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Simultaneous Imaging of Diesel Spray Atomisation and Evaporation Processes in a Single-Cylinder CR Diesel Engine

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ABSTRACT: In direct injection diesel engines, combustion and formation of pollutants are directly influenced by the spatial and temporal distributions of the injected fuel. In this study mixture formation during the pre-combustion phase of a diesel engine was investigated using the laser-induced exciplex fluorescence (LIEF) technique. The main purpose of this investigation was to develop an experimental setup capable of providing the full-field view of both liquid and vapour phases of evaporating diesel sprays during the fuel injection process inside the combustion chamber of a diesel engine with optical access. An expanded laser beam was employed for full combustion chamber visualisation. In this study two model fuels were tested; one consisted of 89% decane, 10% α-methyl-naphthalene and 1% TMPD and the other 88% decane, 10% α-methyl-naphthalene and 2% TMPD. The spray atomisation and evaporation processes during the pre-combustion phase of a diesel engine were measured at an injection pressure of 1200 bar and the engine speed of 1500 rpm. The results demonstrated the capability of the full-field LIEF technique in simultaneous imaging of liquid fraction and fuel vapour distribution during high pressure fuel injection process. It also highlighted the effect of dopant concentration on the fluorescence intensity of liquid and vapour signals. The exciplex system containing 1% TMPD produced better visualisation of the liquid phase, though the crosstalk in the vapour phase precluded accurate detection of the vapour phase signal. In contrast, the exciplex system containing 2% TMPD resulted in satisfactory visualisation of the vapour phase; however the intensity of the liquid phase was compromised as a result. This was presumed to be mainly due to the spectral shift of the exciplex species and/or TMPD decomposition at elevated temperatures and pressures.

Keywords: LIEF, evaporating diesel sprays, injection rate, mixture formation, diesel engine

1   INTRODUCTION

Increasing concern over global warming, stringent emission legislation and also limitations in the available fossil fuel resources enforces the need for improvements towards more efficient and cleaner internal combustion (IC) engines. In direct injection IC engines, fuel sprays injected into a high temperature gaseous atmosphere evaporate due to heat transfer from the surrounding gaseous medium. The combustion characteristics and the exhaust emissions are directly influenced by the fuel evaporation process, fuel-air mixing rate, ignition delay and the location of initial combustion. However, these parameters are all functions of the spatial and temporal distributions of liquid droplets and fuel vapour within the combustion chamber. Therefore, detailed understanding of spray breakup and vaporisation is vital for the optimisation of the fuel injection equipment (FIE) in order to achieve desirable fuel spray, air-fuel mixture and combustion characteristics. The fuel distribution is influenced by the thermodynamic conditions of the gaseous medium in which fuel is injected to (i.e. gas density, temperature, pressure, etc.), the characteristics of the FIE (i.e. nozzle geometry, injection pressure, injection rate, etc.) and the geometrical configuration of the piston bowl and the combustion chamber. In addition, recent fuel diversification further enforces the need for detailed investigation of alternative/renewable fuel properties, such as GTL and biofuels, on fuel spray jets behaviour within the combustion chamber of diesel engines. Therefore, advancement in fuel injection system and engine design requires good understanding of the fuel evaporation and mixing processes during the pre-combustion phase. During the past two decades, the development of nonintrusive laser-based optical diagnostic techniques including Raman scattering [1, 2], photography [3, 4], laser light scattering [5] and two-wavelength laser absorption/scattering [6] have facilitated in-depth analysis of fuel sprays both in microscopic and macroscopic levels. In particular, laser-induced fluorescence (LIF) technique has been widely used to measure the in-cylinder fuel vapour distribution in both gasoline and diesel engines [7]. These techniques are capable of providing information at physically inaccessible locations. However, these methods are not capable of simultaneous and discrete measurement of liquid and vapour phases. This is mainly due to insufficient distinctive spectroscopic characteristics of soluble organic molecules in a polar solvent in the liquid and vapour phases.

In comparison to the single phase LIF technique, laser-induced exciplex fluorescence (LIEF) technique is capable of discrete measurement of liquid and vapour phases at spectrally separated wavelengths. The LIEF technique was initially proposed by Melton [8]. It was based on the addition of organic dopants to the base fuel while maintaining similar chemical and physical properties in comparison to those of standard diesel fuel. This method enabled simultaneous and discrete measurement of liquid and vapour phases, provided that appropriate organic dopants were selected. Melton and Verdieck [9] used tetramethyl-p-phenylene diamine (TMPD)/naphthalene exciplex system with 90% n-decane, 9% TMPD and 1% naphthalene. They reported on the quantitative potential of this exciplex system due to its proportionality to fuel mass concentration, provided that laser scattering and absorption effects as the laser light travels through the sampling volume are compensated for. More importantly, the quenching effects due to molecular oxygen were reported to significantly suppress the vapour phase signal intensity for which the use of an inert gaseous medium such as nitrogen was proposed. The first application of the LIEF technique was reported by Bardsley et al. [10, 11] where liquid and vapour portions of a fuel spray produced by a hollow cone injector were illuminated by a laser sheet from the 4th harmonic of a Nd:YAG laser and the images were recorded by an intensified charge coupled device (ICCD) camera. The same setup was also implemented by Diwakar et al. [12], and Bower and Foster [13] in IC engines for simultaneous measurement of liquid and vapour portions of evaporating fuel sprays.

Melton [14] proposed a quantitative method based on the calibration of several photophysical parameters including light absorption and quantum yield of TMPD/naphthalene exciplex system. However, the accuracy of the calibration data was highly depended on the accuracy of the individual calibration procedures. Subsequently, Rotunno et al. [15] presented a direct calibration procedure in the temperature range from 313 K to 443 K. They quantified the transient behaviour of the vapour and liquid phases of an evaporating fuel spray. Felton et al. [16] also applied the technique to a hollow-cone spray in a two-stroke diesel engine. However, the vapour phase concentration presented by Rotunno et al. [15] exhibited a considerable disparity when compared to the results obtained by Felton et al. [16] through direct-pressure measurement. This was attributed to highly temperature dependent nature of TMPD absorption at temperatures beyond 500 K. Yeh et al. [17] also carried out quantitative analysis of fuel vapour concentration in a rapid compression machine. They calibrated the TMPD fluorescence intensity in a range from 500 K to 800 K. Their result showed that the absorbance of TMPD was minimally affected by the surrounding temperature, contrary to the result reported by Felton et al. [16]. Senda et al. [18] applied the exciplex method to an impinging spray in a constant volume chamber at a temperature of 700 K and a pressure of 25 bar. They used the Lambert-Beer's law to measure the TMPD concentration from the measured fluorescence intensity and subsequently correcting the intensity for the effects of fluorescence quenching, ambient temperature and fuel mixture concentration. The fuel temperature was estimated based on two assumptions; the mixing between the fuel and air was adiabatic and occurred at constant pressure. Kim and Ghandhi [19] also performed a series of LIEF experiments in a constant volume chamber whereby they developed a technique for quantitative analysis of vapour concentration in evaporating fuel sprays.

