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The development of hydroxyl and soot in a methyl decanoate-fuelled automotive-size optical diesel engine

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ABSTRACT

This study presents planar images of laser-induced fluorescence of fuel (fuel-PLIF) and hydroxyl (OH-PLIF) as well as incandescence of soot (soot-PLII) obtained in a small-bore optical diesel engine fuelled with methyl decanoate. The focus is on how jet-wall interaction impacts the temporal and spatial development of a reacting fuel jet, high-temperature reaction, and soot within the flame. A single-hole nozzle was used to isolate the jet-wall interaction from jet-jet interactions and to apply long injection duration corresponding to high-load engine operating conditions in which soot formation is particularly problematic. Methyl decanoate was selected as a surrogate fuel due to its low-sooting propensity and thus reduced laser attenuation, as well as the interests in oxygenated fuels, and the existence of detailed reaction kinetics in the literature. Laser-based images show that the fuel impinges on the bowl wall soon after the start of injection and then bounces off along the wall forming a wall-interacting jet. The fuel jet continues to travel along the bowl wall as well as the bottom surface of the piston bowl. During the premixed burn phase of diesel combustion, the high-temperature reaction starts to occur at the leading edge of the penetrating jet back towards the nozzle, initially near the jet axis and then spreads in the radial direction. During the mixing-controlled burn phase, the high-temperature reaction zone fills up the entire combustion chamber and the soot formation starts to occur in the rich area near the wall impingement point. The soot then flows along the bowl wall in both up-swirl and down-swirl directions. These soot pockets are surrounded by OH and they soon disappear altogether at subsequent crank angle locations, suggesting the soot oxidation by OH radicals. However, some soot pockets are transported into the centre of bowl due to the downward movement of the piston and persist for long as there are no active OH radicals.

Keywords: Automotive diesel; Jet-wall interaction; OH; Soot; Methyl decanoate

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1. Introduction

Soot is one of the most distinctive and problematic emissions of diesel engines due to its complex formation and oxidation processes and negative impact on human health. While after-exhaust treatment systems become increasingly popular, the in-cylinder soot control always plays a key role in reducing engine-out particulate emissions. For instance, high and near-constant injection pressure achieved using a common-rail system, together with small nozzle holes, is widely used to increase the fuel-air mixing and thereby decreasing the soot formation [1-5]. While the soot reduction technology advances, our scientific understanding of in-cylinder soot processes has been improved significantly thanks to non-intrusive optical and laser diagnostics [6]. For instance, studies conducted in heavy-duty diesel engines running at medium-to-high load conditions report that the first soot formation occurs right downstream of the flame base during the premixed burn phase of diesel combustion and then during the mixing-controlled burn phase, soot develops towards the downstream region and across the whole cross-section of the jet, forming a high soot concentration zone at the jet head [7-10]. At low-load conditions, the charge dilution can be used to extend the pre-combustion mixing time while limiting the flame temperature below the soot formation threshold [11]. In this regime, the high-temperature reaction occurs mostly after the end of injection and the soot only forms far downstream in the jet head region [12]. The soot oxidation is also investigated extensively. For instance, it is well known that reduced ambient oxygen concentration and lower flame temperature lead to a lower oxidation rate [12-14]. The soot oxidation due to hydroxyl radical (OH) is also a major player, especially at a high flame temperature range above 2000 K [6, 15, 16]. One study reported that the soot oxidation by OH is even stronger than the CO oxidation by OH [16]. As a result, many studies have carried out the imaging of both soot and OH to analyse the soot oxidation processes in diesel engine environments [11-20], reporting the active soot oxidation evidenced by the disappearance of soot pockets where OH radicals co-exist.

The soot processes are strongly influenced by jet-wall interactions because locally rich mixtures are formed near the jet impingement point due to the limited mixing and thus the soot formation is higher than that of the free (no wall) jet [21]. Also, for a long injection case, the combustion products can be re-directed back towards the nozzle and entrained into the incoming jet (i.e. re-entrainment), resulting in decreased mixing upstream the flame base and thereby increasing the soot formation [22-25]. On the other hand, some studies report that jet-wall interactions lead to the formation of turbulent ring vortices in the wall-jet head region where the mixing is locally enhanced [21, 26]. Furthermore, the cooling effect of the wall is also believed to reduce the soot formation [26]. As such, the soot processes under the influence of jet-wall interactions is more complex than those in a free jet and requires an improved understanding. Compared with heavy-duty diesel engines, the jet-wall interaction becomes much more important in light-duty diesel engines because a small-bore design causes the wall being closer to the injector. With engine downsizing trends, particularly in the automotive market, the importance of jet-wall interaction and its impact on soot will become even higher.

