set-up of LII System

A wide-bandpass filter was selected with a measured peak transmission at 416 nm and 64.4 nm FWHM, This filter maximized the LII signal and offered excellent rejection of interference from flame luminosity, fluorescence and elastic scattering. The LII signal was independent of particle size and represents a measure of the mass of soot captured by the beam.

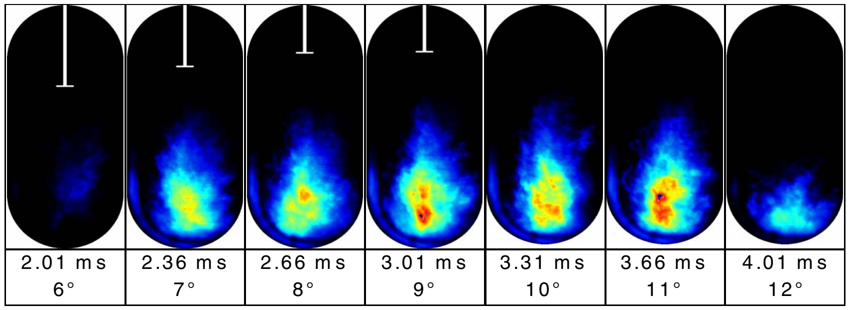

Figure 2: LII images from tests at 160 MPa fuel injection pressure 6 MPa In Cylinder Pressure. Times are in ms after start of injection. White bars show spray liquid penetration length

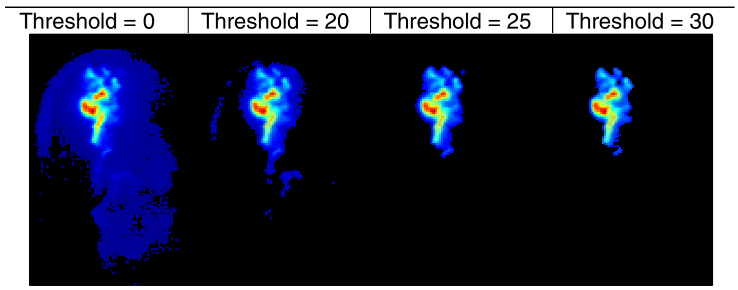

Figure 4: Effect of thresholding (values of threshold 0, 20, 25, 30 applied, from left to right). Threshold of 25 applied in this case.