The LIEF technique has been employed in numerous research studies for detailed investigation of fuel evaporation and mixture formation and their effects on combustion characteristics in both diesel and spark ignition engines. Senda et al. [20] investigated the effect of heterogeneity of vapour concentration on soot formation within the combustion chamber of DI diesel engines using this technique. Wieske et al. [21] investigated the origin of cyclic fluctuations in a direct injection spark ignition engine by means of the LIEF technique. The effect of nozzle hole diameter, injection pressure and ambient condition on diesel spray characteristics was intensively investigated in a pre-combustion type constant volume chamber by Yamashita et al. [22]. Bruneaux et al. [23-25] applied this technique for detailed investigation of fuel evaporation and mixing processes using a single hole common rail (CR) diesel injector inside a constant volume chamber. Matsuoka et al. [26] also studied the state of spray and mixture formation in a pre-combustion type high pressure/high temperature chamber under the thermodynamic conditions similar to those experienced in production type diesel engines. The model fuel was designed such that similar kinematic viscosity and distillation characteristics were obtained in comparison to light diesel fuel, allowing accurate measurement and analysis of fuel evaporation process.

More recently Rogler et al. [27] reported on 3-D visualisation and analysis of vapour and liquid phase of gasoline injectors using the LIEF technique in a high pressure/high temperature chamber. In addition, Zhang et al. [28] investigated flash boiling phenomenon which occur at some operating conditions when fuel is injected into the cylinder of a direct injection spark ignition engine. They applied the LIEF technique with two specially designed dopants, fluorobenzene (FB) and diethyl-methyl-amine (DEMA), in n-hexane to investigate the effects of such phenomenon on liquid and vapour phases of fuel sprays from a multi-hole injector in an optically accessible high pressure chamber. However, the majority of previous LIEF measurements have been performed in a constant volume chamber or in an optically accessible engine

using laser sheet imaging. The application of the LIEF technique to in-cylinder liquid and vapour visualisation was limited to the measurement of only one plane of the fuel spray jets. In this paper, a full volume LIEF setup will be presented that enabled the visualisation of all fuel sprays with minimum laser extinction effects in a single-cylinder CR direct injection diesel engine. Following an overview of the principle of the LIEF technique, the details of the experimental setup and its optimisation procedure are described. The effect of optical setup and dopant concentration on the liquid and vapour phases is demonstrated by the full volume LIEF results.

2   PRICIPLE OF LIEF TECHNIQUE

The principle of the LIEF technique is based on the addition of organic dopants to the base fuel with similar chemical and physical properties to those of standard diesel fuel. This technique allows for the measurement of macroscopic features of a fuel spray such as liquid/vapour penetration length and cone angle as well as microscopic characteristics including local air-fuel ratio and spray sauter mean diameter, provided that appropriate dopants are selected.

2.1   Photophysical Reaction

The absorption and emission spectra of organic molecules dissolved in non-polar solvents, such as decane, are almost identical to those of the same molecule in the vapour phase. An organic molecule M can absorb light to form an excited molecule M^* with an average lifetime of 10-100 ns. The excited molecule may undergo three different processes [29].

$$M^* \rightleftharpoons M + h_{v_M} \qquad \text{(i)}$$

$$G + h_v \rightleftharpoons G^* \qquad \text{(ii)}$$

$$M^* + G \overset{K}{\rightleftharpoons} E^* + h_{v_E} \qquad \text{(iii)}$$

$$E^* \rightleftharpoons M + G + h_{v_M} \qquad \text{(iv)}$$

i. M^* may return to the ground state without light emission referred to as fluorescence quenching.

ii. M^* may transfer part of its energy to excite another molecule G, referred to as partner, due to reactive collision. The newly formed excited molecule G^* could subsequently fluoresce, provided that G had an adequate energy level prior to collision.

iii. M^* may bind reversibly with G to form an exciplex molecule, E^*, which could subsequently fluoresce.

iv. E^* may fluoresce and return to the ground state.

Therefore, in favourable cases it is possible to react an excited fluorescent monomer, M^*, with an appropriate partner, G, to form new species in an excited state, E^*. The reaction between M^* and G is reversible; therefore the concentration of the latter can be adjusted so that the fluorescence emission produced by the liquid and vapour phases are dominated by E^* at longer wavelengths and M^* at shorter wavelengths respectively. Nevertheless, there exists a region in which the liquid and vapour signals overlap. This is commonly referred to as cross-talk which is a major concern when quantifying the LIEF results. This phenomenon is more paramount at elevated temperatures where the fluorescence emission of the exciplex molecules is blue-shifted (i.e. the liquid signal peaks at lower wavelengths) resulting in higher cross-talk between the liquid and vapour signals. In contrast, the influence of the vapour signal on the liquid phase is relatively small since the measured fluorescence intensity is proportional to the mass of the excited molecules in the measuring volume. The understanding of the formation and dissociation processes involved in an exciplex system is multifaceted since the exciplex species are formed in a reversible equilibrium with a reaction constant K whose value is highly temperature dependent, reaction (iii).

2.2   Exciplex System

In order to spectrally separate the fluorescence emission spectra of the liquid and vapour phases of an evaporating fuel spray, an appropriate exciplex system must be selected. The exciplex system selection

criteria are based on several factors including the exciplex binding energy, spectral shift, volatility and boiling point of the organic molecules. The solvent is often an alkane due to its nonfluorescent characteristics and the organic molecule M is carefully selected such that it coevaporates with the solvent, capable of forming exciplexes and fluoresces when excited. Thus, the organic molecules which satisfy these criteria are exceptionally limited, making the selection process very challenging. The most commonly applied and best suited system for the investigation of diesel fuel sprays is 0.5-1% (w/w) TMPD, 10% (w/w) α-methyl-naphthalene and balance alkane (decane, tetradecane or hexadecane) [8, 9, 29]. In this system α-methyl-naphthalene serves as the partner and TMPD as the monomer. The exciplex species are formed due to reactive collision of the excited monomer with the partner in a dense region such as the liquid phase where the reaction probability is much higher [30, 31]. Therefore, by careful adjustment of the concentration of M and G fluorescence emission from the exciplex species and the excited monomer serve as the markers of the liquid and vapour phases respectively.

Decane is photophysically inert at the excitation wavelength used in this study, 308 nm, thus organic dopants were added to this base fuel in order to trace the liquid and vapour phases [32]. The boiling point of TMPD, α-methyl-naphthalene and decane are 260°C, 244.8°C and 214.5°C respectively, thus the overall boiling point of TMPD/ α-methyl-naphthalene exciplex system lies within the range of 200 to 300°C which is comparable to that of standard diesel fuel. Thus, it is assumed that the mixture of decane, α-methyl-naphthalene and TMPD coevaporates at approximately the same rate as that of standard diesel fuel which is crucial when analysing macroscopic and microscopic characteristics of evaporating diesel sprays.