This study bridges this gap by performing planar laser-induced imaging of soot incandescence (PLII) and planar laser-induced fluorescence imaging of OH (OH-PLIF) in an automotive-size, optical diesel engine. These images are supported by line-of-sight integrated images of natural combustion luminosity, cool-flame chemiluminescence and excited OH (OH*) chemiluminescence. In-cylinder pressure measurement was also conducted to identify the combustion phases of corresponding images. When no high-temperature reaction was expected at a given crank angle, PLIF images are interpreted as fuel fluorescence, which are then used to discuss the fuel jet development. In the present study, the original injector tip with seven holes was laser-welded to leave only one nozzle hole open so that the

jet-wall interaction is isolated from jet-jet interactions. Also, this single-hole approach allowed for long injection duration, creating significant jet-wall interactions.

2. Experimental setup and diagnostics

2.1. Engine setup and operating conditions

Figure 1 shows the schematics of the single-cylinder optical diesel engine used in this study. Also shown at the bottom is the path of the laser beam travelling through the sheet-making optics and the quartz liner window before entering into the piston bowl. The optical engine specifications and operating conditions are summarised in Table 1. The engine has a displacement volume of 497.5 cm^3 with 83 mm bore and 92 mm stroke. The combustion chamber is bounded by a cylinder liner, a piston top with a curved-lip bowl design, and a flat cylinder head where the centrally-mounted common-rail injector and two intake and exhaust valves are located. The laser-induced signals are visualised through the quartz piston bowl and 45° mirror placed at the bottom of the hollow extended piston body.

It is well understood that the impact of piston bowl geometry on diesel flame development is very significant [27] and thus its clear definition is important. For optical diagnostic purposes, the engine piston used in the present study underwent design modifications from the production version in two aspects- one is the removal of dome pit within the bowl and replacing the piston-bowl region by a flat quartz window, the other is a cut-out of a portion of the bowl-rim as illustrated in Fig. 1. The former was to allow for the wall jet to penetrate back towards the nozzle and then across the piston bowl without optical distortion and therefore the visualisation was easier for the high-sooting jet-head region [10-12]. *However, this mitigated the fuel penetration into the squish region guided by the dome pit [12] and thus the mixture distributions could be different to the production engine. This limitation should be taken into account in interpreting the results of this study. On the other hand, the curved bowl lip on which the fuel jet impinges was retained to ensure the jet-wall interaction, the main topic of this study, is as realistic as possible.* It is also noteworthy that the piston top quartz window provided the field-of-view that covers the entire bowl. The removal of a 35-mm-wide portion of the bowl rim was to insert the laser sheet into the bowl region even when the piston was near the top dead centre. However, our full-cycle modelling study proved that this cut-out does not affect the in-cylinder swirl flow [28] and more importantly, our previous study [29] showed that the flame development is not impacted as the target jet penetrates towards the opposite side of the bowl rim and the main combustion event completes before the flames reach the cut-out region. Considering these piston design modifications, the geometric compression ratio is estimated at 15.5.

The engine is naturally aspirated and has a fixed swirl ratio of 1.4. The wall temperature was kept constant at 363 K using heated water circulation through the cylinder liner, engine head and block. The intake temperature was measured at 303 K with minimal variations ($< \pm 1 \text{ K}$) throughout the experiment. Methyl decanoate ($\text{C}_{11}\text{H}_{22}\text{O}_2$) was selected as a surrogate fuel for soot diagnostics. The fuel was preferred due to its low-sooting propensity and thus less laser attenuation issues. Also, it is widely known as a biodiesel surrogate fuel due to its alkyl chain (representing fatty acid methyl esters) and detailed chemical kinetics are available for computational modelling [30]. Moreover, the ignition delay time and negative temperature coefficient (NTC) behaviour [31] as well as cetane number [32] are similar with a conventional diesel fuel and its good lubricity requires no hardware modification for engine operation offer a practical advantage. For the direct fuel injection, a common-rail system (Bosch second-generation) was used. The injector has a single-hole nozzle tip with $134 \mu\text{m}$ in diameter (nominal) and 150° included angle. The original nozzle had 7 holes with even hole-to-hole spacing, which was laser welded so that only one target hole is left open.