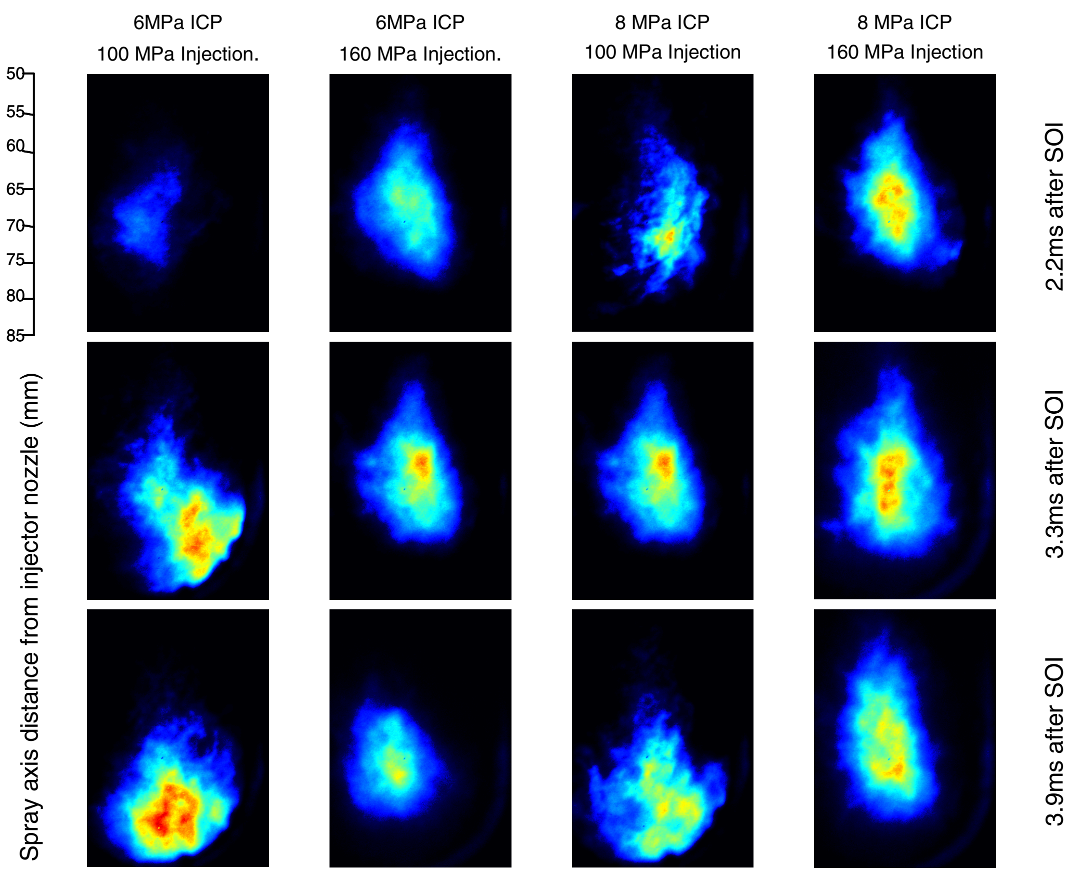

Figure 10: Threshold LII Images at 2.2, 3.3 and 3.9ms after the start of injection. Scale shows distance from injector nozzle

TEST MATRIX

A range of fuel injection pressures and in cylinder pressures were studied. Other parameters were held constant. The experimental set up was as follows:

Motored Air Pressure[1]	6, 7, 8, 9 MPa
Fuel Rail Pressure	100, 140, 160 MPa
Motored Air Temperature[2]	720 K
Injector Nozzle	0.2 mm VCO, single hole
Start of Injector Pulse	15° Before TDC

[1] Measured at TDC from motoring tests

[2] Calculated at TDC from motored pressure curve

The charge air temperature and pressure were pre-conditioned to achieve the desired in cylinder pressure at constant in cylinder temperature.

A low sulphur fuel, mixed with Ethyl Hitec 4103 in the ratio of 0.375 cm^3 per litre was used. The additive raised the Cetane number of the fuel from 55 to 57 and reduced the effects of window fouling by soot deposits.

A set of 27 to 30 images were taken for each data set, while fuel was injected every 4^{th} engine cycle to ensure good purging of the optical chamber of combustion products before the next fuel injection.

RESULTS AND DISCUSSION

LII IMAGES – QUALITATIVE COMPARISON

The 27 to 30 LII images were processed to determine the average and standard deviation of the data set at each time bin. An example sequence at 60 bar ICP and 160 MPa injection pressure is shown in figure 2. The spray liquid and vapour penetration, cone angle and cylinder pressure was previously measured using high speed imaging [17]. The results of this work are reproduced in figure 3.

The evolution and structure of the soot formation process is broadly in line with the conceptual model proposed by Dec [12]. The first soot is observed 2 ms (6° crank) after the start of injection, just before the auto-ignition (determined from the rise in cylinder pressure over the non-fired case, see figure 3). A rich region of soot is observed towards the head of the spray within the diffusion flame plume that forms around the vapour cloud ahead of the liquid spray. All the soot detected was observed to form in the vapour region of the spray plume. The results from this study indicate that the Dec model is valid at the high fuel injection pressures used in modern diesel engines.

