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QUANTIFICATION OF 3D TRANSIENT FUEL FILMS FOR G-DI SPRAYS UNDER ELEVATED AMBIENT CONDITIONS

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ABSTRACT

This paper describes the development of a quantitative Laser Induced Fluorescence (LIF) technique to measure 3-Dimensions of transient liquid fuel films formed as a result of spray impingement. It follows work from Alonso et al [1] who proposed using total internal reflection to control the propagation of a laser beam so as to target the excitation of the liquid fuel film only and not the airborne droplets above the film. The LIF technique relies on the principle that upon excitation by laser light the intensity of the fluorescent signal from a tracer is proportional to the film thickness. A Nd:YAG laser was used as the excitation light source (utilising the fourth harmonic at wavelength 266nm) and an intensified CCD camera recorded the results as fluorescent images. A binary mixture of 3-Pentanone in Isooctane was used as a substitute of gasoline due to its similar properties. This paper presents some preliminary experimental results of a transient spray from a gasoline direct injector impinging on to a quartz crown, with observations of the development of the transient fuel film at elevated ambient conditions relevant to G-DI application.

INTRODUCTION

Spray/wall interaction upon solid surfaces is an unavoidable phenomenon that occurs in direct injection internal combustion engines, influencing greatly the air-fuel mixing and combustion. Impingement is particularly very significant in Gasoline Direct Injection (G-DI) engines working in stratified charge mode where the fuel is injected late in the compression stroke virtually guarantying interaction with in-cylinder surfaces.

Stratification at part load is generally achieved by a combination of three mechanisms: spray dynamics, impingement on in-cylinder surfaces and the interaction with the in-cylinder flow field. For that reason, all the G-DI combustion systems that have been proposed in the literature thus far can be classified into three major groups depending on the primary strategy they use to achieve stratification: spray-guided, wall-guided and air-guided systems. Regardless of the classification, stratification at part load is generally achieved by some combination of all three mechanisms for which impingement is always present to some degree [2].

For wall-guided systems the amount of fuel deposits due to impingement are the most significant as they use the piston to re-atomise the fuel and direct it towards the spark plug as a primary method of stratification. Impingement is relatively less significant for spray guided and air guided systems. However, there is still present an important amount of spray/wall interaction at late injections, mainly because of the high spray penetration and confined geometries.

Fuel impingement is generally undesirable because its association with UBHC emissions, particulate emissions, and fuel economy. For instance, for G-DI engines working at part load literature has shown that if 10 % of the mass injected impinges on the piston crown there is a 60-90 % associated increase in UBHC emissions compared to complete vaporisation, and a 30 % associated increase at idle load [3,4]. For those reasons it is of great importance to improve the understanding of fuel impingement and the first step is to obtain accurate measurements of the fraction of fuel deposited.

This article describes the development of a temporally-resolved 3-D laser induced fluorescence (LIF) technique to analyse and quantify the transient fuel film formed due to impingement of a pressure swirl G-DI spray on a quartz flat surface. The technique complements time resolved post-impingement spray characterisation published by Kay *et al* [5,6].

It also follows work published by Kay *et al* [6], who developed a 3-D LIF technique to quantify the fuel film thickness formed as a result of impingement of a presure swirl injector on a flat surface. The technique relies on the principle that upon excitation by laser light, the intensity of the fluorescent signal from a dopant is proportional to the film thickness. Initial results at atmospheric conditions showed that airborne droplets affected the fluorescent signal from the fuel film. This is due to the fact that the laser continues its path upwards and the light excites the airborne liquid fuel above the piston surface, increasing the fluorescence signal detected by the camera.

However, a single injection on the quartz piston demonstrated the potential of the technique, as the overall intensity of the fluorescence from the fuel film decreased as the fuel evaporated. Therefore, the limitation of this technique was present only analysing transient fuel films for multiple injections, where there is airborne fuel above the film. Another limitation of this technique concerns the strong presence of the laser beam pattern in the images, producing bright and dark areas for points with the same thickness introducing errors to the system. These issues contributed to problems experienced in achieving plausible quantitative data in that study.

