

The Effects of Charge Homogeneity and Repeatability on Particulates Using the PLIF Technique in an Optical DISI Engine

Quan Liu, Alasdair Cairns, Hua Zhao, and Mohammadreza Anbari Attar
Brunel Univ.

Luke Cruff and Hugh Blaxill
MAHLE Powertrain LLC

ABSTRACT

The work was concerned with visualisation of the charge homogeneity and cyclic variations within the planar fuel field near the spark plug in an optical spark ignition engine fitted with an outwardly opening central direct fuel injector. Specifically, the project examined the effects of fuel type and injection settings, with the overall view to understanding some of the key mechanisms previously identified as leading to particulate formation in such engines. The three fuels studied included a baseline iso-octane, which was directly compared to two gasoline fuels containing 10% and 85% volume of ethanol respectively. The engine was a bespoke single cylinder with Bowditch style optical access through a flat piston crown. Charge stratification was studied over a wide spectrum of injection timings using the Planar Laser Induced Fluorescence (PLIF) technique, with additional variation in charge temperature due to injection also estimated when viable using a two-line PLIF approach. Overall, both gasoline-ethanol fuels generally exhibited a higher degree of stratification, albeit at least partly alleviated with elevated rail pressures. Under both warm and cold liner conditions the E10 fuel showed clear evidence of fuel droplets persisting up until ignition. Interestingly, with late injection timing the repeatability of the injection was superior (statistically) with higher ethanol content in the fuel, which may have been associated with the higher charge temperatures aiding control of the evaporation of the main mass of alcohol.

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INTRODUCTION

It is currently widely acknowledged throughout the automotive sector that the internal combustion will remain key for decades to come, albeit operating in refined form and in some cases as part of a hybrid powertrain. In recent years European CO₂ emissions targets have been met through increased diesel sales. However, the distillation of crude oil results in high proportions of both gasoline and diesel fuel [1] and ultimately this has resulted in Europe becoming "diesel lean" at times [2]. The current status of the European fleet indicates that significant work is still required in the field of gasoline Spark Ignition (SI) engines and recently proposed legislation in California indicates that the US market will enter a period of aggressive CO₂ emission reduction. Overall, in order to meet future global CO₂ emissions goals, in the short term it will be necessary to improve the fuel consumption of the gasoline engine and in the longer term source sustainable alternatives to crude oil.

In recent years various technologies have emerged to improve the fuel economy of the SI engine, with considerable interest in methods such as direct fuel injection including homogeneous

and stratified variants [3, 4, 5], variable valvetrain systems [6, 7, 8, 9], friction reduction technologies [10, 11], advanced downsizing [12, 13, 14] and low temperature combustion modes including Controlled Auto-Ignition (CAI) [15, 16, 17]. Over the last decade or so the downsizing technique has become widely considered as a highly promising short-to-medium term solution [5, 12, 13, 14, 18, 19], with moderately downsized production engines emerging [20, 21, 22]. The basic principle is to reduce the capacity of the engine and hence enforce a larger proportion of operation to higher loads. As a result, pumping losses can be significantly reduced for a given road load requirement. Although specific friction may increase due to higher peak in-cylinder pressures, a net reduction in absolute friction is usually achieved by reducing the number of engine cylinders. In order to compensate for the inherent power loss, some form of intake air pressure charging is usually required, together with direct fuel injection and variable valve timing to help cool the charge and optimise the chamber scavenging respectively [4, 23]. Overall, for a large family-sized saloon car, it has been practically demonstrated that halving total engine capacity from 2.4 to 1.2 litres can reduce fuel consumption by up to 25-30%, with overall

performance of the car otherwise unaffected [13]. However, the most aggressively downsized engines are not without problems, including issues with supercharger parasitic losses or transient response due to turbocharger lag [23]. An additional limitation is the abnormal combustion phenomenon referred to as “Low-Speed Pre-Ignition” (LSPI), the violent combustion associated with which can lead to catastrophic engine failure [24, 25].