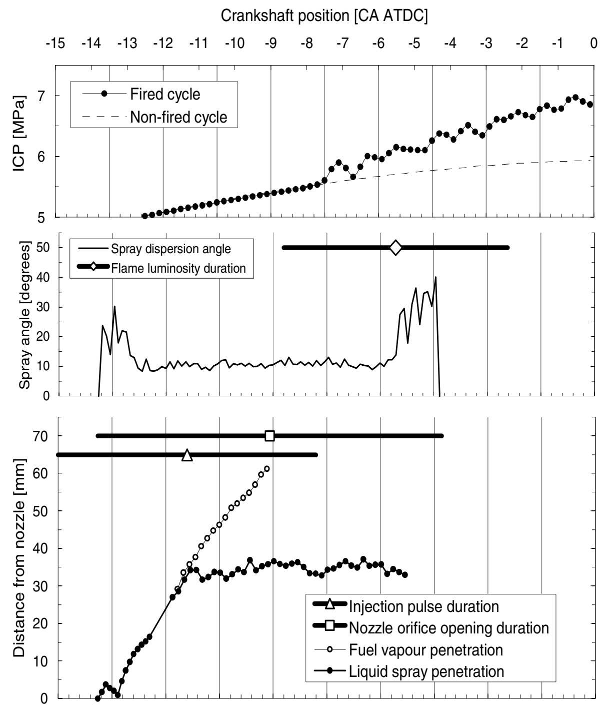

Figure 3: Cylinder pressure, measured spray angle, liquid and vapour penetration at 160 MPa fuel injection pressure 6 MPa

CALCULATION OF SOOT CONCENTRATION

The raw LII image data sets were post processed to determine the soot concentration. A threshold was first applied to each image to eliminate the LII signals resulting from soot on the windows and pick up only the pixels that were detecting parts of the spray. The threshold level was carefully chosen by inspection to remove the window effect without losing information from the LII signal from the fuel spray. The same threshold level was used for all images collected in a given time bin. An example of the effect of different thresholds is shown in figure 4. There is a risk in applying this technique that information will be lost from the spray, particularly if a large region of low density soot was present. This might particularly be the case at the beginning or end of the soot formation process. The raw images from each data set were inspected to attempt to pick out any data sets that may be vulnerable to significant loss of information by the application of image thresholding The total image intensity of the thresholded image was then determined. For each data set at each time bin, the image intensity was plotted against the number of pixels above the threshold for each image in the data set. An example of the results from this process are shown in figure 5. A linear relationship between the number of pixels and the image intensity is observed. This indicates a relationship between image intensity and area (number of pixels) and hence the gradient represents a measure of the average concentration.

