

Laser induced fluorescence measurements of the thickness of fuel films on the combustion chamber surface of a gasoline SI engine

by

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ABSTRACT

Up to 90% of the unburnt hydrocarbon emissions (UHCs) from modern 4-stroke gasoline engines occur during cold starting. Slow vapourisation particularly from films of fuel in the intake port, and on the manifold and cylinder walls leads regions of rich mixture and incomplete combustion. To reduce UHCs it is useful to know where, and how thick, these wall films are during the intake and compression strokes.

In the present work the fuel film is imaged and its depth measured with a laser induced fluorescence technique. The technique uses a with a pulsed laser, diffuse illumination and a camera and images the film on the metal combustion chamber surface, in an inexpensive rig closely approximating the flow in an port injected gasoline engine under cold start. The temporal resolution of $\sim 100\text{ns}$ and spatial resolution of $\sim 0.5\text{mm}$ are sufficient to reveal the detailed dynamics of the film formation and transport.

The technique functions well in the imperfect optical environment of a piston engine cylinder. In contrast to previous studies the film depth is measured, quantitatively, on the metal combustion chamber surface with correct roughness and film transport properties, rather than on a smooth glass wall. The uncertainty in depth is $\pm 16\mu\text{m}$ but may be reduced to $\pm 5\mu\text{m}$. With open valve injection a $30 \pm 16\mu\text{m}$ thick film forms on the exhaust side cylinder wall. Such films lead to high unburnt hydrocarbon (UHC) emissions. The technique has high temporal (100ns) and spatial (0.5mm) resolution and may be applied to acceleration transients, lubricating oil films, GDI and Diesel engines.

1. INTRODUCTION

Up to 90% of the unburnt hydrocarbon emissions (UHCs) from modern 4-stroke gasoline engines occur during cold starting (Heywood 1988, Cheng et al. 1993, Stanglmaier et al. 1999). Films of fuel in the cylinder vaporise slowly when the engine is cold and unburnt fuel can persist until swept out during the exhaust stroke. To reduce UHCs it is useful to know where, and how thick, these wall films are during the intake and compression strokes.

Of the many methods which have been used to measure wall film thickness, laser induced fluorescence (LIF) has been one of the most successful in i.c. engines. The film is illuminated with a laser and a fluorescent compound in the fuel emits red-shifted light with an intensity which depends on the film depth. LIF offers a signal that is robust in the dirty optical environment inside a piston engine. It has been applied to the fuel films formed in intake manifolds and cylinders of spark ignition (SI) engines in several optical configurations: using fibre optics to carry the signal and/or exciting light (Felton et al. 1995, Johnen and Haug 1995, Hentschel et al., 1997), to measure a fuel film on a transparent surface by total internal reflection (Heavens and Gingell 1991, Evers and Jackson 1995, Coste and Evers 1997, Kull et al. 1997) or without total internal reflection (Le Coz et al. 1994, Cho and Min 2003, Senda et al. 1999), by illumination and detection through a window to measure the fuel film on the metal splitter separating the two branches in a Siamesed port (Almkvist et al. 1995), and to visualise fuel on the inner metal surfaces of the cylinder, though without quantitative measurement of the thickness (Witze and Green 1996, 1997).

In the present work the technique is implemented with a pulsed laser, diffuse illumination and a camera, in an inexpensive rig closely approximating the flow in an SI engine under cold start. In contrast to previous studies the film depth is measured, quantitatively, on the metal combustion chamber surface, rather than on a smooth glass surface.

2. EXPERIMENTAL METHOD and PROCEDURES

2.1 Test rig

The test rig (Fig. 1) approximated the intake and cylinder flow of a six cylinder 4-valve port-fuel-injected 2.5 litre engine at cold start and idle. It had similar optical access to a typical single cylinder optical research engine. A bellmouth to measure the air mass flow was followed by a 25litre plenum to reduce the flow oscillation in the bellmouth. This was followed by a throttle and a section of production intake manifold in which the fuel injector was mounted. This fed the intake port of a 4-valve cylinder head. The intake valves were operated by a camshaft driven by an electric motor. The exhaust valves were kept permanently shut. The combustion chamber surface was anodised. A fused silica cylinder of the correct diameter took the place of the cylinder bore. The lower end of the cylinder has a machined metal unit containing a flat fused silica window at the base and above this four outlets connecting the cylinder to a centrifugal fan. This was used in place of the piston to draw air through the rig.