The strong synergy between downsizing and Direct Injection Spark Ignition (DISI) is now reasonably well understood, with charge cooling, volumetric and thermal efficiency gains previously well quantified [5, 12, 18, 19, 20, 21, 22, 23, 26, 27]. However, delivery of the fuel directly into the cylinder inherently results in delay in charge mixing, with increased chamber wall wetting primarily governed by the penetration, break-up and atomisation of the spray that varies with overall operating conditions. Ultimately some degree of charge stratification often remains, even under “homogeneous” targeted conditions [28, 29]. As a result DISI engines may produce increased particulate emissions compared to fully optimised Port Fuel Injection (PFI) counterparts. Such particulate emissions contribute to atmospheric pollution and have been shown to be hazardous to human health [30]. Particulate Matter (PM) number concentration and morphology could be more relevant toxicological metrics than the total PM mass, which is especially concerning for DISI engines which have been reported to be a bigger contributor to ultrafine and nano-sized particulate emissions [31, 32, 33].

Particulate matter emissions emitted from internal combustion engines mainly comprise of solid carbonaceous material (soot), Volatile Organic Compounds (VOC's), sulphur and ash. While soot is generally formed from locally rich combustion of the fuel and oil, the VOC's mainly arise from vaporised oil and fuel in the crevice volumes. The sulphur arises from the fuel, whereas the ash consists of any non-combustible metallic additives in the fuel and oil as well as metallic particles from engine wear [33]. In automotive applications, diesel vehicles have been historically considered as the major source of PM emissions, with both PM mass and Particulate Number (PN) now being regulated fairly strictly. Even though gasoline vehicles emit relatively low PM emissions by mass, recent studies have shown that modern gasoline engines may emit substantial amounts of ultrafine and nano-sized particles. Once released into atmosphere, these superfine particles of very low mass but high number [34, 35, 36], may penetrate deep into the lungs and ultimately may cause cardiovascular disease [30, 33]. For these reasons, Europe has recently finalised the regulation for its PM emissions on DISI engines, with not just PM mass but also PN (6.0×10^{11} #/km) restricted, to be effective from 2017 (Euro 6). Similar proposals were also included by the California Air Resources Board (CARB) for the upcoming LEV III. Although the PN emissions target has not yet been set the intention of PN to be regulated in the future is firm [37, 38].

As the expected shortage of crude oil will sooner or later become a limiting factor, sourcing alternative renewable energy is another problem facing the automotive industry. Alcohol based fuels are one major candidate to displace fossil fuels, especially if they can be blended within the existing gasoline pool [39]. Ethanol and gasoline blends have been widely adopted as first generation biofuels, while ethanol can be produced from renewable sources and incur advantage in source to wheel CO₂ emissions [40]. Nonetheless, issues of practicality remain on current wheat ethanol due to feedstock being limited globally, hence in the long term cellulose ethanol may dominate [41] albeit significant challenges remain before this can be considered as viable [42]. Two key significant advantages of ethanol are high latent heat of vaporisation and the associated high octane number providing knock resistance, providing the DISI “charge cooling” effect and improved performance [43]. On these terms ethanol seems a favourable component within gasoline for future boosted DISI engines, where higher compression ratios can be utilised to further improve fuel economy. However, the Lower Heating Value (LHV) of ethanol, at a reduction of ~33% in comparison with gasoline, is a major drawback which results in increased volumetric fuel consumption. Additionally, the high latent heat of vaporisation and differences in vapour pressure lead to an adverse effect on cold-start behaviour of gasoline-ethanol blends [44]. Furthermore, in recent years, reports on PM emissions of gasoline-ethanol blends in DISI engines remain highly contradictory. For example, Storey et al. [45] stated reduced content of ethanol in the fuel (E10-E20) decreases PM emissions, while He et al. [46] observed lower content of ethanol has similar PM emissions as gasoline. Elsewhere Francqueville [47] demonstrated an increase in ethanol proportion (E85) decreases PM emissions, whereas Chen et al. [48] concluded both PM mass and PN emissions increase with the ethanol content of the fuel increased.

The currently reported work has focused on improving understanding of the fundamental mechanisms leading to particulate emission formation in future homogeneous DISI engines. The ultimate goal of the research is to help allow future stringent emissions legislation to be met using a standard three-way catalyst after-treatment system. A bespoke single-cylinder DISI engine with optical access was used to investigate the effects of different fuels on in-cylinder fuel distribution and temperature via the PLIF method, capable of providing both fuel distribution and charge temperature history as detailed further below.