This modification allows for very long injection duration of 2.24 ms (actual) while the in-cylinder pressure is well within the burst pressure of quartz windows. At fixed common-rail pressure of 100 MPa, the injected mass per hole was measured at around 10 mg corresponding to high-load conditions in automotive diesel engines in which soot is very problematic. The fuel injection timing was fixed at 7 crank angle degrees before TDC (°CA bTDC) at which bulk gas temperature and density were estimated at 858 K and 11.16 kg/m³, respectively. The engine speed was held constant at 1200 rpm using an AC motor. To further reduce thermal loading on the quartz windows as well as to limit the residual gas from previous cycles, the engine was operated under a skip-firing mode with an injection every 10th cycle (i.e. 9 motoring cycles and 1 firing cycle).

2.2. Diagnostics

2.2.1. In-cylinder pressure and heat release rate

As shown in Fig. 1, a piezoelectric pressure transducer (Kistler 6056A) was installed on the cylinder head to measure the in-cylinder pressure. The pressure traces were ensemble-averaged over 20 firing cycles, which was used to derive the apparent heat release rate, Q_{app} , based on a simple one-dimensional energy equation [33]:

$$\frac{dQ_{app}}{d\theta} = \left(\frac{\gamma}{\gamma - 1} \right) p \frac{dV}{d\theta} + \left(\frac{1}{\gamma - 1} \right) V \frac{dp}{d\theta} \quad (1)$$

where θ is the crank angle degree, γ is the specific heat ratio, p is the measured in-cylinder pressure at a given θ , and V is the volume of combustion chamber at a given angle θ . The apparent heat release rate was plotted to evaluate the in-cylinder conditions and to help identify the combustion stage at the imaging time.

2.2.2. Natural combustion luminosity

Images of natural combustion luminosity, predominantly hot soot luminosity [11, 26, 34], were taken using a high-speed CMOS camera (VisionResearch Phantom v7.3) and a 50-mm Nikkor lens at 36,000 frames per second and 10 μ s exposure time. Although the images cannot provide detailed information of soot regions within the flame, the hot soot luminosity movies are useful to understand the overall flame development and can provide preliminary data before laser-based imaging diagnostics are performed. Examples of hot soot luminosity images are displayed in Fig. 2 for both conventional diesel and methyl decanoate. In each image, a dashed line pointing at 2 o'clock is illustrated to denote the jet trajectory of a single-hole nozzle. The circles drawn using dashed lines indicate the distance from the nozzle, with 5 mm gap in radius between adjacent circles. The green horizontal lines shown on the left illustrate the bowl-rim cut-out region from which the laser sheet is inserted. On the bottom-left and bottom-right corners of each image, the corresponding crank angle location (°CA aTDC) and time after the end of injection (°CA aEOI) are noted, respectively. Figure 2 shows that the hot soot luminosity appears earlier at 7.9°CA aTDC for diesel than that of methyl decanoate at 9°CA aTDC. At a given crank angle location, the hot soot region is much larger for diesel and the signal lasts longer. For example, at 25°CA aTDC, the diesel soot luminosity is still strong and retains the flame structure but the methyl decanoate signals are almost all burnt out (bottom-right image). Therefore, one can easily expect much less significant beam attenuation for methyl decanoate. While the soot luminosity signal strength is very different, it is important to note that the dynamics of the wall-interacting jet development characterised by the fuel impingement on the wall soon after the start of injection, its bouncing off to the bowl wall, the penetration back towards the nozzle, and the flow along the wall curvature are very similar between two fuels. The strong circulating signals in the wall-jet

head region, indicating the ring vortices formed during the jet-wall interaction [21, 26, 29], are also evident for both fuels. Therefore, the hot soot luminosity images in Fig. 2 confirm that methyl decanoate is an excellent surrogate fuel to study the development of a wall-interacting diesel jet while its less sooting tendency helps reduce the laser attenuation issue.