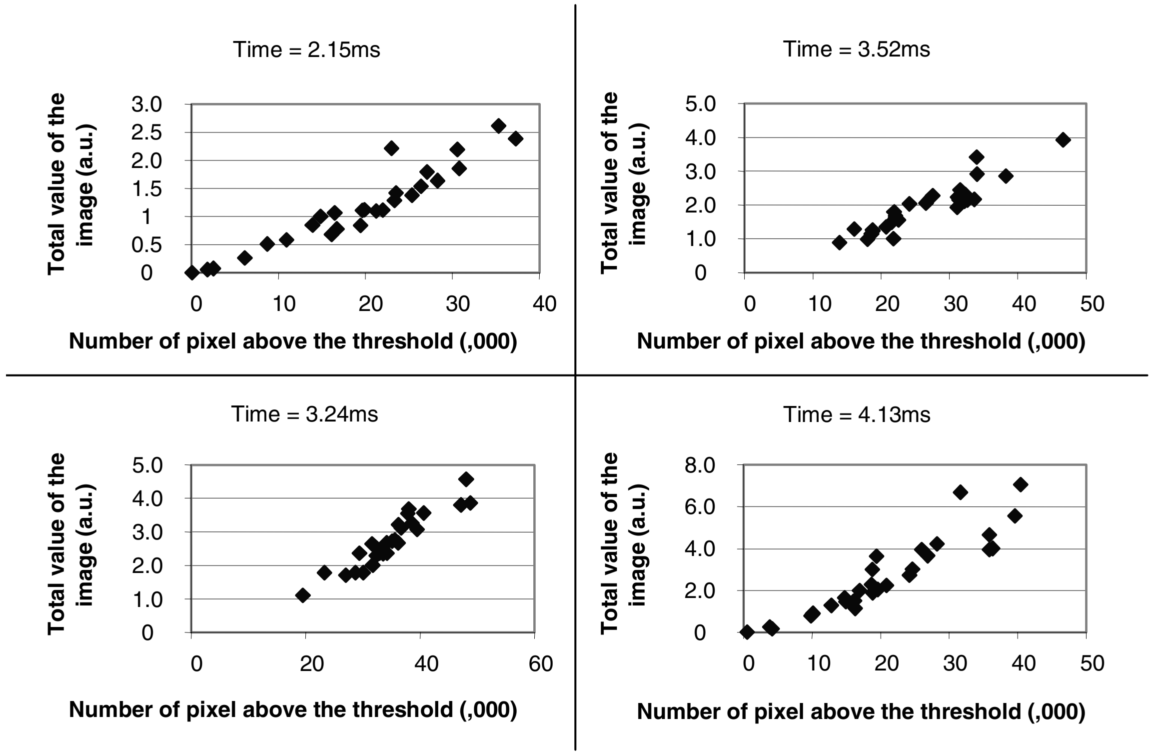

Figure 5: Relationship between LII intensity and area for determination of soot concentration