EXPERIMENTAL ENGINE

The experiments were performed in a bespoke optical single-cylinder DISI research engine. The key engine specifications are summarised in [Table 1](#). The bottom end was based upon a Ricardo Hydra, mounted on a 30kW Cussons test bed with integrated oil and coolant control ($\pm 2^\circ\text{C}$). The Hydra was fitted with a custom cast iron block, wet liner and Bowditch piston as illustrated in [Figure 1](#). The extended piston was made of aluminium utilising PTFE compression rings lubricated with

grease. The piston crown included a Ø55mm flat-topped quartz piston window providing access to ~50% area of the bore when considered on a planar basis. A sandwich plate was designed to mate between the cylinder head and the extended block, with additional optical access to the combustion chamber available via two side windows of 21mm height. In the current work these were used to allow laser light entry in a plane through the combustion chamber with the piston at 30°bTDC firing, where the laser sheet was aligned at 5.77mm above the optical piston and 10.5mm below the spark plug. The cylinder head was a machined-from-solid prototype, where the combustion chamber was of pent-roof spray-guided direct injection design, with four valves operated by double overhead camshafts housed in an aluminium casing, mating with an extended cylinder/piston assembly. A view of the combustion chamber is provided in Figure 2.

Table 1. Key engine specifications

Displaced volume	447 cc
Stroke	89 mm
Bore	80 mm
Compression ratio	8.67:1
Inlet valves diameters	29.5 mm
Exhaust valves diameters	21 mm
Valve lift	9 mm
Cam duration	220°c.a. (end of ramp)
EMOP	265°aTDC (compression)
IMOP	455°aTDC (compression)

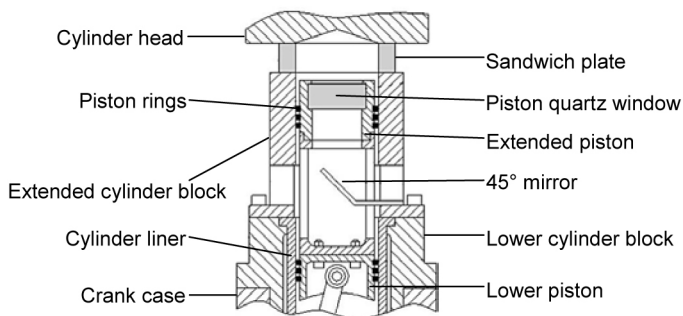


Figure 1. Engine setup schematic

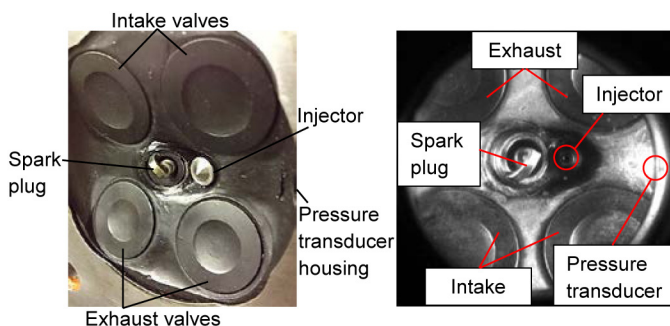


Figure 2. Bottom view of the combustion chamber Note: View via 45° mirror shown on the right

The injector used in the work was a current production Piezo, which sprayed a 90° cone-shape charge of fuel directly in front of the spark plug. To achieve the precise requirements for the

spray pattern, moderate modifications to the cylinder head and injector were carried out to comply with manufacturer guidelines (indicated in Appendix A). The bespoke fuel supply system consisted of a PowerStar4 double ended air driven pump with an amplification ratio of 64:1. With the regulated air inlet pressure at ~5.5bar this pump could generate rail pressures of up to ~340bar. The pressure variation in the fuel rail was measured at ±4bar at 200bar fuel pressure with 0.5ms injection duration using iso-octane.

PLIF SETUP

Planar Laser Induced Fluorescence is a well-known diagnostic technique that allows the distribution of the fuel, residual burned gases and in-cylinder gas temperature to be qualified. In the current work this technique provided valuable information on the tendency for in-cylinder particulate emission formation due to stratification of the fuel and/or (to a lesser degree) differences in charge temperature. The PLIF system consisted of two lasers, a Raman converter, a dual-frame ICCD camera and the ancillary optics including mirrors, a prism, lenses and filters for steering, shaping and collecting the laser beams. The two excitation wavelengths of 308nm and 277nm were generated by a XeCl Excimer laser (Lambda Physik COMPexPro 102) and via Raman shifting of a 248nm KrF Excimer laser (Coherent COMPex 102) respectively, as illustrated in Figure 3.