2.2.3. Cool-flame chemiluminescence

During the ignition delay period, weak chemiluminescence signals are emitted from CH, CO and formaldehyde (HCHO) through the breakdown of ketohydroperoxide (KHP) species ([12, 35, 36]) which are the products of first-stage, low-temperature reactions. This cool flame chemiluminescence signal was captured using an intensified charge-coupled device (ICCD) camera (LaVision NanoStar) equipped with a 105-mm f/4.5 lens. This bottom-view imaging setup is shown in Fig. 1. The lens was UV-enhanced, achieving over 85% transmission at 250~650 nm range, suitable for the detection of cool-flame signals in the 360~560 nm range [37, 38]. Also, the camera gain was set at a maximum value and long exposure time of 100 μ s ($\sim 1.5^\circ$ CA at 1200 rpm) was used with no optical filters placed in front of the lens. The cool flame chemiluminescence images were captured at various crank angle locations until the signal became an order of magnitude stronger with the start of high-temperature reaction. At each crank angle, a total of 20 images were taken from 20 firing cycles.

2.2.4. OH* chemiluminescence

During high-temperature exothermic reactions of hydrocarbons at near stoichiometric condition, a large amount of electronically-excited hydroxyl (OH*) radicals are produced (e.g. $\text{CH} + \text{O}_2 \rightarrow \text{CO} + \text{OH}^*$) [44]. As the excited OH* radicals return to its ground state (OH), strong chemiluminescence signal is emitted in the 306~310 nm range [25, 37]. Therefore, the OH* chemiluminescence images are useful to identify high-temperature reaction zones within the flame [19, 25, 39] where high heat release occurs. The same ICCD camera and UV-enhanced lens used for the cool-flame chemiluminescence imaging was also used for the OH* chemiluminescence imaging. To isolate the 306~310 nm emission range of the OH* chemiluminescence signals, a set of optical filters including a WG-305 glass filter and a 300 nm band-pass filter (FWHM 40 nm) was placed in front the ICCD camera lens. The ICCD gate was set at 70 μ s (half a crank angle at 1200 rpm) with the gain set at 25% of the maximum value.

2.2.5. Planar laser-induced fluorescence of OH (OH-PLIF)

Figure 3 illustrates the laser sheet coverage within the bowl, the selected single hole (the jet of interest aiming at 2 o'clock direction), and three horizontal laser planes at 7, 9, and 11 mm below the cylinder head together with a postulated fuel jet. The 7 mm laser plane corresponds to the area where the nominal jet axis intersects the piston bowl wall during the injection event and thus will be used as a reference plane. *The multi-plane imaging of OH was to ensure the appearance and disappearance of the PLIF signal is correctly interpreted because the OH radicals within the bulk gas can be transported to other locations at subsequent crank angles. In this study, the images captured in other planes were used as complementary information to evaluate the LIF signals in a certain plane.* An example image taken at this plane and post-processed for presentation is shown on the bottom-right corner. The original image was rotated so that the fuel jet is shown to be injected upwards (12 o'clock direction) and the wall-impinged jet is

penetrating downwards (back towards the nozzle) at this imaging time. The same laser planes and presentation were used for three different planar laser imaging diagnostics of OH-PLIF, fuel-PLIF, and PLII.