2.3 Fluorescence Quenching

Quenching is defined as a process which decreases the fluorescence intensity of a matter. Quenching may occur through several mechanisms such as dynamic quenching, static quenching, quenching through energy transfer and quenching due to charge transfer reaction (photochemistry). Although there are several mechanisms through which fluorophores undergo quenching, dynamic or collisional quenching is considered to be the major contributing factor. Quenching is often highly dependent on the pressure and temperature of the surrounding environment. This phenomenon poses a problem when applying spectroscopic techniques such as LIEF to IC engines whereby elevated pressures and temperatures exist at the time of fuel injection. Furthermore, molecular oxygen is one of the best-known collisional quenchers for all fluorophores [33]. Oxygen molecules deactivate the excited species, precluding fluorescence emission. The reduction in fluorescence intensity is directly proportional to the decay in fluorescence lifetime of quenched species. The fluorescence quenching of the liquid phase is insignificant since the liquid droplet lifetime is relatively short prohibiting the diffusion of oxygen molecules into droplets. In addition, dissolved oxygen molecules present in the fuel can be purged prior to testing. In contrast, dynamic quenching is a major concern in the vapour phase in particular when performing quantitative analysis. Therefore all the experiments must be carried out in a nitrogen environment to avoid collisional quenching by oxygen molecules.

3 ENGINE AND OPTICAL SETUP

3.1 Single-cylinder Optical Engine

All experimental testing in this study was carried out in a single-cylinder optical diesel engine equipped with a production cylinder head, designed to be representative of a typical modern high-speed direct injection (HSDI) diesel engine. The engine consisted of a Ricardo Hydra engine crankcase, extended cylinder block and piston and a standard production Ford 2.0 litre ZSD 420 Duratorq engine cylinder head. The engine specifications are detailed in Table 1.

Table 1. Single-cylinder optical engine specifications

Ricardo Hydra Single-Cylinder Engine	
Bore	86 mm
Stroke	86 mm
Swept Volume	499 cm^3
Compression Ratio	16:1
Piston Bowl	43.4/11.6 mm
	Re-entrant bowl with flat bottom
Swirl Ratio (Ricardo)	1.4

The FIE consisted of a fuel filter, a 12V low pressure pump which drew the filtered fuel from the fuel tank, a pneumatic high pressure pump and a Delphi CR fuel injector. The injector utilised in this study was a Delphi multi-hole valve covered orifice (VCO) injector capable of injecting up to 1600 bar. The specifications of the FIE are listed in Table 2.

Table 2. Fuel injection equipment specifications

Injection System	
1st Generation CR System with Pneumatic Pump	
Maximum Injection Pressure	1600 bar
Delphi Standard VCO Injector	
Number of Holes	6
Hole Size	0.154 mm
Cone Angle	154°
Flow Rate	0.697 l/min

In this study, a Kistler 6125 piezoelectric pressure transducer was installed in place of the glow plug for in-cylinder pressure measurement and heat release analysis. Optical access was provided by the Bowditch piston design which allowed for the visualisation of the combustion chamber through the axis of the cylinder via a glass window, made from fused silica, mounted in the crown of the piston. An extended piston and cylinder block were required in order to accommodate such an optical configuration which consisted of lower and upper parts with a 45° angled mirror, made of glass with aluminised front surface, between the sections. Therefore, the combustion chamber and cylinder walls were fully visualised, Figure 1. In addition, the upper cylinder block had three rectangular wall cut-outs which were fitted with glass windows, made of fused silica, for side optical access. Two of these windows were in the same plane while the third window was positioned at 90°, premeditated for imaging and detection purposes.
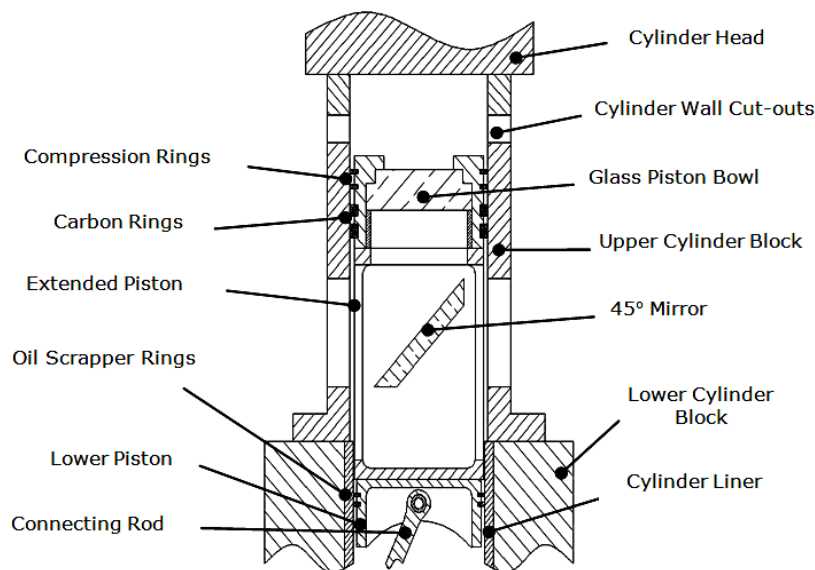

Figure 1. Sectional schematic view of the optical layout

3.2   High-speed fuel spray and combustion visualisation

The high-speed video imaging technique was employed to record colour images of fuel sprays during the fuel injection period, Figure 2. In order to visualise the fuel sprays, a high repetition copper vapour laser was utilised. The output of the laser was delivered to the engine via an optical fibre so that the whole combustion chamber could be illuminated by the divergent laser beam leaving the optical fibre. The short laser pulse of 30ns effectively defined the exposure time of the spray images, which was critical to obtain sharp images of sprays travelling at very high speeds. A NAC Memrecam FX6000 high-speed colour video camera was utilised which was equipped with a high-speed complementary metal–oxide semiconductor (CMOS) sensor. The high-speed camera was synchronised to the pulsed laser outputs to capture videos at 10,000 frames per second with an image resolution of 512 x 248 pixels. A Nikon 50mm lens was used at maximum aperture, f/1.4. A light-emitting diode installed in the field of view of the camera provided the reference signal at top dead centre (TDC) in the high-speed video images.
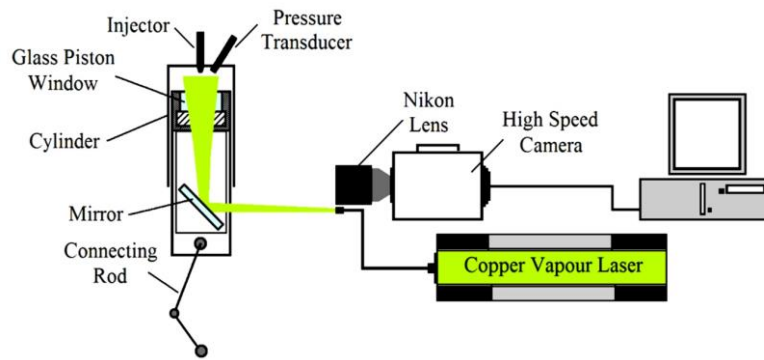
Figure 2. Schematic diagram of high-speed fuel injection visualisation setup

3.3   LIEF Optical Setup

This section includes detailed explanation of the experimental setup employed, outlining the characteristics of the detection system utilised.