This paper uses the optical setup proposed by Alonso [1] in which the propagation of the laser sheet is carefully controlled so that only the fuel film is illuminated. Some preliminary experimental results of a transient spray from a gasoline direct injector impinging on to a quartz crown are presented, with observations of the transient nature of the fuel film at elevated ambient pressures relevant to G-DI applications.

QUANTITATIVE LIF FOR LIQUID FILMS

Planar laser induced fluorescence (PLIF) is a widely used and extremely useful technique for quantitative or semi-quantitative analysis of transient flows, providing spatially and temporally resolved information in a desired plane. The general principle of LIF is to excite a molecule of fuel with a light source at a critical wavelength. An electron in that molecule, initially at a lower ground state, is excited to a higher electronic energy level. After a short time it emits a photon in order to return to its more stable ground state. The release of the photon can be observed as fluorescence at a different wavelength compared to the excitation wavelength. The fluorescence wavelength is always red-shifted as a result of energy lost during the excite state. The excitation wavelength needs to be carefully selected so it matches with the absorption wavelength of the substance in study.

The Lambert-Beer law governs the fluorescence of an excited substance and it states that when a collimated light source of intensity I_o passes through an L length of substance of molar concentration C, light with intensity I_t is transmitted and some with intensity I_a is absorbed by the substance. Thus:

$$I_t = I_o \cdot e^{(-\varepsilon . C \cdot L)} \tag{1}$$

$$I_a = I_o - I_t = I_o\left(1 - e^{(-\varepsilon . C \cdot L)}\right) \tag{2}$$

Then, the intensity of the fluorescence signal measured I_f is given by:

$$I_f = Q \cdot I_o\left(1 - e^{(-\varepsilon . C \cdot L)}\right) \tag{3}$$

Where ε is the molar absorption coefficient and Q is the quantum efficiency. Then, the intensity of the fluorescence signal measured can be approximated to:

$$I_f = Q \cdot I_o \cdot \varepsilon \cdot C \cdot L \tag{4}$$

Thus, the intensity of the fluorescence signal is proportional to the film thickness for homogeneous and optically thin films. Kay et al [6] showed a linear ratio between thickness and fluorescence signal of 3-pentanone for up to 500 microns. Hentschel et al [7] proved linearly between thickness and fluorescence for gasoline films of up to 300 microns. Initial visualisation tests of the injector in study provided information about the footprint size of the film deposited, and given that the total mass injected is known, the film thickness was estimated to be smaller than 150 microns, well within the linear phase.

TRACER SELECTION

Often the liquid being examined is unsuitable for LIF therefore it is preferred to replace the test liquid with a well under-stood tracer. The ideal tracer should have extremely similar properties to the base fuel it is added in terms of: evaporation rate, droplet formation, convection, and diffusion, among others. Additionally, the fluorescence that it emits when excited should be insensitive to pressure and temperature variations, and also insensitive to the quenching effects of the surrounding gas it is immersed into [8]. Unfortunately, it is virtually impossible to meet all this requirements especially for multi-component fuel blends like gasoline, which already contain potentially fluorescent substances. Consequently, gasoline is often replaced in LIF studies by binary mixtures of a fluorescent tracer and a non-fluorescent base fuel in order to provide a solution for concentration changes in gasoline from different batches.

The fluorescent tracer selected for this study was 3-Pentanone due to its similar properties to gasoline and excellent absorption when excited at 266 nm. It is well documented that the fluorescence emissions of 3-pentanone when excited at a wavelength of 266 nm peaks at around 400 nm [8]. Therefore, a narrow band filter was used to optimise the quality of the fluorescent signal recorded.

Iso-octane is commonly used as a base fuel for gasoline studies as it is a non-fluorescent substance with similar properties the mid-boiling point fractions of gasoline (50% of the components evaporate below 109°C). Consequently, a binary mixture of 10% (by vol) of 3-pentanone in gasoline was selected for this study. This mixture is widely used as a substitute of gasoline in combustion systems research due to its similar properties [8]. Also, it has been proven to be chemically stable under typical test conditions [9, 10, 11].