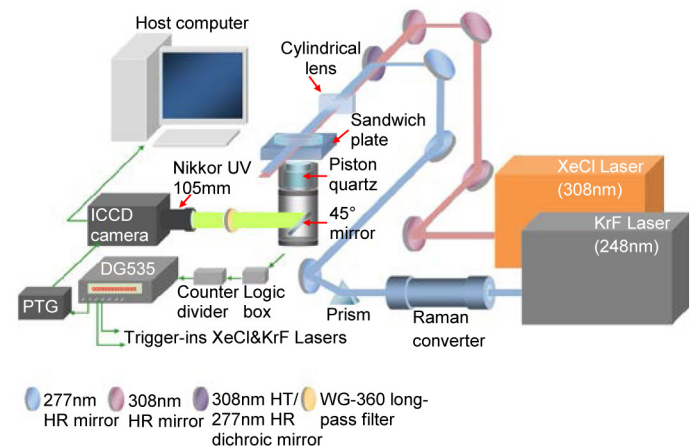


Figure 3. PLIF system setup schematic

The in-cylinder temperature measurements via the tracer based PLIF technique can be summarised in two basic steps. Firstly, by capturing images from rapidly triggered successive two-line excitation pulses the ratio of the two fluorescence signals can be cross-referred to temperature. Secondly, by adopting two different tracers and a single excitation pulse the ratio of the fluorescence signals may also be analysed to indicate temperature [49, 50]. In recent work such a technique was adopted by Rothamer et al. [51] who indicated a high accuracy of ±5% for in-cylinder temperature measurement when compared to 1-D engine simulation results.

The two-line PLIF technique requires two precise spatially overlapping laser sheets to illuminate the targeted plane in the combustion chamber. The output beam generated by the XeCl laser went through a beam splitter while the KrF laser beam was sent through the Raman converter and passed through a dispersive prism. Both laser beams were then redirected by highly reflective mirrors, combined using a dichroic mirror and finally focused by a cylindrical lens. The dichroic mirror was a key component that allowed spatial overlap of the two laser beams, while the special coating helped transmit the 308nm (>90% efficiency) and reflect the 277nm wavelengths (>97% efficiency). Both Excimer laser beam divergences were measured at 9mrad and 1mrad for the vertical and horizontal axes respectively using a pulse energy meter and a knife-edge technique. The laser sheets (55mm wide and ~0.5mm thick) were transmitted through the side optical window with high divergence in the horizontal axes and low divergence in the vertical axes to maximise the homogeneous illumination coverage over the targeted plane. The pulse energies of the 308nm and 277nm lasers were 40mJ and 20mJ respectively, with typical shot-to-shot pulse energy variation kept below 2% (308nm) and 1% (277nm) throughout the experiments (a pulse energy meter was used to monitor and record prior to each test, samples can be found in [Appendix B](#)).

The imaging system included a Princeton Instrument PI-MAX III ICCD camera that provided a low noise and high dynamic range. The readouts could be scanned at a variety of pixel rates. When carrying out two-line PLIF Double Image Frames (DIF), the overlapped operation allowed a new exposure to begin while the existing one was still in progress. Thus overall the system was capable of capturing two images in very rapid succession. A Nikkor UV 105mm f/4.5 lens and a Schott WG-360 long-pass filter were used to collect the fluorescence signal and block the unwanted wavelengths. The camera and lasers were synchronised to the engine via a crankshaft encoder. A counter/divider was used to provide the camera and laser trigger-in signals. The camera Programmable Timing Generator (PTG) and DG535 delay generator were used to set the delays between the lasers and the camera trigger-in signals (with a maximum total system delay of 77ns recorded).

EXPERIMENTAL FUELS AND FUEL DOPANT

The key properties of the fuels and dopant used are presented in [Table 2](#). The two gasoline-ethanol blends were selected as potential “real” fuels for DISI engines. For both fuels a pump grade 95RON unleaded gasoline (ULG) was splash blended with the ethanol on a volumetric basis. Fuel containing 10% volume ethanol was of interest as such blends are now widely available in the US market and still being considered within the EU. The E85 type blend has also emerged in key markets and was required to provide information on the behaviour of a higher ethanol content fuel under DISI flex-fuelled conditions. Iso-octane was also used to establish a single component benchmark for comparisons with these real fuels.