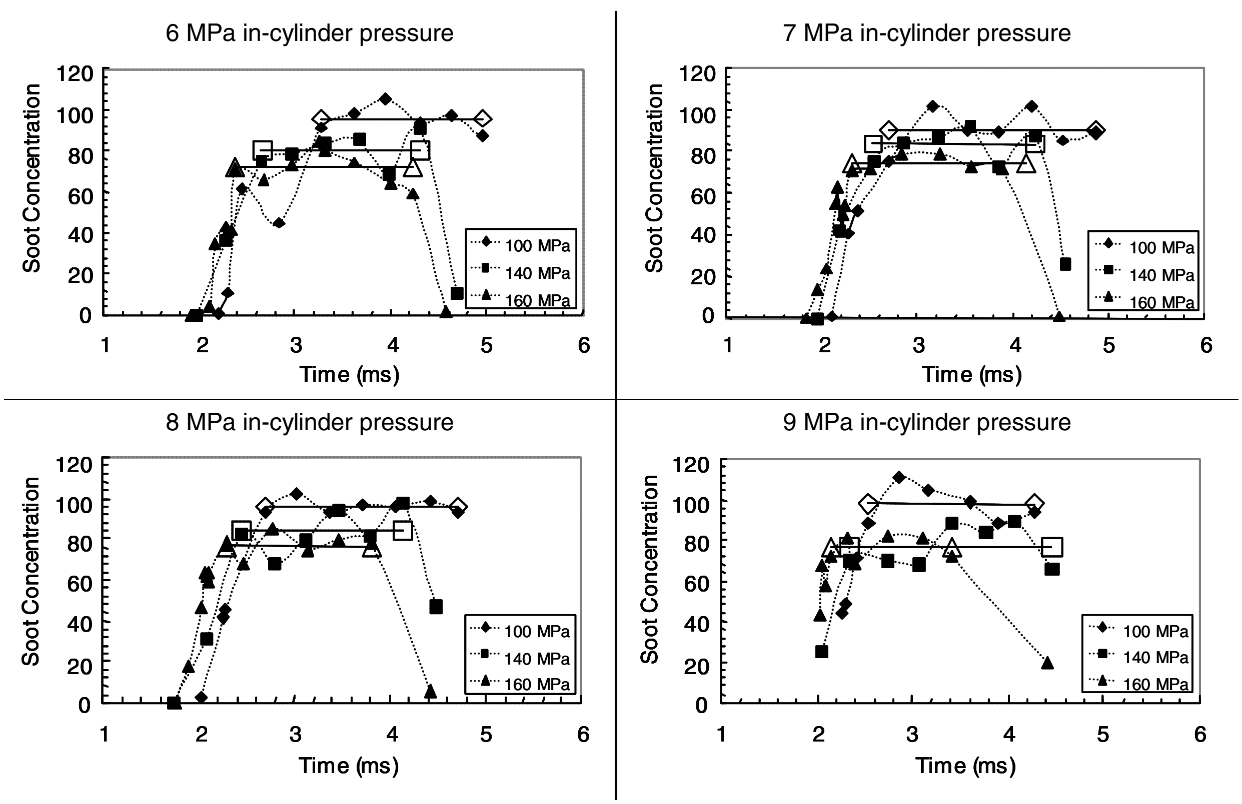

Figure 6: Influence of injection pressure on soot concentration. Times are after start of injection. (Open legends show average peak value).

The individual LII images at each time bin would expect to show variability due to variability in the auto-ignition delay, spatial position of the spray relative to the (fixed) laser sheet and rate of combustion. The linear relationships shown in figure 5 indicate that the average LII signal has meaning as there is a relationship between signal strength and area at each time bin within a data set despite the variability of the spray formation and combustion process.

EFFECTS INJECTION PRESSURE AND IN CYLINDER PRESSURE ON TEMPORAL SOOT CONCENTRATION

The influence of injection pressure on the temporally resolved soot concentration is shown in figure 6 for the injection pressures and In Cylinder Pressures studied. In all cases, but particularly at high in cylinder pressures, the initial rise in soot formation is more rapid at high injection pressures. Conversely, the soot concentration is observed to decrease earlier in the cycle at higher injection pressures. This indicates more rapid pyrolysis of the fuel early in the process but more complete combustion of the soot particles at high fuel injection pressures.

The data presented in figure 6 are observed to have a relatively flat peak, indicating the soot formation and destruction processes are in balanced during the main part of the combustion process. The 'peak soot concentration' was determined by averaging the data points falling on the plateau, as shown in figure 6. The peak values were plotted against cylinder pressure (figure 7) and injection pressure (figure 8).

In Cylinder Pressure

Varying the in-cylinder air pressures was achieved by modifying and controlling of the boost intake air pressure. An increased will therefore result in a reduction in the global AFR. Since this overall AFR is in the range 600:1 to 900:1 it is considered that the local mixing and atomisation effects are the driving factors.

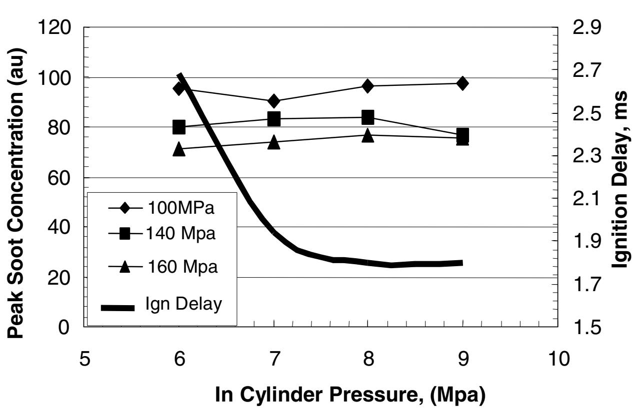

Figure 7: Influence of cylinder pressure on peak soot concentration and ignition delay for three injection pressures

From figure 7 it can be seen that there is no correlation between the peak soot concentration and the in-cylinder pressure. The change in in-cylinder pressure strongly effects the charge air density, raising the density by 46% for a change in pressure from 6 MPa to 9 MPa. The spray break-up length is effected by air density, where previous work reported break up length being proportional to air density to the power 0.25 [23] and 0.345 [24]. This would suggest a change in spray break up length of between 10 and 15% for the range of air pressures used in this study. This change in break-up length is observed to have a minimal effect on the peak soot concentration. The effect of the change in in-cylinder pressure on the measured auto-ignition delay, for a fixed injection pressure of 160Mpa, is also plotted on figure 7. The delay was shown to be independent of injection pressure [26]. Figure 7 shows that a change of ignition delay of about 1 ms has little effect on the peak soot concentration, under these conditions of changing density.