TOTAL INTERNAL REFLECTION

To avoid a fluorescence signal form airborne droplets, the propagation of the exciting laser beam must be limited in a way that only excitation of the fuel film takes place. This work proposes using the principle of total internal reflection to eliminate or reduce this source of error. When light strikes a medium with lower refractive index, *n,* from a medium with higher refractive index, *n*', (interface quartz-air), it will be totally reflected if the incident angle is larger than the critical angle determined by the Snell law (Equation 5).

$$\sin(\phi_c) = \frac{n}{n'} \qquad \textbf{(5)}$$

Previous work by Kull et al [12] and Hoon et al [13], used a LIF technique to visualize fuel films on quartz surfaces, and showed that if the incident angle of the light is such it is totally internally reflected. However, the light can propagate from the quartz into the fuel due to the similarity in the refractive indices. This is due to the fact that the path of light hardly changes when it propagates into mediums with similar refractive indices. The proportion of light transmitted into the liquid film can be calculated from the Fresnel Equations, so the transmittance of the electromagnetic field for parallel and rectangular polarisation is given by:

$$T_{\parallel}(\phi_i) = \frac{2 \cdot n_{rel} \cdot \cos(\phi_i)}{n_{rel}^{2} \cdot \cos(\phi_i) + \sqrt{n_{rel}^{2} - \sin^2(\phi_i)}} \qquad (6)$$

$$T_{\perp}(\phi_i) = \frac{2 \cdot \cos(\phi_i)}{\sqrt{n_{rel}^{2} - \sin^2(\phi_i)} + \cos(\phi_i)} \qquad (7)$$

Where $n_{rel} = n/n'$ and $Ø_i$ corresponds to the incident angle of light. Additionally, the ratio of the beam areas of the incident and transmitted beams is given by:

$$F_a(\phi_i) = \frac{\sqrt{n_{rel}^{2} - \sin^2(\phi_\mathrm{i})}}{n_{rel}^{2} \cos^2(\phi_\mathrm{i})} \qquad (8)$$

Thus, the relative intensity of the laser light penetrating into the liquid film can be written as a function of the incident angle using the following equations:

$$I_{\parallel} = T_{\parallel}^{2}(\phi_i) \cdot F_a(\phi_\mathrm{i}) \cdot n_{rel} \qquad (9)$$

$$I_{\perp} = T_{\perp}^{2}(\phi_i) \cdot F_a(\phi_\mathrm{i}) \cdot n_{rel} \qquad (10)$$

Figure 1 shows the transmission in the quartz-fuel interface as a function of the incident angle for a UV graded quartz of refractive index 1.499 and the binary mixture of iso-octane and 3-pentanone of refractive index 1.392. Given that the critical angle to ensure total internal reflection is 43.81°, and figure 3 shows no transmittance in quartz-fuel interface above 69°, the angle of incidence needs to be selected between these values. The optimum angle of incidence found for this experiment was 65°.

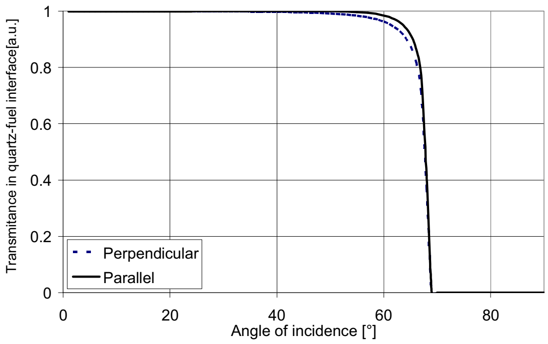


Figure 1: Normalised transmittance in the quartz-fuel interface as a function of the incident angle.