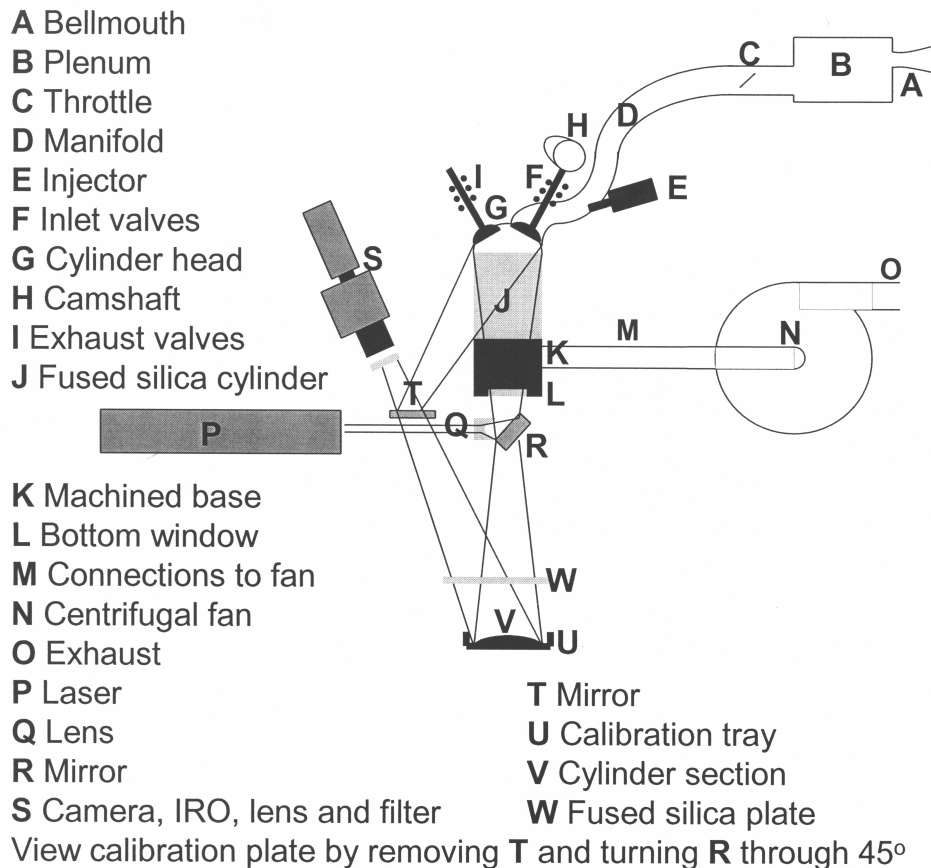


Figure 1 Schematic of the rig

A cold start engine operating condition was simulated. The cam speed was 650rpm (i.e. crank speed 1300rpm), the air mass flow was 2.8gs^{-1} and the cylinder pressure 912Pa below ambient i.e. 101,288Pa absolute. The inlet valve opened approximately 30° after top dead centre (ATDC) and closed approximately 276° ATDC. The injection duration was 7.3ms with end of injection at 120° ATDC i.e. open valve injection. All angles are crank angles i.e. there are 720° for one revolution of the camshaft.

In a real engine, fuel films would be largely evaporated or burnt by the flame every cycle. Since the rig used here does not ignite the fuel there is a risk of fuel persisting from previous cycles and giving an overestimate of the amount of fuel present in film form. For this reason fuel was injected only every tenth cycle. This was found to be sufficient for the air flow to clear the cylinder of fuel before the next injection.