When the diesel combustion enters its mixing-controlled burn phase, most naturally-excited hydroxyl (OH*) radicals have returned to their ground state and only the ground-state OH is produced [36, 40, 41]. During this period, planar laser-induced fluorescence of hydroxyl (OH-PLIF) imaging is widely used to study the diesel flame development [11, 29, 41, 42]. The OH-PLIF detects the fluorescence signals emitted when OH radicals excited by a high energy laser beam return to their ground state [43]. The excitation laser wavelength commonly used for the OH-PLIF imaging in the engine environments is 284 nm (vacuum wavelength) with the resulting fluorescence emissions in the 308~320 nm range [43, 44]. In this study, a Rhodamine-6G filled dye laser (Sirah CobraStretch) pumped by a frequency doubled beam (532 nm) from an Nd:YAG laser (Quanta-ray Pro-230) was used to produce a fundamental emission at ~568 nm. This was frequency doubled by a beta-barium-borate (BBO) crystal to achieve the desired OH excitation wavelength of 284 nm. The laser beam was converted into a 300 μ m thick and 35 mm wide sheet using the sheet making optics shown in the bottom of Fig. 1. In the selected OH absorption range and under UV excitation, interference signals from fluorescence of other combustion products such as polycyclic aromatic hydrocarbons (PAH) and soot luminosity are problematic [11, 27, 40, 42]. As some of these interferences are broadband signals, they are unavoidable even with the use of a series of optical filters. One method to address this issue is a comparison between online and offline OH-PLIF images. It is well known that OH fluorescence absorption and emission change drastically with a very small difference in the excitation wavelength [40, 44]. By comparing images taken under the wavelength tuned on and off the OH excitation fluorescence line, the location and intensity of the interferences can be identified [29, 42, 45], which help interpret the online OH-PLIF images for the high-temperature reaction zones within the diesel flame. The offline images of the present study were taken with the laser wavelength at 283.9 nm (i.e. 0.1 nm off to the OH excitation wavelength of 284 nm) and was repeated with the same capturing settings for all the crank locations that the online images were obtained. In front of the camera lens (Fig. 1), a series of optical filters were placed including a 300 nm band-pass filter (40 nm FWHM with around 70% maximum transmission in the range) and a WG-305 glass filter to reject the scattering from the excitation laser beam. The online/offline OH-PLIF images were captured using the same ICCD camera and UV lens used for other imaging diagnostics but with a much shorter gate of 100 ns and a gain of 90% maximum value. The OH-PLIF was performed at the same operating condition as other diagnostics and 20 images were taken at each crank angle location.

For presentation purposes, online and offline OH-PLIF images were pseudo-coloured with blue and yellow, respectively. The processed online and offline signals were then combined into one image for ease of interpretation. An example of the individual offline and online images as well as the combined image at 7.5°CA aTDC is shown in Fig. 4(a), which indicates that at this imaging time, the online OH-PLIF signals cover larger areas than the offline OH-PLIF signals, particularly at the leading edge of the wall-jet. It was noted that although the offline and online images were not taken simultaneously, the overall structures of the signals from the selected individual images match very well. This selection method for a representative individual image [33, 38] will be discussed in more detail later in the cyclic variations section.

2.2.6. Fuel-PLIF

Using the same setup of the OH-PLIF diagnostics, fuel-PLIF imaging was also performed. While the methyl decanoate used for this study does not contain any aromatics inducing strong fluorescence signals as in conventional

diesel [29], it still produces fuel fluorescence, similar to other single-component fuels [11]. The UV-excited fuel fluorescence can act as interference to the OH-PLIF signals due to its broadband emissions, which is very different to the fine-scale structure of OH-PLIF spectrum [11, 45]. However, qualitatively, the fuel-PLIF can provide valuable information on the vaporising fuel jet development prior to the start of combustion when no OH-PLIF signals are expected. In this study, the PLIF signal before the start of combustion is interpreted as fuel-PLIF and is used to discuss the jet development and jet-wall interactions prior to the high-temperature reaction.

2.2.7. Soot planar laser-induced incandescence (PLII)

A fundamental 1064 nm output of the 10-Hz pulsed Nd:YAG laser was used to heat up soot particles so that strong incandescence signals are released for the planar imaging of soot distributions within the flame [34] – *i.e.* PLII. Shorter wavelengths such as 355 and 532 nm were also considered due to their high incandescence energy; however, the 1064 nm beam was selected to avoid interferences from polycyclic aromatics hydrocarbons (PAHs) [46-48]. *The output laser energy was set at 250 mJ per pulse (or 0.3 J/cm²), higher than the fluence limit for the vaporisation of soot particles – i.e. the plateau region of LII signal where the LII intensity no longer increases in proportion to the soot volume fraction. This was to ensure the laser energy is high enough to mitigate the shot-to-shot fluctuations.* Due to very high temperature that the soot particles reach, the emissions from laser-induced incandescence are predominantly in the visible and UV range (below 500 nm) [49, 50]. However, the strong laser fluence will also cause fluorescence signals from C₂ at around 500 nm [49]. In the present study, a combination of a 430 nm band-pass filter (10 nm FWHM) and a 450 nm short-pass filter was placed in front of the lens to block these interference signals. The same ICCD camera and UV-enhanced lens as in the PLIF imaging was used to capture the PLII signals but with very short gate time of 50 ns and a low 60% gain. For presentation purposes, the soot PLII images were pseudo coloured using red and combined with the OH-PLIF images taken at the same crank angle location. Figure 4(b) shows an example of a selected soot PLII image, an OH-PLIF image, and the combined image of these two obtained at 13°CA aTDC when the soot formation is very active. The PLII imaging was performed for 20 firing cycles at various crank locations and at three different planes of 7, 9, and 11 mm below the cylinder head, similar to the OH-PLIF imaging.