Hoon *et al* [13] showed that after passing the fuel layer and exciting the fuel film, the light interacts with the fuel-air interface, and is totally reflected. They concluded that if the curvature of the fuel film surface is small, the light is totally reflected because of the large difference in the refractive index. Thus the light only excites the fuel on the piston and there is no fluorescence contribution from airborne droplets

OPTICAL SETUP

Figure 2 shows a schematic of the optical set-up proposed for this technique based on the principle of total internal reflection. In order to implement this technique it was necessary to design a quartz piston in which the exciting laser beam could be directed towards the top surface at a desired angle, in this case an angle greater than the critical angle to ensure total internal reflection

A Nd:Yag laser utilising the fourth harmonic (266 nm) was used as the excitation light source. Even though the repetition rate of the laser is 10 Hz, the maximum repetition rate of the camera is 5 Hz. Therefore images were acquired from several cycles in order to build a full map of the transient fuel film. The fluorescence signal was acquired through a 50mm Nikkor Lens (f/1:4) onto a gated image intensifier linked to a HiSense Mk II CCD camera with a resolution of 1344x1024 pixels. It was possible to capture only the fluorescence from the excited fuel using a 400 nm short band pass filter mounted in front of the lens. In addition, specially coated mirrors were used to maximise the transmittance of both laser the excitation light (266 nm), and the fluorescence signals (400 nm). Also, by means of an energy pulse monitor (EPM) it was possible to monitor and record laser power fluctuations (shot-to-shot variation), so that this parameter can be taken into consideration for the calibration.

A 5° full width half maximum (FWHM) UV diffuser optic was used to attenuate the typically uneven power distribution of the Nd:Yag laser beam pattern, making the beam profile more homogeneous (‘top-hat shape’). Without an UV-diffuser, there would be relative hot spots and dark areas in the laser beam, introducing sources of error.

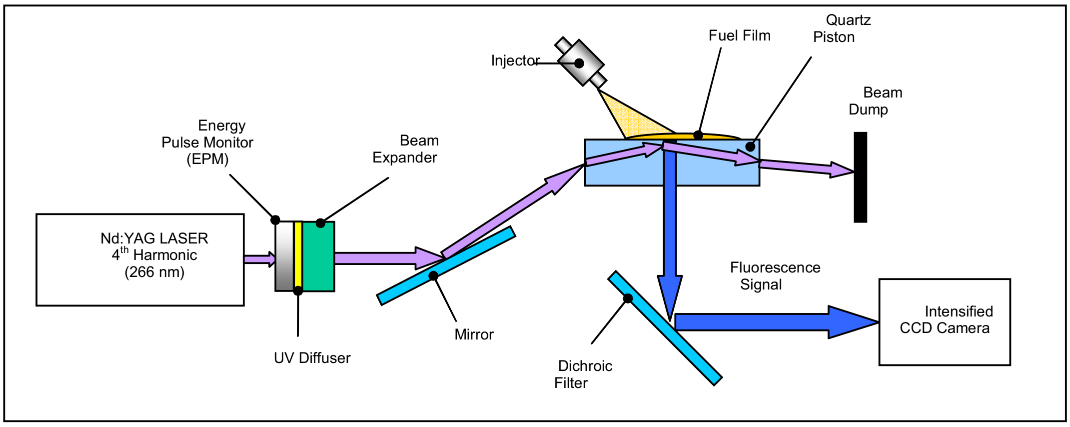


Figure 2: Optical Setup to control the light propagation by total internal reflection.

CALIBRATION PROCEDURE

As mentioned previously, the intensity of fluorescence emitted by 3-pentanone excited at 266 nm would be linearly proportional to its concentration, and hence proportional to the volume for a 'thin' film layer of a homogeneous mixture. Therefore, to calibrate this technique it is essential to determine the ratio between the fluorescence signal emitted and the corresponding liquid film thickness.

The calibration method proposed by this technique is similar to that used in RIM imaging (refractive-index-matching imaging), where known volumes of liquid fuel films are placed on the measurement surface to obtain calibration images. For the application of LIF to fuel films measurements, it is possible to determine the ratio between fluorescence and film thickness when the Volume, footprint area, and intensity distribution of a fuel film are known. A micro-syringe was used to deposit a known volume of fuel on the quartz surface. The fluorescent signal of various volumes from 10 to 50 micro-litres was acquired to build the calibrations curve. A typical image used for the calibration of this technique, after subtracting the background, is presented in Figure 3.