2.2 Optical layout

A Spectra Physics Quanta Ray Nd:YAG laser with Type II SHG crystal produced 540mJ pulses of 532nm light. The beam was expanded with a -50mm focal length spherical lens and directed through the base of the fused silica cylinder to illuminate the head (Fig. 1). A LaVision SprayMaster 3 CCD camera with IRO image intensifier, 50mm Nikon lens at f/2.8 viewed the head through the fused silica cylinder, via a mirror. The intensifier gate was 200ns. A 2mm thick Schott RG610 filter passed the fluorescence and blocked the reflected 532nm light.

The fuel was a mixture of hydrocarbons with average molecular weight 80 plus $\approx 0.1\text{wt}\%$ disodium fluorescein.

2.3 Calibration

A tray filled with fuel was illuminated and imaged with the same imaging equipment at the same distances as were used to image the head. The tray depth varied across the base. The cylinder section was treated to achieve the same surface finish as the cylinder head.

Intensity versus depth curves were extracted for two 10 pixel high horizontal strips. The intensity versus depth relationship depends on the distance of the imaged region from the camera since the camera viewed both calibration tray and head obliquely, giving a perspective effect.

The intensity versus depth curves are given in Fig. 2.

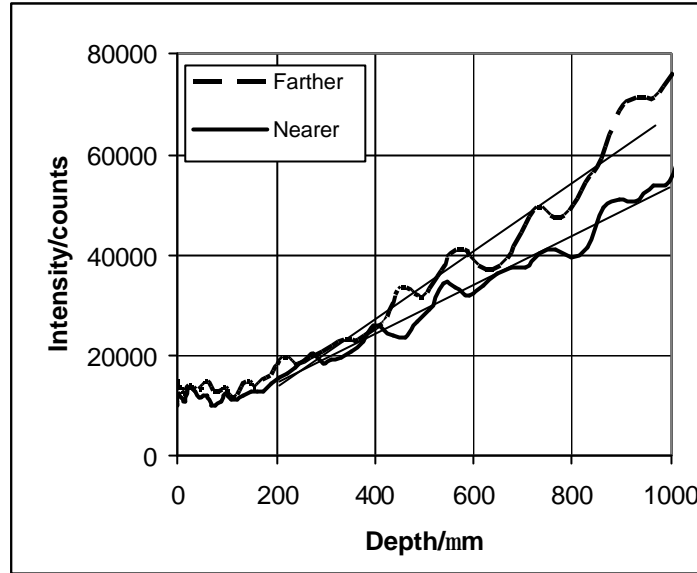


Figure 2 Intensity versus depth relationship

2.4 Imaging of the head and data processing

Images were taken every 40°. 10 data (i.e. air on, fuel on) and 10 background (air on, fuel off) images were taken at each of the same crank angles and averaged.

To further reduce the effects of laser power fluctuation, the averaged image at each crank angle was multiplied by a factor. The factor was calculated to make the intensity in a chosen region of the image the same as the intensity in this region averaged over all crank angles. The region chosen was a strong reflection breaking through the filter from a spot near the cylinder wall. Were the laser power constant the intensity at this point would not change with crank angle.

The background subtracted images were corrected for the spatially non uniform illumination by dividing by a normalised image of the laser beam falling on a white card inserted underneath the head.

The data images were then background subtracted.

Sequences of processed images are shown in Fig. 3. The images are in false colour with hot colours indicating high intensities. Crank angles after top dead centre are marked in the top left corner.

3. DISCUSSION

3.1 Calibration

The calibration curves shown in Fig. 2 have a nonzero intercept since the cylinder section is not completely submerged and a thin film of fuel is held by surface tension on the exposed part. Therefore there is an offset error on the depth axis of Fig. 2, however only the slope and not the intercept of this plot is used. At depths greater than 200µm the cylinder is completely submerged and any meniscus effects have decayed, and the curves are approximately linear. The absorption of the beam by the fuel follows the Beer-Lambert law so the curves should be weakly exponential if measured with very low noise. A linear fit to the section between 200 and 1000µm is shown superimposed on each curve. The slope of these fits is used below to estimate the depth of films imaged in the rig.

The curve from pixel rows farther from the camera have a higher intensity. This is due to the perspective effect (a single pixel covers a larger real area the farther it is from the camera) and the angle of view (the further from the camera the more oblique the line of sight and the more fuel it passes through).