An excimer XeCl laser; COMPex 102 Lambda Physik; operating at 308 nm was employed as the excitation source. The laser intensity fluctuation was found to be significantly lower at higher pulse energy. Consequently the laser pulse energy of 100 mJ was selected for the purpose of this investigation which resulted in maximum laser intensity fluctuation of <5%, measured with a pulse energy meter. The specifications of the laser are listed in Table 3. An ICCD camera, Oriel InstaSpec V, equipped with a special UV transmitting macro photography lens, Nikkor 105 mm f/4.5 (maximum aperture), was used in this study to capture still images of the fuel sprays. The camera was equipped with a control unit premeditated for triggering and data transfer purposes. The camera was triggered internally for focusing purposes and externally for fuel spray measurements. Due to inherent long acquisition time of the imaging system, the ICCD image acquisition rate was limited to 0.2 Hz.

Table 3. Excimer laser specifications

XeCl Excimer Laser	
Type: COMPex 102 Lambda Physik	
Wavelength (nm)	308
Maximum Pulse Energy (mJ)	200
Pulses Width (ns)	10-15
Maximum Pulse Repetition Rate (Hz)	20

As previously stated, oxygen molecules severely quench the vapour signal, thus the experiments were carried out in a nitrogen environment in order to minimise such an effect. A surge tank was filled with nitrogen prior to the onset of each test and a pneumatic actuator was installed upstream of the intake manifold, controlling the opening and closing of the surge tank outlet valve. In order to perform the full volume LIEF measurements in an oxygen free environment, it was critical to synchronise the laser, ICCD camera, fuel injection and nitrogen filling events. As the camera had an update time of approximately five seconds between frames (0.2 Hz), it was necessary to run the engine in the skip-injection mode to prevent unnecessary window fouling. This was achieved by a specially designed synchronisation unit in combination with a SRS DG535 delay generator unit. In this study, the shaft encoder reference signal served as an input to the synchronisation box. In such a configuration two output signals were produced upon the detection of an input signal from a shaft encoder box. The first output signal was connected to the delay generator from which fuel injection, laser and camera trigger signals were generated while the second signal was connected to the nitrogen filling system.

The start of injection took place 510 µs after the injection signal was transmitted to the injector, due to the inertia of the system, and the laser had an internal delay of 950 ns. Thus, the laser was triggered 509 µs after the injection signal was sent to the injector driver module while the camera was triggered 950 ns after the laser. The gate width of the ICCD camera was set to 200 ns to minimise the background light. The fluorescence lifetime of the exciplex system was found within the range of 10 to 100 ns. The laser and the camera trigger signals were further delayed at fixed intervals in order to obtain fuel spray images at different timings, increment of 50 µs was used in this study corresponding to approximately 0.5 crank angle degree at the engine speed of 1500 rpm. The second output was used to trigger the actuator of the

nitrogen supply system. Figure 3 shows the intake manifold pressure as a function of the nitrogen valve actuator timing and the start of injection. The synchronisation unit was set such that fuel injection took place when the intake manifold and the combustion chamber were completely flushed with nitrogen. The intake heating system was not used since nitrogen entered the intake manifold at very high speeds, limiting the time available for heating.
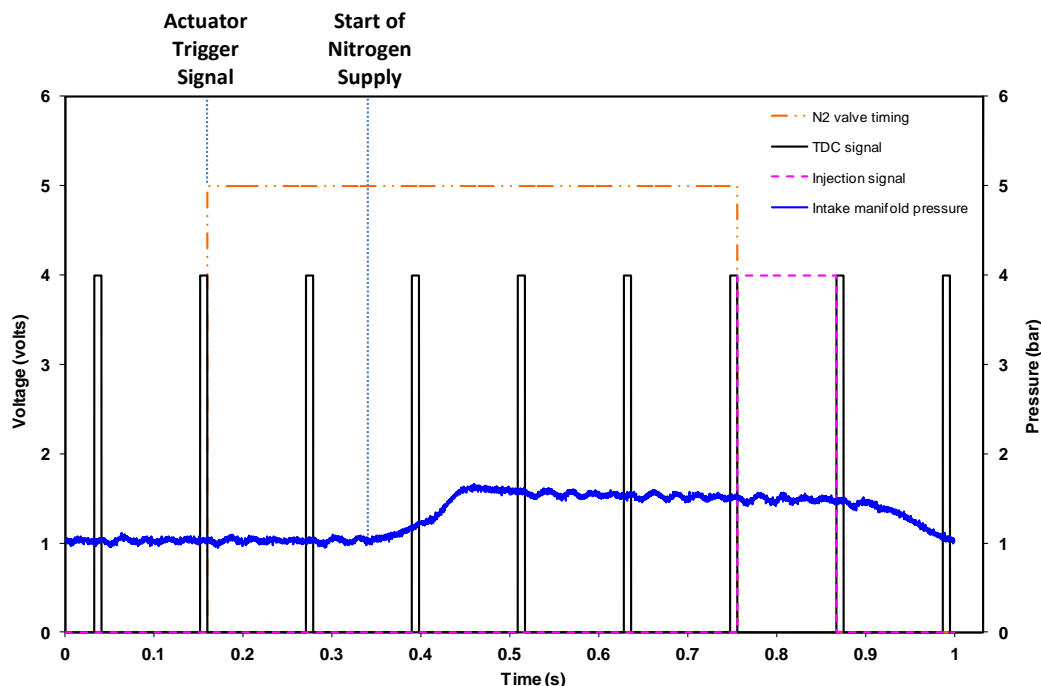