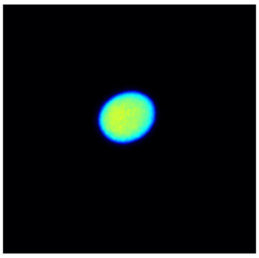


Figure 3: Intensity recorded from a 10 mm^3 fuel drop deposited on the piston using a microsyringe

Since the fluorescence of 3-Pentanone has been proven to be dependent on ambient pressure, the calibration procedure was performed both at atmospheric pressure and at 4 bar (absolute) to match the test conditions.

Figure 4 shows the fluorescence intensity of various volumes of fuel deposited on the piston for 2 different ambient conditions. For both cases the volume shows a linear relationship between intensity and fuel film volume. For the high pressure case, with an ambient pressure of 4 bar (abs), there is a significant increase in fluorescence with respect to the case at 1 bar (abs).

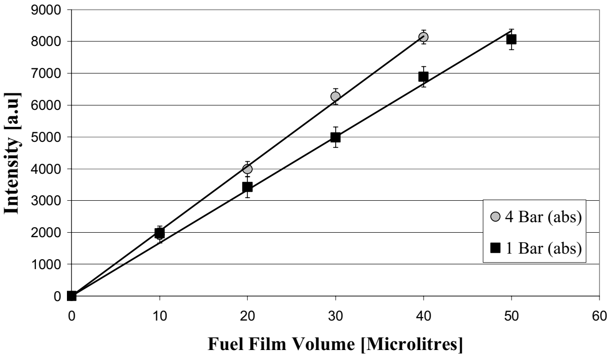


Figure 4: Fluorescence dependency on gas pressure

The calibration factor derived from fig 4 is 1179 and 1363 a.u/micro-litre for 1 and 4 bar respectively. The post-processing method is detailed in the following section.

POST-PROCESSING

In order to obtain quantitative information from LIF studies, the raw images need to be post-processed. The first step of post-processing involves the removal of systematic errors present in the imaging system. According to Zhao *et al* [14] and Seitzman *et al* [15], the digital signal recorded for a single pixel of a CCD camera during LIF experiments can be expressed as:

$$S_{pixel} = \left[N_p \left(\frac{P_c}{P_o} \right) R_{total} + S_b + S_d \right] \tag{11}$$

Where N_p is the number of fluorescence photons leaving the collection volume within the collection solid angle, P_c corresponds to the laser energy within the collection volume, P_o is the nominal laser energy, R_{total} the total responsivity of the detection system, S_d is the dark current signal, and S_b corresponds the background signal associated with the laser induced process (e.g. Rayleigh and Mie scatterings, window fluorescence, and ambient light). Solving equation 11 for the fluorescence signal we obtain:

$$N_p = \left[S_{pixel} - (S_b + S_d)\right] \cdot \left(\frac{P_o}{P_c}\right)\left(\frac{1}{R_{total}}\right) \qquad (12)$$

Equation 12 suggests a suitable procedure for correcting systematic errors in the recorded image. First, an image combining the background and dark current signals (S_b+S_d) is subtracted from the recorded image. This image can be obtained by removing the fluorescent particles from the system. Since the background varies from shot to shot, an average background is preferred to minimise this effect.

Then, the resulting image is then multiplied by a correction image to account for the spatial variations in the responsivity of the detector (R_{total}). Finally, the new image is multiplied by another corrector factor to account for non-uniformities of the laser sheet (P_c/P_o). Zhao et al [14] proposes recording the combined effect of the responsivity of the detector and the non-uniformities of the laser sheet by obtaining an image from a homogeneous mixture containing fluorescent particles (S_{uni}) minus the background image (S_b+S_d). Thus, the fluorescent signal of each pixel can be rewritten as:

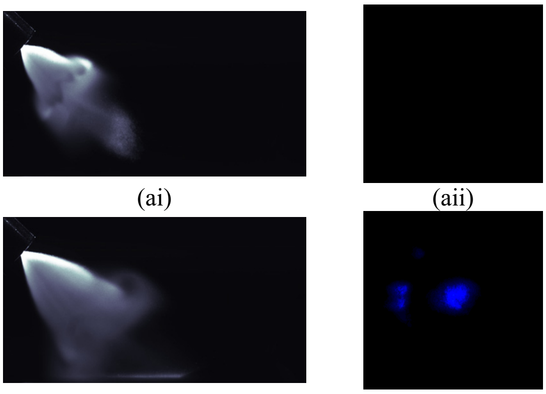
$$N_p = \frac{\left[S_{pixel} - (S_b + S_d)\right]}{\left[S_{uni} - (S_b + S_d)\right]} \qquad (13)$$

The corrected image of the fluorescent signal can be calibrated using the calibration curve obtained presented in Figure 4. Finally, the method produces a quantitative image of the liquid film where both the thickness and footprint dimensions can be calculated.