The curves are noisy due principally to imperfect mixing of the dye in the fuel. This noise determines the depth resolution. However the noise on the intensity/depth function is expected to be lower than that in Fig. 2 for the reasons given in the next paragraph.

When the calibration curves were measured the laser intensity was actually 19.3mJ/pulse and the camera aperture f/8. Then intensity/depth slope will be linear with power and aperture so the y-axis of Fig. 2 has been scaled by a factor of 248 to account for the greater intensity and aperture used in the rig measurements giving a slope of ≈ 59 counts/micron for the rig measurements. The noise fluctuations in the original calibration curves are ± 20 counts amplitude. The noise amplitude in the rig measurements will differ for several reasons: it will increase by the square root of the laser power and aperture increases, i.e. to $20 \times \sqrt{248} = 314$. There is an additional uncertainty due to the dye deposits in the rig causing imperfect background subtraction. By inspection of the background images this is estimated to be ± 900 counts. Adding the uncertainties due to noise and background in quadrature gives an uncertainty level of ± 953 counts or $\pm 16 \mu\text{m}$. In addition to the power and aperture changes, the fuel was better mixed for the rig measurements. This will decrease in the noise by an unknown amount.

The depth uncertainty can be further reduced by reducing the laser power fluctuation, by reducing the background, and by increasing the laser power to increase the slope of the intensity versus depth curve. If the background subtraction uncertainty alone can be reduced to ± 50 counts, for example by using a more soluble dye, the depth uncertainty can be reduced to $\pm 5 \mu\text{m}$.

3.2 In-cylinder images

The images are in Fig. 3. The most striking feature of the fuel behaviour begins at 145° when fuel emerges from the inlet valves and crosses the cylinder to the exhaust side. From white light imaging tests the fuel is known to be at least partly airborne while crossing the chamber. Here it strikes the wall and forms a film on the cylinder wall. This film persists at least until the next TDC ($\sim 50\text{ms}$), but since it is not seen at the beginning of the sequence and injection occurs every tenth cam cycle, it must dissipate in less than ten cycles ($\sim 1\text{s}$).

The film forms where the domed combustion chamber meets the cylinder bore, forming a sheltered 'corner'. The air velocity component parallel to the wall is likely to be weak here. Mixing of the fuel evaporating from this wall film into the rest of the cylinder is likely to be poor, leading to rich burn here and high UHC and CO emissions. The authors of (Stanglmaier et al. 1999) deposited artificial gasoline films at various points in the cylinder of an SI engine running on vapourised propane, and found that deposits in this region, the exhaust-side cylinder wall, caused the greatest rise in UHC emissions.