Figure 3. Nitrogen system synchronisation diagram

Appropriate optical filters must be selected in order to allow discrete measurement of liquid and vapour phases; therefore it was essential to obtain the fluorescence emission spectra of the selected exciplex systems. The fluorescence spectra of the liquid and vapour phases were obtained using a constant volume chamber. The pressure and temperature inside the chamber were set at 5 bar and 500 K respectively when measuring the vapour phase spectrum and 5 bar and 300 K when measuring the liquid phase spectrum. The spectral response of the exciplex systems excited by an excimer laser operating at 308 nm was measured with an Oriel MS127i spectrograph with spectral resolution of 0.22 nm scanning over a wavelength range from 200 to 640 nm. The fluorescence spectra of two exciplex systems consisting of 89% decane (w/w), 10% α-methyl-naphthalene (w/w) and 1% TMPD (w/w); and 88% decane (w/w), 10% α-methyl-naphthalene (w/w) and 2% TMPD (w/w) is shown in Figure 4. In the subsequent sections these fuel mixtures are referred to as model fuel (MF), the former as MF1 and the latter MF2.
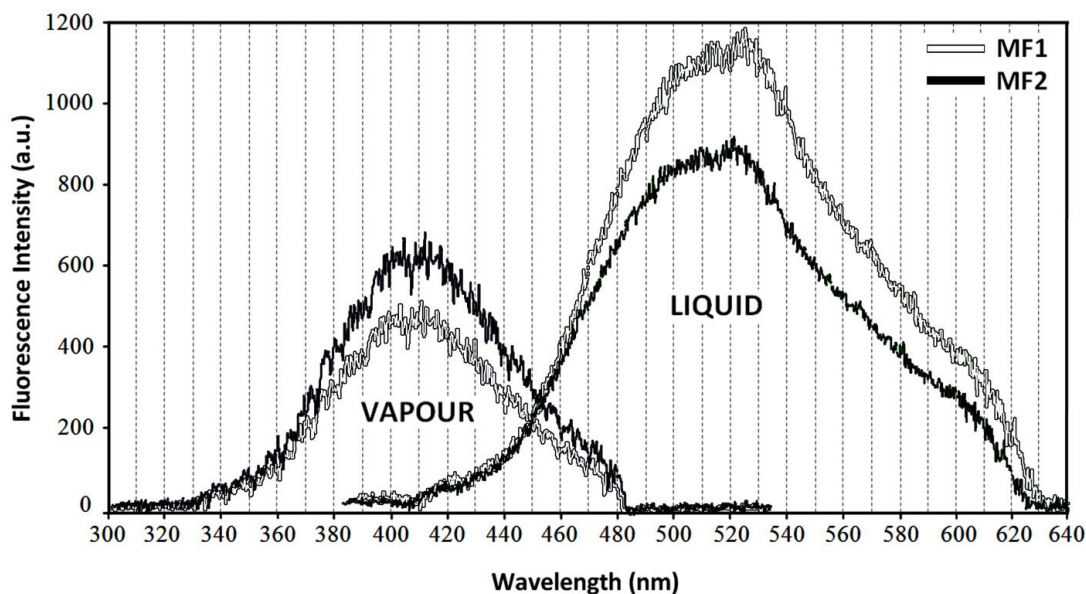

Figure 4. Fluorescence emission spectra of MF1 and MF2

The optical setup used for the application of the LIEF technique in the single-cylinder optical research engine is shown in Figure 5.
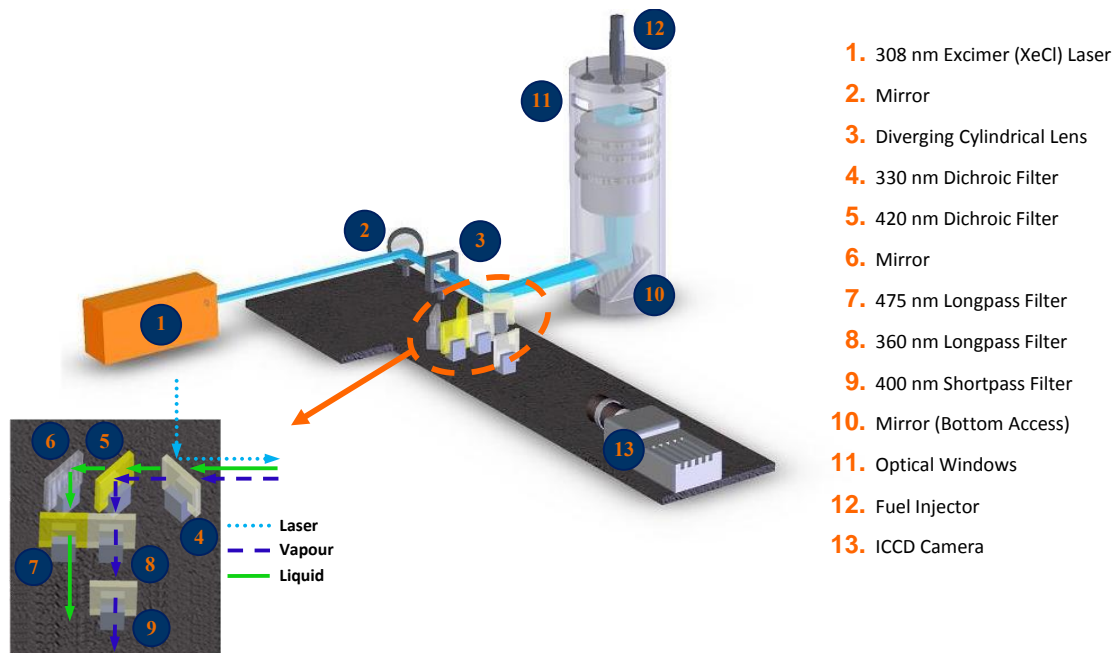

Figure 5. Schematic diagram of the LIEF setup

The laser beam was expanded using a cylindrical lens with a focal length of 150 mm and subsequently reflected onto a 330 nm Dichroic filter (DCF) with an angle of incidence of 45°. The laser was reflected to the mirror positioned at 45° on the lower portion of the piston and was subsequently reflected into the combustion chamber. Thus, combustion chamber was flooded with laser light, illuminating the entire combustion chamber. In such a configuration, laser extinction effects were substantially minimised. The liquid and vapour signals were transmitted by the 330 nm DCF since the excited monomer and exciplex species fluoresced at wavelengths longer than 330 nm. Based on the recorded fluorescence spectra of the selected exciplex systems, a 420 nm dichroic filter was selected and positioned in the path of the transmitted signal in order to separate the liquid and vapour signals. The vapour signal was reflected by this filter while the remaining (i.e. liquid) signal was transmitted and subsequently reflected by a normal mirror. In order to further minimise the effects of laser light scattering and background noise, the vapour signal was passed through a 360 nm long-pass filter (LPF). In addition, the vapour signal was passed through a 400 nm short-pass filter (SPF) in order to minimise the cross-talk effects. On the other hand, the liquid signal was passed through a 475 nm LPF in order to isolate the liquid signal.

3.4 Image Acquisition and Processing

Two background images were obtained for each image sequence, one with the laser while fuel injection was deactivated (laser light scattering) and the other without the laser and fuel injection (background noise). Although the average background signal was removed by the program, the remnant of the background noise may be present in the processed images due to statistical fluctuations in the background signal. The image post processing was performed using a LabVIEW program in which both the averaged background and laser light scatter signals were subtracted from the measured liquid and vapour signals. The programme was set to generate and output a file containing the contours of the spatial distribution of the liquid and vapour phases at a given measured crank angle.