RESULTS AND DISCUSSION

Transient fuel thickness measurements are presented in this section for selected times after start of injection (ASOI), with observations of the transient nature of the fuel film resulting due to impingement. They illustrate the development of the liquid film formed as a result of impingement for a BOSCH C2-70 pressure swirl injector located at 21 mm and 45 ° with respect to the normal of the impact surface. The fuel line pressure was 100bar.

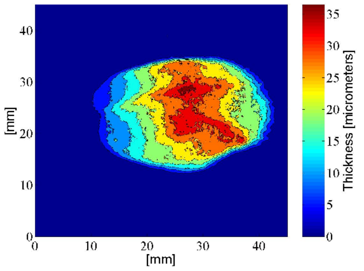
Results are discussed in light of two different ambient conditions, one case at ambient pressure (1 bar (abs)) and one case at elevated ambient conditions (4 bar (abs)), which is pertinent to late injections for G-DI applications. The temperature for both cases was ambient (295K).


(ai) (aii)

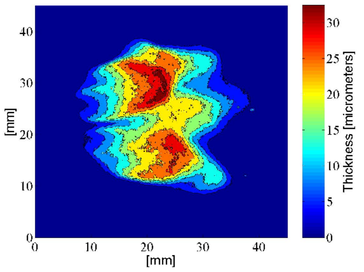
(bi) (bii)

Figure 5: Transient fuel film images at ambient pressure for timebins: (a) 1.00 ms ASOI, (b) 1.25 ms ASOI (left: side view, right: Average footprint image with background subtracted)

Figure 5 can be used to illustrate the benefits of using the principle of total internal reflection to illuminate the fuel film. It presents the side view and footprint image recorded at 1.00 and 1.25ms ASOI. Figure 5ai shows clearly the presence of airborne fuel above the quartz piston, however, no fluorescence signal is recorded in figure 5aii implying that the fuel has not impacted the piston. This figure confirms that fuel is excited only after contacting the piston surface and not from pre-impingement airborne droplets, hence eliminating the potential source of error proposed by Kay [6]. Image 5bii shows the first evidence of impinging fuel 1.25ms ASOI. The corresponding side view (figure 5bi) corroborates the impact of fuel as the film can be seen at the bottom of the image.



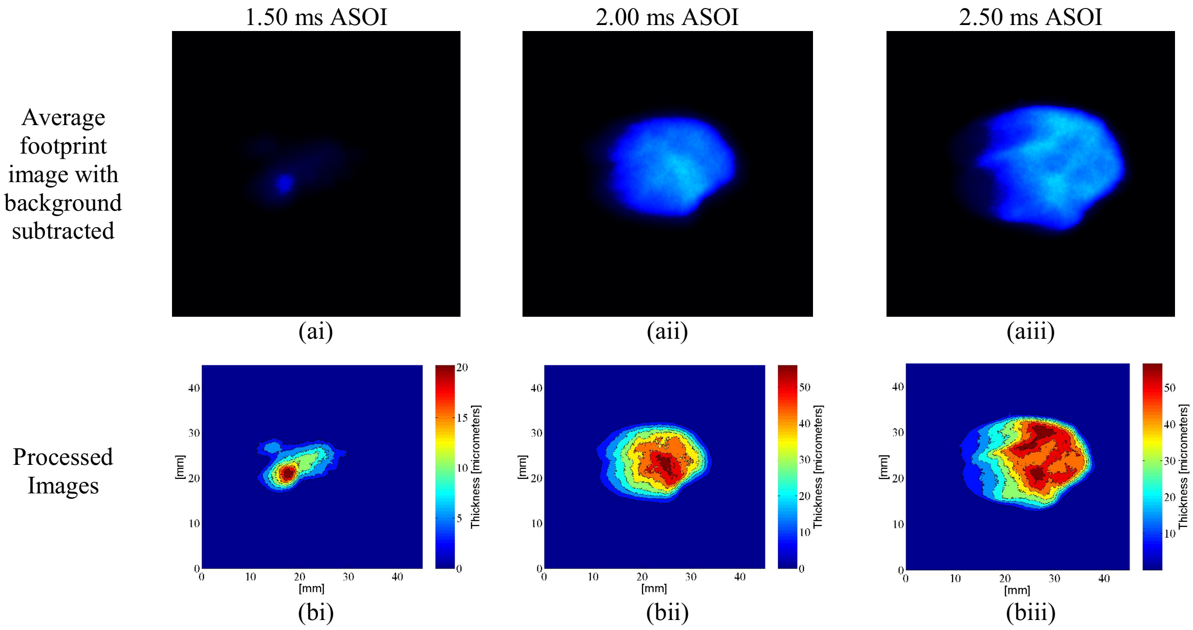
i) 4 bar (abs)