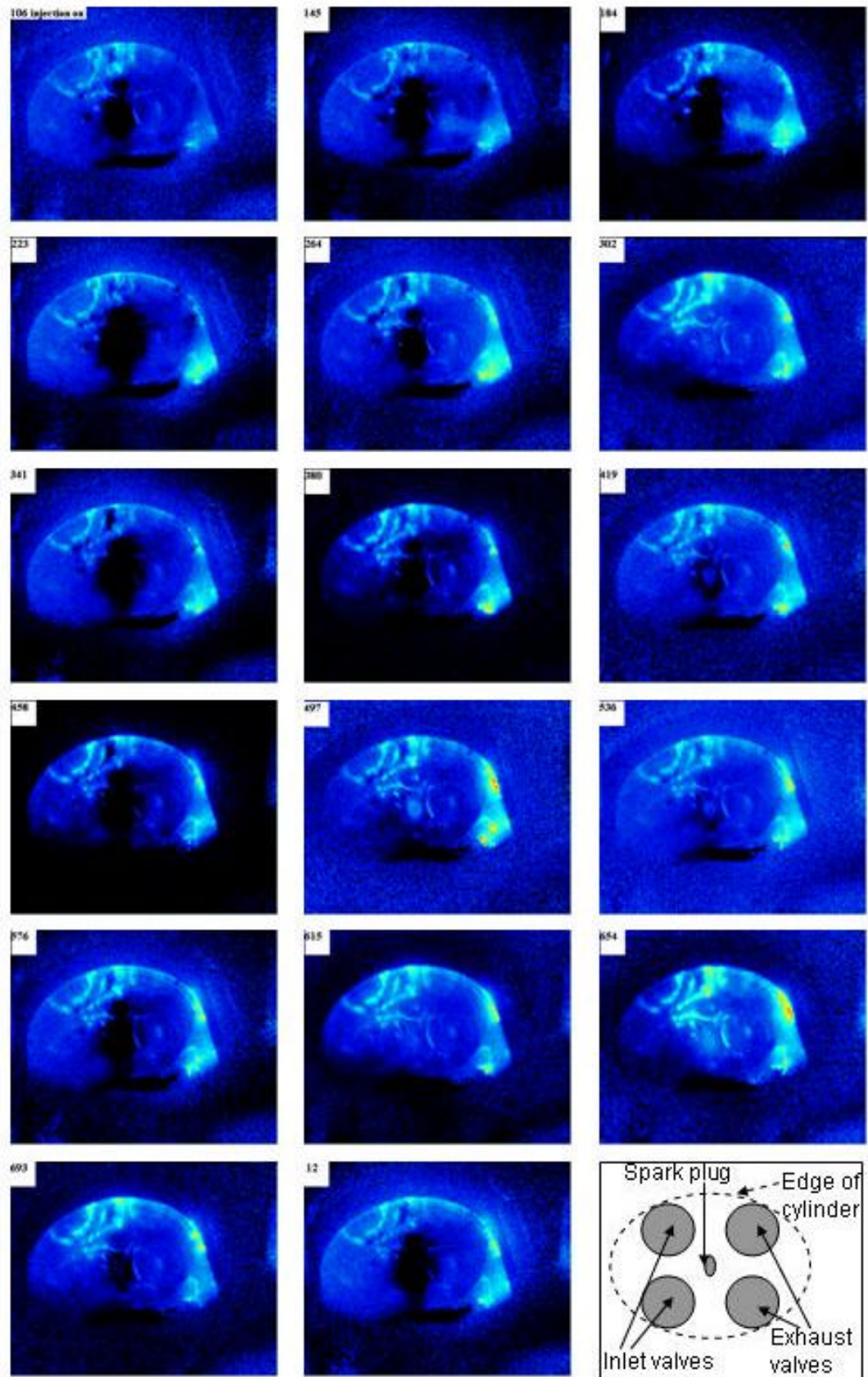


Figure 3 Sequence of processed images showing one complete cam cycle. Crank angles after top dead centre are marked in the top left corner.

The intensity of the fluorescence indicates the film thickness is $30\pm 16\mu\text{m}$ here. The result agrees well with Cho and Min (2003) in which a maximum thickness of $45\mu\text{m}$ was observed, albeit under different operating conditions.

The images show regions of high intensity which change little through the cycle, e.g. around the edges of the inlet valves. At least part of the intensity here is caused by deposits of dye left by evaporating fuel. This leads to imperfect background subtraction.

4. CONCLUSIONS

Laser induced fluorescence has been used to image and measure the depth of fuel films on the inner metal surfaces of a rig that mimics a port fuel injected i.c. engine. In contrast to previous studies the film depth is measured, quantitatively, on the metal combustion chamber surface, with the correct surface roughness and film transport properties, rather than on a smooth glass surface. The technique functions well in the imperfect optical environment of the rig. The depth uncertainty is $\pm 16\mu\text{m}$ but it seems possible to reduce this to $\pm 5\mu\text{m}$. The most significant problems were caused by the build up of dye deposits.

The results show that with open valve injection a film of $30\pm 16\mu\text{m}$ depth forms on the exhaust side cylinder wall. This is likely to result in high UHC emissions.

The technique could be applied in the manifold or port of port injected engines to study spray targeting and film behaviour during transients such as acceleration, or to study the fuel films in the cylinder that contribute to unburnt hydrocarbon, CO and soot emissions, and spark plug fouling. The technique could also be applied to fuel films in gasoline direct injection and Diesel engines, or to lubricant oil films.

5. ACKNOWLEDGEMENTS

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