Injection Pressure

Referring to figure 8, a correlation is observed between the injection pressure and peak soot concentration. The increase in injection pressure will effect both the injection velocity and the droplet sizes of the spray during the break up process [25]. Siebers [15] has proposed the residence time of the fuel in the combustion chamber is proportional to the peak soot concentration. Siebers proposed that residence time is proportional to the injection velocity, which is proportional to the square root of the pressure difference between the fuel at the nozzle and the charge air. Regression analysis of the data shown in figure 8 showed the peak soot concentration is proportional to the pressure drop across the fuel injector nozzle to the power -0.47. This is close to the theoretical value for the relationship with injection velocity which is –0.5. A correlation therefore exists between the peak soot concentration and the injection velocity, and it is proposed that this is a function of the residence time of the liquid fuel within the combustion chamber.

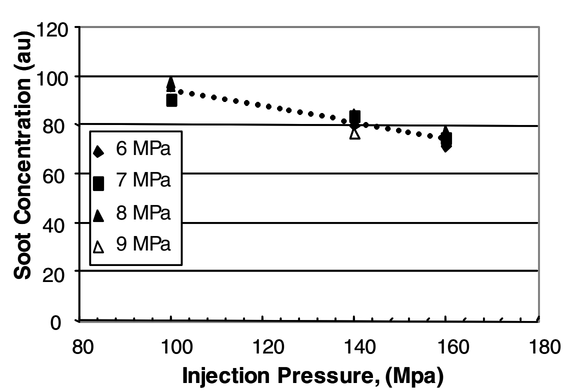

Figure 8: Influence of Injection Pressure on Soot Concentration. Best fit line applied to the complete data set