Given its similar boiling behaviour to iso-octane, 3-Pentanone is a common and arguably highly suitable PLIF tracer for such work [52, 53, 54] and was chosen to be the tracer used. For the fuel distribution visualisations, all fuels were doped with tracer (9:1 fuel to dopant in volume), premixed in the fuel tank and injected directly into the combustion chamber. For the in-cylinder temperature measurements, the tracer was injected (at 4.5mg/cycle) into the intake air via a port fuel injector mounted on the intake port.

Table 2. Key properties of the experimental fuels and dopant

	ULG	Iso-octane	E10	E85	3-Pentanone
Lower Heating Value (MJ/kg)	43.16	44.31	41.64	29.28	33.4
RON	95	100	98	108	-
MON	86	100	88	90	-
(R+M)/2	91	100	93	99	-
Density at 15°C (kg/dm ³)	0.74	0.69	0.75	0.78	0.81
H/C Ratio	1.891	2.25	1.945	2.769	2
O ₂ (% weight)	0	0	3.35	29.5	18.6

EXPERIMENTAL ARRANGEMENT

Experiment 1 - Planar Fuel Distribution Visualisations

The fuel injection pulse width was determined in prior firing setup tests (with the optical windows still fitted). For each fuel the pulse width and intake throttle position was fixed to the value required to maintain a load of 3.5bar net IMEP with optimum spark timing, fixed SOI timing of 270°bTDC and a rail pressure of 100bar. This process was then repeated to determine the required pulse width to be used with each fuel at 200bar rail pressure. Hence one limitation of the work, for a given fuel pressure, was the assumption that the pulse width would remain fixed throughout the injection timing sweeps. In all of the motoring tests the single-line PLIF technique was adopted, with the 308nm XeCl laser employed alone. The three fuels used were iso-octane, E10 and E85 which were all evaluated at both 100bar and 200bar rail pressure, with the SOI timing swept but the pulse width held constant at that mapped in firing mode for each fuel. For the image processing,

Single Image Frames (SIF) was adopted and two sets of 20 frames were taken under i) background and ii) DI (fuel & tracer) conditions for test, as detailed in [Table 3](#).

Table 3. Experiment 1 - Planar fuel distribution visualisations

Fuel	Iso-octane	E10	E85
Speed (rpm)	1200	1200	1200
IMEPn (bar)	~3.5	~3.5	~3.5
λ	1	1	1
SOI (°bTDC)	330 → 90 (60°c.a. incr.)	330 → 90 (60°c.a. incr.)	330 → 90 (60°c.a. incr.)
Fuel Pressure (bar)	100 & 200	100 & 200	100 & 200
Injection Duration (ms)	0.54 & 0.41	0.59 & 0.44	0.80 & 0.64
Coolant Temperature (°C)	30 & 60 & 90	30 & 60 & 90	30 & 60 & 90
Camera Capture Timing (°bTDC)	30	30	30

Experiment 2 - Planar Gas Temperature Measurements (Charge Cooling Effects)

For the two-line PLIF experiments DIF was used to capture both images (308nm and 277nm) with a burst period (delay) of 30 μ s in succession. In consideration of 139 μ s duration for each crank angle degree at 1200rpm this delay was not considered to be significant. Three sets of 40 frames (20 for each laser) were captured as background, PFI (tracer) and PFI (tracer)+DI (fuel) images for iso-octane under motoring conditions, as illustrated in [Table 4](#).

Table 4. Experiment 2 - Planar gas temperature measurements

Fuel	Iso-octane
Speed (rpm)	1200
IMEPn (bar)	3.5
λ	1
SOI (°bTDC)	330 → 90 (60°c.a. incr.)
Fuel Pressure (bar)	200
Injection Duration (ms)	0.41
Coolant Temperature (°C)	30 & 60 & 90
Camera Capture Timing (°bTDC)	30

PROCESSING OF IMAGES

Planar Fuel Distribution Visualisations

The output images of the fuel distributions were saved in one file for each different fuel used. WinView 32 data acquisition software was employed to process the large amount of data. The image processing procedure is illustrated in [Figure 4](#). By averaging the background images, then subtracting these from the DI (fuel & tracer) images at different test points. The variation in background laser light intensity throughout the imaging area was appropriately taken into account.