3.5 Operating Conditions

In order to avoid excessive window fouling, both the coolant and the lubricating oil were heated prior to the onset of the measurements to ensure reasonable engine temperature was achieved. The fuel-air mixing process during the pre-combustion phase of a HSDI diesel engine with a single injection strategy was examined. In order to obtain the gain curves of the injector utilised, injection rate and quantity of single injection strategies as a function of injection pulse width and injection pressure were experimentally evaluated using a FIE calibration test rig based on Zeuch's method presented by Ishikawa et al. [34]. Detailed explanation of the experimental setup/procedure can be found in [35, 36].

Several single injection strategies with different injection duration were tested at the injection pressure of 1200 bar in order to evaluate the fuel injection quantity as a function of injection pulse width, Figure 6. The total fuel injection quantity is presented in Table 4 for the tested strategies.
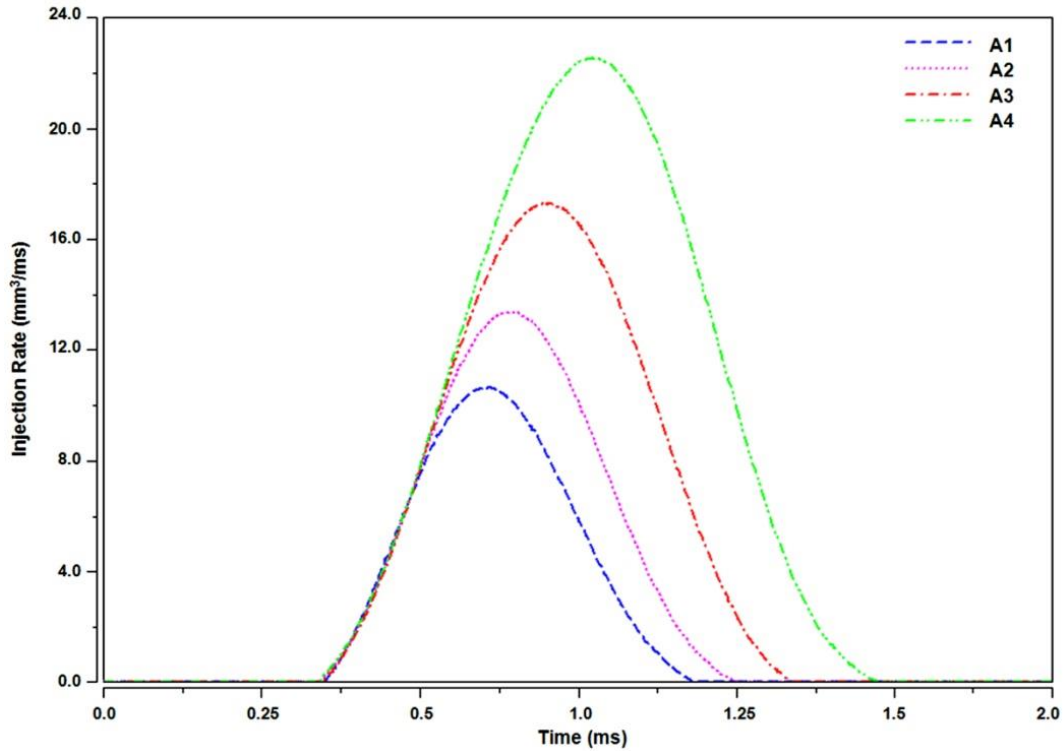

Figure 6. Injection rate profiles for single injection strategies

Table 4. Injection strategies

Strategy	Test No	Injection Duration (μs)	Injection Pressure (bar)	Fuel Injection Quantity (mm³)
Single Injection	A1	300	1200	3.0
	A2	326	1200	5.0
	A3	364	1200	7.0
	A4	422	1200	10.0

The fuel evaporation and mixture formation processes with a single injection quantity of 10 mm^3, A4 strategy, at the engine speed of 1500 rpm was studied, Table 5.

Table 5. Test conditions

Excitation Source	Excimer 308 nm (XeCl)
Laser Pulse Duration	25 ns
Average Energy	100 mJ
Laser Beam Dimension	47x47 mm^2
ICCD Camera Array Size	389 x 579
Image Resolution	8 pixels/mm
Intake Temperature	40º C
Intake Pressure	1.5 bar (Absolute)
Injection Timing	25º CA BTDC
Injection Quantity	10 mm^3
Injection Pressure	1200 bar
Engine Speed	1500 rpm

4   RESULTS AND DISCUSSION

4.1   Simultaneous Images of Fuel Liquid and Fuel Vapour

The fuel spray images at different preset time intervals after the start of injection (ASOI) using MF1 are illustrated in Figure 7.
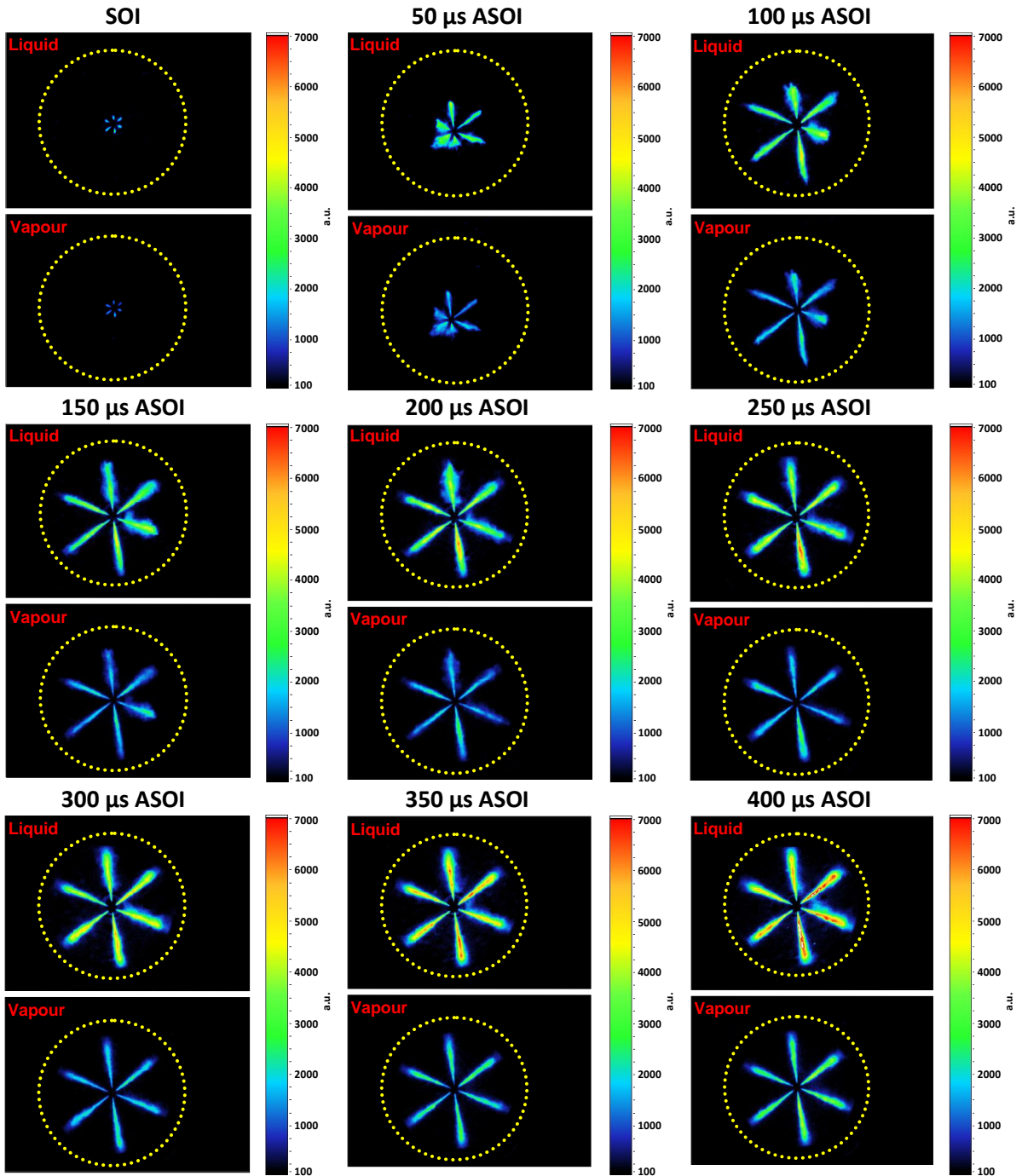