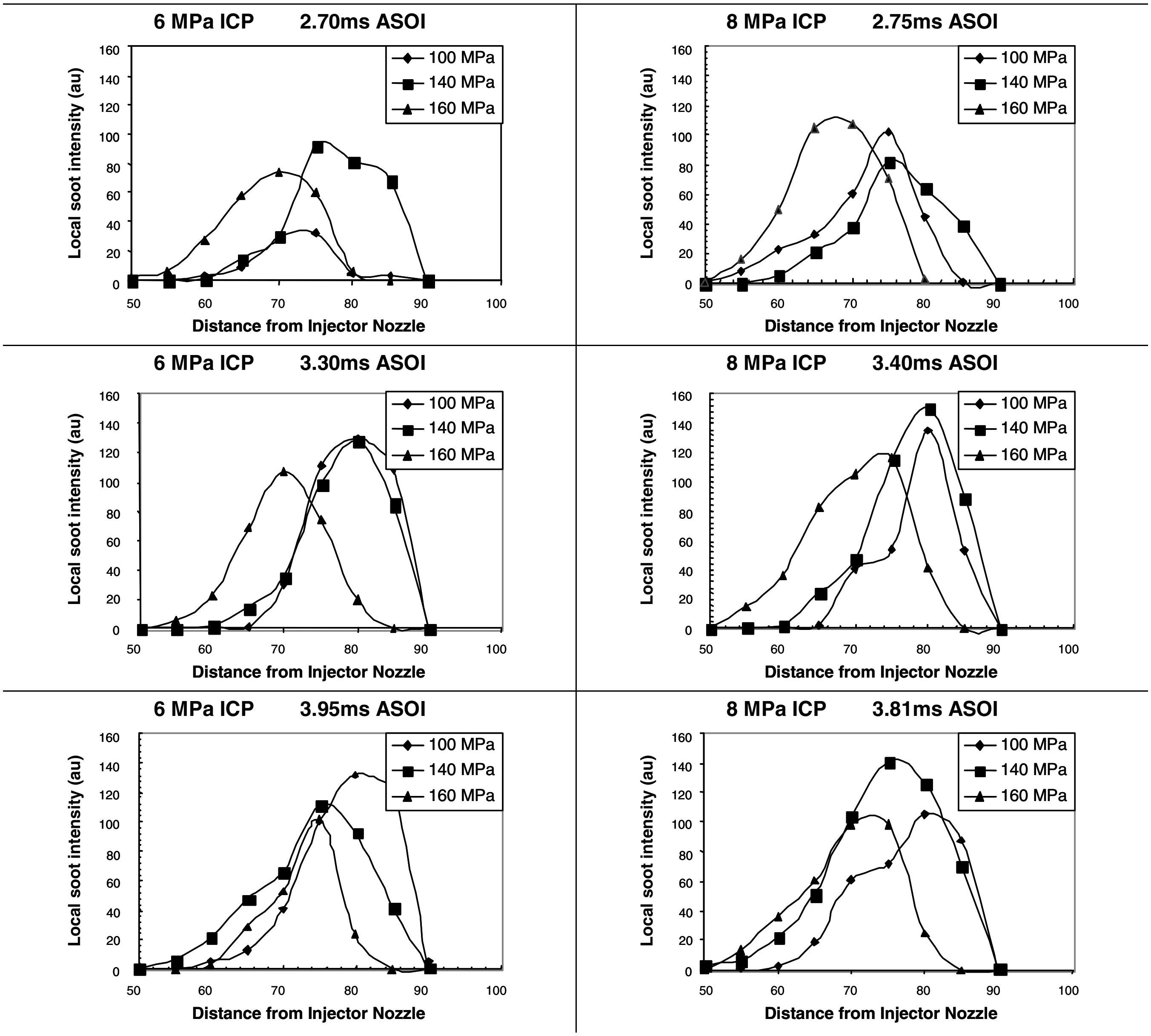

Figure 9: Spatial variation of soot concentration for three time bins, two in-cylinder pressures and three injection pressures (N.B. The crank angle based control system results in a slight real-time shift for varying ICP)

SPATIAL DISTRIBUTION OF SOOT

The distribution of soot down the centre line of the spray was determined at three time bins for three injection pressures and two in cylinder pressures. The results are shown in figure 9, with the corresponding thresholded average LII images for the 100 MPa 160 MPa injection pressure at 6 and 8 MPa In Cylinder Pressure cases in figure 10 (see earlier in text).

At the timing of approx. 2.75ms (8° crank) after the start of injection, (corresponding to just after the start of auto-ignition), soot can be observed to form closer to the injector nozzle for the 1600 bar injection cases relative to the lower injection pressure cases. This trend is also present at 3.3ms (10° crank). However, after, 3.8ms (12° crank) the soot concentration curves are similar in shape and position, if not magnitude. There are three effects that could explain this observation:

1. More fuel available to form soot at the earlier timings, due to the higher rate of injection at higher injection pressures early in the cycle
2. Better mixing of the fuel with the hot charge air, promoting pyrolysis of the fuel and soot formation at higher injection pressures early in the cycle
3. Better heat transfer to the fuel due to the higher surface area of the smaller fuel droplets at higher injection pressures, promoting pyrolysis.

Visual inspection of the LII images and concentration curves indicate that the soot formation process occurs nearer the nozzle at the higher injection pressures. As discussed it is likely this is a mixing and heating effect, as at the time bins in question a substantial quantity of fuel will have reached these locations even at the lower injection pressures cases. This suggests two conflicting processes may be influencing the evolution of the soot particles at high injection pressure:

1. Early pyrolysis due to mixing and heating with the hot charge air
2. Lower residence time (promoting less soot) due to the higher velocity of the fuel jet

It is possible that both effects are significant. For higher injection pressures, pyrolysis of the fuel due to heating and good heat transfer from the smaller droplets, results in more rapid early production of soot. The fuel and newly formed soot particles will be well mixed with the charge air and can be carried down the spray vapour plume. The lower residence time of the fuel prior to combustion limits further pyrolysis and the improved mixing promotes more complete consumption of the more disperse soot later in the process. This is supported by the observed lower soot concentration later in the process for the high injection pressures.