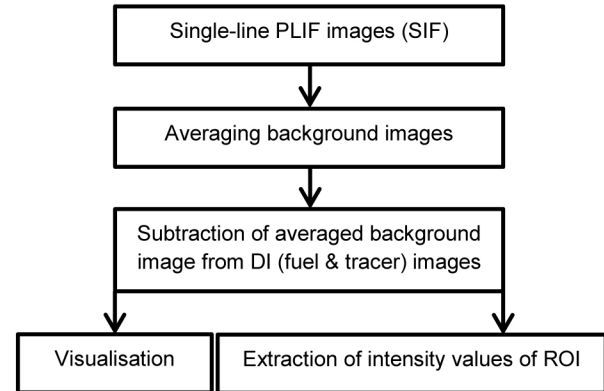


Figure 4. Image processing procedure for Planar Fuel Distribution Visualisations

Planar Gas Temperature Measurements

In the current work, a calibration curve was used to quantify the degree of charge cooling with iso-octane at varied conditions. Although the relationship between the fluorescence signal intensity ratio of two beams and the temperature of the sampling area can be determined via theoretical models developed for fluorescence quantum yield and absorption cross section of the tracer, it was found that further validations and adjustments are usually needed [55]. Therefore in recent alternative work at Brunel on the same engine, a Constant Volume Chamber (CVC) was developed to replicate the 'real' engine motoring condition for an experimentally based calibration. The CVC was used as a steady state calibration device (without any piston motion), being primed and sealed with gas containing the same proportion of tracer as used in the currents tests. In addition, the top of the CVC was mounted and sealed with the same optical cylinder head to ensure the consistency in light transmission efficiency. The CVC had a working pressure of up to 3bar and temperature up to 850K (imposed by the melting point of the material used). A combination of cartridge heaters and tubular heaters were attached to the CVC thus temperature could be specified. A tracer supply system was designed to feed a homogenous mixture of both tracer and air via an inlet and outlet valve on the chamber. Two-line PLIF images were captured from room temperature up to 750K in 10K increments under a constant atmospheric pressure as reported elsewhere [55]. Shown in [Figure 5](#) are the calibration results, where the red data points represent the fluorescence signal intensity as a

function of CVC temperature for both lasers. The temperature calibration curve was obtained by calculating the signal intensity ratio at each data point, with the fitted trend line shown superimposed.

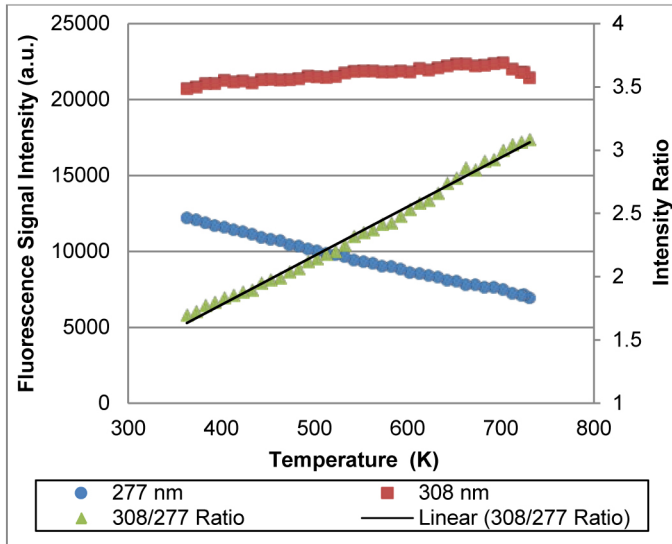


Figure 5. Two-line PLIF CVC calibration [55]