ii) 1 bar (abs)

Figure 6: Comparison of fuel thickness measurements 5.00ms ASOI for atmospheric conditions and elevated pressure case

Figure 6 shows processed images for both cases for corresponding timebins. There are clear differences in the size and distribution of the fuel films which can be attributed to the different developments of the pre-impinging sprays.



(ai) (aii) (aiii)

(bi) (bii) (biii)

Figure 7: Transient fuel thickness measurements for high pressure case (4bar).

The high pressure case presents a more compact fuel film which propagates slightly further from the tip of the injector. The size of the fuel film is likely to be smaller for the high pressure case as the structure of the pre-impinging spray is more compact due to pressure effects. Even though the spray is more compact, it is expected to have bigger droplets with more inertia which are presumed to apply more momentum to the fuel film making it travel further in the measurement surface, up to 43 mm across from the tip of the injector projection on the surface. Figure 6ii shows a spread fuel film for the atmospheric pressure case, with observations of a thicker film around the edges. This fuel distribution is perhaps more intuitive for a hollow cone pre-impinging spray.

The development of the fuel film is presented in Figure 7 showing the average footprint images and their corresponding calibrated images for selected times ASOI for the high pressure case. Figure 7ai shows the first evidence of consistent impinging fuel 1.50ms ASOI. At 1.25ms ASOI the images recorded are intermittent for this condition, suggesting that the spray arrives to the piston exactly at this timebin with some small shot-to-shot variations from the injector. The sac volume can be clearly identified on this image, which is characteristic for the structure of a spray from this injector.

Subsequent timebins at 2.00ms (ii) and 2.50ms ASOI (iii) illustrate a fairly symmetric fuel film distribution with a maximum fuel thickness around 50 microns. Particularly at 2.5ms, it can be seen how the film tends to be thicker at the front, carrying momentum and moving forward similar to a small wave-front. Time resolved measurements showed that the maximum cumulative total mass deposits are achieved around 2.25 to 2.50ms ASOI. Therefore, unsurprisingly the maximum film thickness, circa 55 microns, was recorded at this time. Later timebins show the film to thinner and bigger.

CONCLUSION

This paper describes the development of a quantitative Laser Induced Fluorescence (LIF) technique to measure 3-dimensions of transient liquid fuel films formed as a result of spray impingement. Preliminary experimental results of a fuel film formed by a G-DI spray impinging on a flat surface showed that the technique was successful in describing the development of the fuel film both qualitatively and quantitatively. The main conclusions in this study are:

- The technique proved successful at quantifying the transient effect of the fuel film thickness and shape.
- Significant differences were found for the fuel film produced at 2 different sets of ambient conditions.
- For elevated ambient pressures (4 bar), a thicker and smaller film which travels further from the tip of the injector.

Future work will attempt to perform impingement tests at elevated temperatures, and development of fuel spray impingement methodologies.

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