CORRELATION WITH 'REAL ENGINE' DATA

The peak soot measurement used in this paper has a number of limitations when attempting to infer the effect of conclusions made from the LII data on actual engine tail-pipe emissions:

1. The measurements were taken from a single plane through the centre of the spray and may not represent the global behaviour
2. The measurement is qualitative
3. There is no discrimination between the levels of soot particle production and oxidation during combustion
4. Effects late in the cycle after the time frame studied are not accounted for.

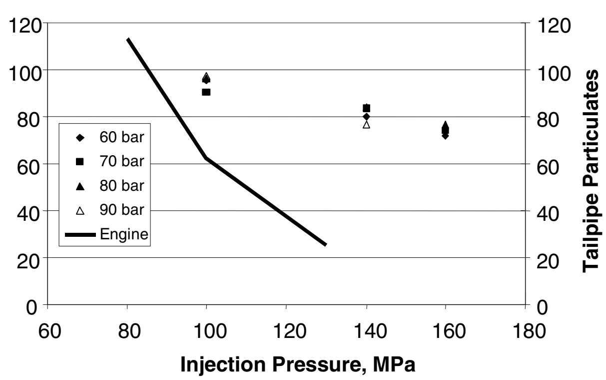

Figure 11: Comparison of LII Soot Concentration with Measured Tailpipe Soot from a Single Cylinder Engine

As a 'sanity check', to verify the results have relevance with the performance of a real engine, the peak soot concentrations were compared with the results from a 2ℓ single cylinder engine test program using similar common rail fuel injection equipment. The engine was run in a low swirl configuration without EGR at a lean air-fuel ratio to try and isolate the effects of injection pressure alone on tail-pipe particulates. The same linear trend (see figure 11) of decreasing particulates with increasing injection pressure was observed. This crude correlation gives encouragement to the use of the peak soot concentration as a parameter for studying the likely impact of fuel system operating conditions on the performance of a real engine.

CONCLUSIONS

The LII technique was successfully applied to a diesel fuel spray under conditions representative of a modern diesel engine. The effects of in cylinder pressure and injection pressure were studied.

Qualitative inspection of the LII images agreed with the model proposed by Dec over a range of fuel injection pressures. The following observations were made:

1. Soot was first observed just before the start of auto-ignition.
2. The early soot cloud forms downstream of the liquid jet in the vapour cloud.
3. A dense soot region is seen to grow during combustion towards the head of the vapour plume.

It can be concluded that the Dec conceptual model is applicable to high pressure fuel sprays.

No correlation was observed between the peak soot concentration and cylinder pressure. Since this parameter has been shown to influence both ignition delay and spray break-up length, it suggests that they are not determining factors for peak soot concentration.

A relationship was observed with injection pressure and the peak soot concentration. Increasing injection pressure was observed to reduce the peak soot concentration. Regression analysis of the data showed the peak soot concentration was proportional to the nozzle pressure difference to the –0.47 power. This correlates well with the exit velocity of the fuel which is proportional to the nozzle pressure drop to the –0.5 power. The reduction of soot with increased injection pressure could be due to improved mixing and reduced residence time of the fuel in the combustion chamber.

High injection pressure was observed to promote early soot formation closer to the injector. It is proposed that mixing of the fuel spray caused by better atomisation of the liquid at high injection pressures promotes more rapid pyrolysis of the fuel due to heating by the hot charge air.

The soot concentration was observed to reduce more rapidly later in the cycle at higher injection pressures, with both mixing and residence time contribute to this observation. Good mixing of the fuel early in the cycle promotes more complete combustion and the shorter residence time of the fuel reduces the available time for growth of the soot particles.

The observation that higher fuel pressures promote soot production closer to the nozzle suggests improved mixing and atomisation are the main causes of the reduction in soot with increased fuel pressure rather than shorter residence time where as all factors will be influential in the reduction of soot later in the cycle.

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DISCLAIMER

The views represented in this paper are those of the authors and do not necessarily represent those of the sponsoring organizations.

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