Figure 7. Contour maps of spatial distribution of liquid and vapour phases of evaporating diesel fuel sprays, MF1

Since the laser pulse lasted 10-20 ns and the fluorescence lifetime of the exciplex system lied within the range of 10 to 100 ns, frozen flow images of the fuel sprays were obtained. From the image sequence presented in Figure 15 at 50, 100 and 150 μs ASOI, the asymmetry of the fuel sprays is evident. At low needle lift condition the VCO nozzles suffer from uneven distribution of pressure field inside the nozzle holes due to eccentric or radial motion of the needle tip, caused by close proximity of the needle seat to the nozzle holes [37]. This phenomenon existed at the initial stages of the fuel injection and diminished once the injector needle was fully open as evident in Figure 7. The liquid and vapour concentrations

increased in the image sequence at 200, 250, 300, 350 and 400 μs ASOI as more fuel was injected. The fuel sprays in these images were almost fully developed with the liquid length almost impinging on the piston bowl. However, the penetration observed in the images is in the radial direction, since the fuel sprays were illuminated using a laser beam through the piston crown. Thus the actual penetration should be calculated using the cone angle of the injector utilised. The vapour fuel distribution almost followed the same pattern as that of the liquid phase which was not expected. This may be attributed to the crosstalk effect which must be further investigated by acquiring the fluorescence spectra of the exciplex system at elevated pressures and temperatures.

The fuel spray images at preset time intervals after the start of injection using MF2 are illustrated in Figure 8.
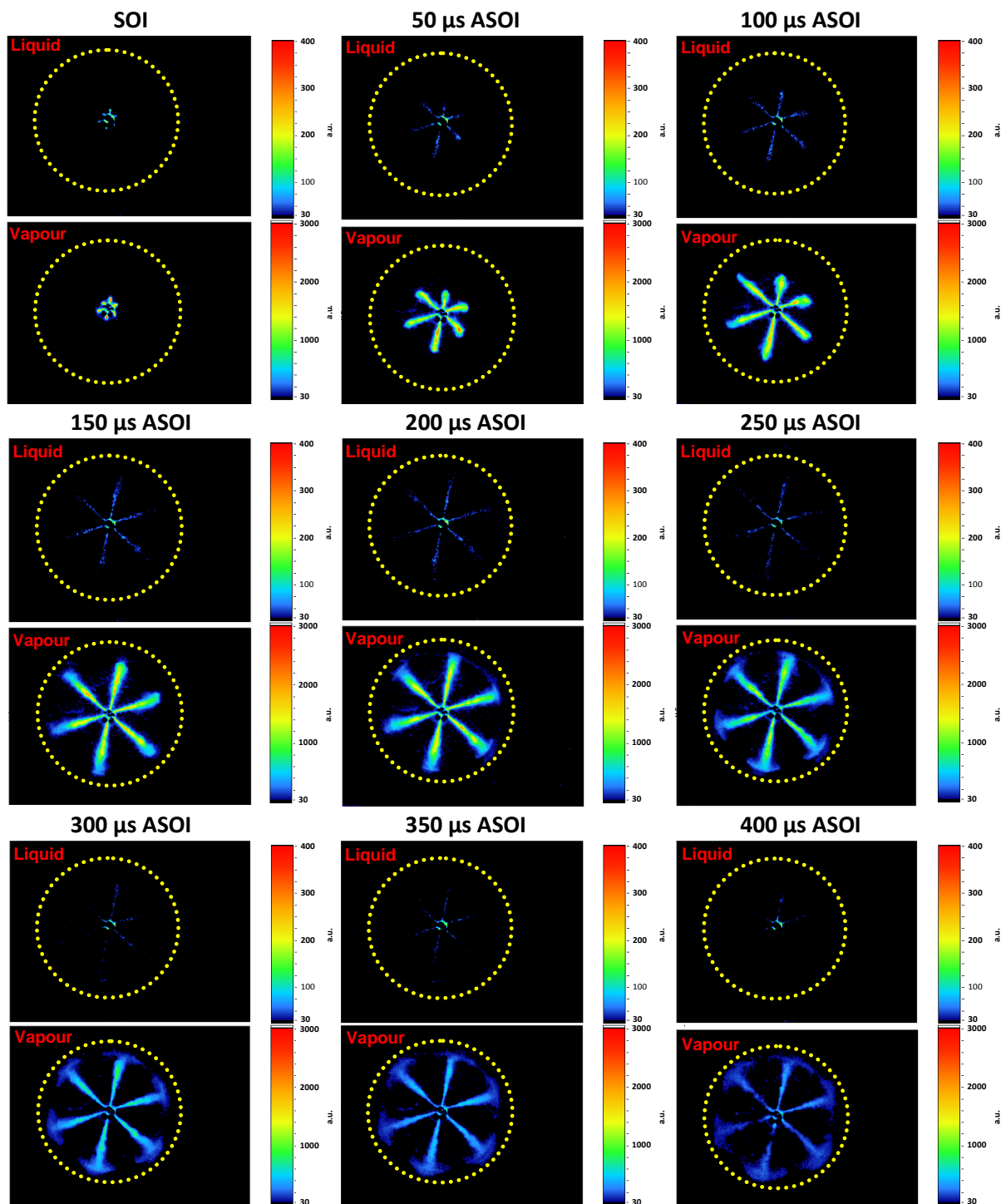
Figure 8. Contour maps of spatial distribution of liquid and vapour phases of evaporating diesel fuel sprays, MF2