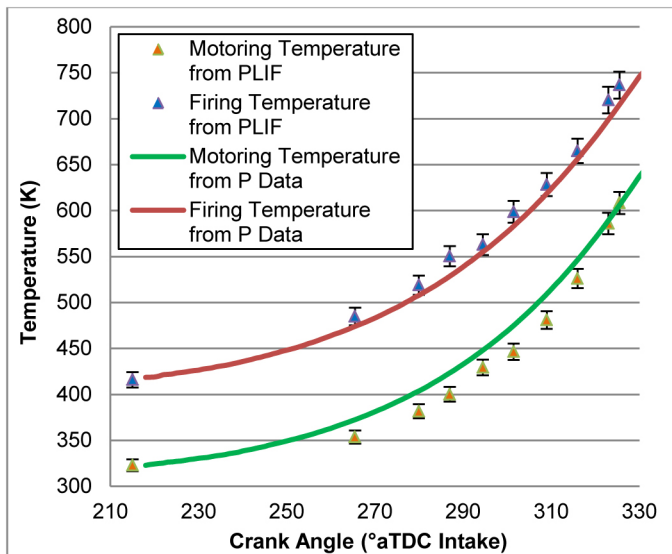


Figure 6. Validations under motoring and firing conditions [55]

In this previous work at Brunel [55], validation measurements were also performed in the same engine by comparing the calculated temperature from in-cylinder pressure data with the PLIF temperature calibration results, under similar motoring and firing conditions to those employed here. The results are illustrated in Figure 6. When using pressure data the perfect gas law was used in conjunction with air & fuel flow and gas temperature measurements in the ports. For the motoring case, the average percentage difference between the two methods was 3.53% with a standard deviation of 2.37%, while for the firing test the average percentage difference was found to be 2% with a standard deviation of 1.28%. Overall, from this

prior work, it was concluded here that the PLIF calibration technique was acceptable for the current tests given identical tracer concentration would be used at similar engine conditions.

Figure 7 details the image processing procedure for temperature measurements. Customised software was used to separate odd and even files for 308nm and 277nm respectively from the combined 40 frames captured. By using WinView 32 to subtract the averaged background images from averaged data images in which the PFI (tracer) and PFI (tracer)+DI (fuel), thus the averaged intensity values of a fixed ROI for both lasers could be obtained.

$$R_{PFI} = \frac{308PFI_{avg} - 308BK_{avg}}{277PFI_{avg} - 277BK_{avg}} \quad (1)$$

$$R_{(PFI+DI)} = \frac{308(PFI+DI)_{avg} - 308BK_{avg}}{277(PFI+DI)_{avg} - 277BK_{avg}} \quad (2)$$

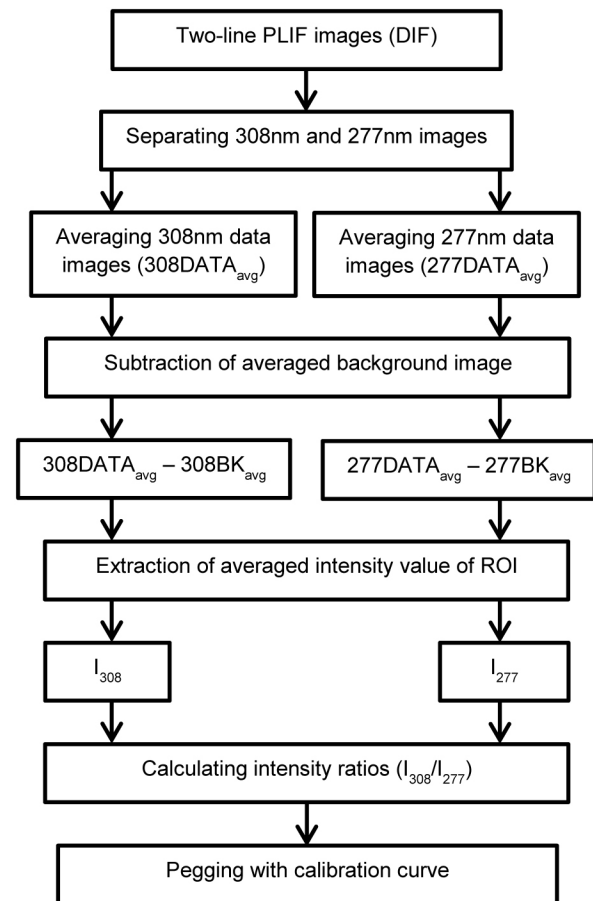


Figure 7. Image processing procedure for Planar Gas Temperature Measurements

Equation 1 indicates the ratio of intensities for PFI (tracer) which was intended to analyse the averaged charge temperature without fuel injection. Whereas Equation 2