From the image sequence presented in Figure 8 at 50 and 100 µs ASOI, the asymmetry of the fuel sprays is evident, the same explanation holds true as previously stated for MF1. The liquid signal intensity was substantially lower than the vapour phase; this may be due to the spectral shift of the exciplex species at elevated pressures and temperatures with the fuel mixture used and/or TMPD decomposition at elevated pressures and temperatures. In contrast, increase in TMPD concentration resulted in much improved vapour signal. The spatial distribution of the vapour phase was clearly observed in the image sequence at 150, 200, 250, 300, 350 and 400 µs ASOI. The mushroom structure due to spray impingement on the piston bowl is clearly evident in Figure 9, this trend was also observed in high-speed images recorded under the same operating conditions, Figure 10. The tip of the spray (i.e. the leading portion of the vapour phase) represents the fuel-lean region of an evaporating diesel spray where maximum mixing with air takes place.
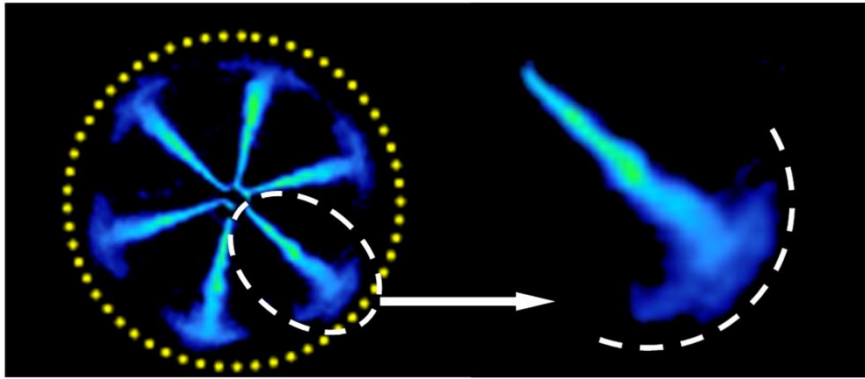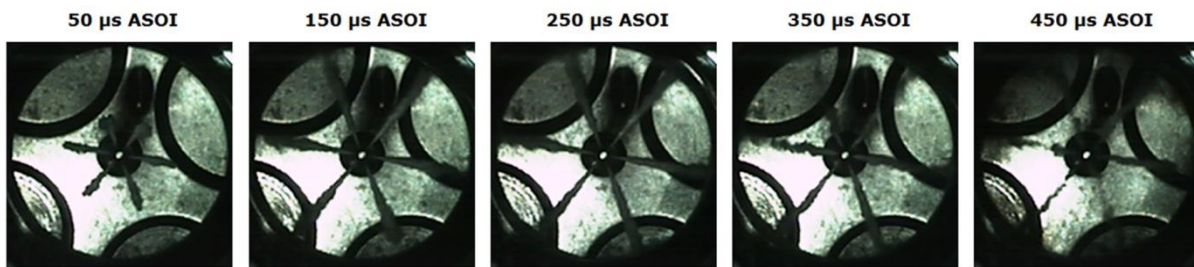

Figure 9. Magnified view of spray wall impingement

Figure 10. Fuel spray development image sequence for A4 strategy

The results indicated that the fuel mixture used for MF2 resulted in clear indication of the vapour phase while the MF1 mixture led to clear exhibition of the liquid phase. Therefore, an optimum fuel mixture must be identified in order to balance the signal intensities in both liquid and vapour phases. In addition, the fluorescence spectra of the fuel mixtures utilised must be further examined under the thermodynamic conditions similar to those experienced in HSDI diesel engines.

5 CONCLUSION

The main purpose of this investigation was to develop an experimental setup capable of providing qualitative information on diesel spray atomisation and evaporation processes in the combustion chamber of a diesel engine through the piston crown. The LIEF technique was adopted and successfully implemented for full-field simultaneous visualisation of fuel liquid and vapour phases in an optical single-cylinder diesel engine. Unlike the majority of previous studies whereby only one plane of the fuel sprays was studied and analysed, the optical setup developed as part of this investigation was capable of providing detailed information on all fuel spray jets with minimum laser extinction effects. Two TMPD/naphthalene exciplex systems were tested; one consisted of 89% decane, 10% α-methyl-naphthalene and 1% TMPD and the other 88% decane, 10% α-methyl-naphthalene and 2% TMPD. The fluorescence emission spectra of these two exciplex systems were acquired based on which appropriate optical filters were utilised. The fuel evaporation and mixing processes during pre-combustion phase of a diesel engine with a single injection strategy, 10 mm^3 total fuel injection quantity, was qualitatively visualised and studied. The liquid and vapour phases of evaporating diesel sprays were simultaneously measured using the aforementioned exciplex systems. The results indicated that the exciplex system containing 1% TMPD resulted in satisfactory visualisation of the liquid phase, though the crosstalk in the

vapour phase precluded accurate detection of the vapour phase. In contrast, the exciplex system containing 2% TMPD resulted in satisfactory visualisation of the vapour phase, however the intensity of the liquid phase was compromised as a result. This was presumed to be mainly due to the spectral shift of the exciplex species and/or TMPD decomposition at elevated temperatures and pressures. Further detailed characterisation of different composition of TMPD and α-methyl-naphthalene exciplex systems at elevated temperatures and pressures is currently being carried out by the authors in order to ascertain an optimum model fuel capable of providing accurate spatial and temporal contours of liquid and vapour phases.

Although the LIEF technique is capable of simultaneous measurement of the liquid and vapour portions of evaporating diesel sprays, the accuracy of the calibration processes as well as the disparity in the physical and chemical properties of the model fuel in comparison to multi-component standard diesel fuel are amongst primary shortcomings of this technique.

ACKNOWLEGMENT

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ASOI	After Start of Injection
CMOS	Complementary Metal–Oxide Semiconductor
CR	Common Rail
DCF	Dichroic Filter
DEMA	Diethyl-Methyl-Amine
FB	Fluorobenzene
FIE	Fuel Injection Equipment
GTL	Gas to Liquid
HSDI	High-speed Direct Injection
IC	Internal Combustion
ICCD	Intensified Charge Coupled Device

LIEF	Laser-Induced Exciplex Fluorescence
LIF	Laser-Induced Fluorescence
LPF	Longpass Filter
MF	Model Fuel
SPF	Shortpass Filter
TDC	Top Dead Centre
TMPD	Tetramethyl-p-phenylene diamine
VCO	Valve Covered Orifice