2.2.8. Cyclic variations and image selection

Despite our efforts to minimise cyclic variations through the fixed coolant (wall) temperature and intake air temperature as well as skip firing for minimal residual gases, some cyclic dispersion caused by the irregular mixture/temperature distributions and turbulent flames are unavoidable. Figure 5 shows the traces of in-cylinder pressure and corresponding apparent rate of heat release (aHRR) for all 20 firing cycles at a selected operating condition of the present study (Table 1). Also shown using a red line are ensemble-averaged traces. It is observed that before the start of injection at 7°CA bTDC, the individual in-cylinder pressure traces match well with the ensemble-averaged trace. However, as the injection starts, the variations due to evaporative cooling become noticeable. The variations during the combustion event are also measurable with the rise of the in-cylinder pressure starting between 3~5°CA aTDC and the peak pressure varying between 4.3~4.4 MPa.

In our previous studies conducted in the same engine, both PLIF [29] and OH*/cool-flame chemiluminescence images [51] showed some cycle variations due to turbulent nature of diesel combustion. Figure 6 shows that the cyclic variations are also measurable in the PLII images. For example, the LII signals are found near the bowl wall at 12 o'clock position in most of the images; however, it is also seen that the soot pockets are scattered as in the second last

row or non-existent as in the bottom row. One way to deal with these cyclic variations is to produce ensemble-averaged image. For instance, the average of all 20 images shown on the top-right corner of Fig. 6 might represent the entire image set, which can be repeated for other crank angle locations. However, a closer look at the averaged image suggests the signals are smeared out and thus there are many missing details. To address this issue, we applied a correlation-coefficient based method to select an individual image that is the best representative of all 20 images. The two-dimensional correlation coefficient was calculated for each image set using [27]:

$$r_{2d,xy} = \frac{\sum_i \sum_j (x_{i,j} - \bar{x})(y_{i,j} - \bar{y})}{\sqrt{\sum_j (x_{i,j} - \bar{x})^2 \sum_j (y_{i,j} - \bar{y})^2}} \quad (2)$$

where x is the ensemble-averaged image count, $\bar{x}$ is the image mean of the ensemble-averaged image count, y is an image count of an instantaneous image, $\bar{y}$ is the image value of the instantaneous image, and i and j denote the row and column pixel, respectively. This coefficient evaluates the similarity between the two images; the higher the coefficient, the closer resemblance they have. Practically, this means the selected individual image for the highest correlation coefficient will be the most similar to the averaged image, and thus best representing the entire image set while retaining fine-scale details of soot structures. More details about this image selection method are found in our previous work [29, 51]. The selected image using this method is shown next to the averaged image in Fig. 6, which suggests a good agreement in terms of the overall structure while revealing structural details such as a few soot pockets with different sizes and shapes. For consistency, the same selection method was also applied for the presentation of cool-flame and OH* chemiluminescence as well as PLIF images in the following sections.

3. Results

3.1 In-cylinder pressure and apparent heat release rate

Figure 7 shows the 20-cycle-averaged in-cylinder pressure traces for motoring and firing modes (top) and the derived aHRR trace (bottom). The fuel injection profile, measured using a Bosch-tube-type injection rate meter, is also shown in the figure. Added on the traces are symbols to indicate the corresponding imaging times with circles and squares for the ignition delay period, triangles for the premixed burn phase, and diamonds for the mixing-controlled burn phase of diesel combustion. Figure 7 shows that the in-cylinder pressure of the firing mode initially follows the motoring trace but becomes lower as the fuel injection starts at 7°CA bTDC. This was due to the evaporative cooling of liquid-phase methyl decanoate, which also explains the negative aHRR at this time [10, 39]. During this early stage, identified as the ignition delay period, PLIF signals will be predominantly from vaporising fuel. While the fuel injection continues, a mild increase in the aHRR is noticeable at around TDC to 4°CA aTDC. This corresponds to the first-stage ignition and low-temperature reaction [12, 29] where cool-flame chemiluminescence signals can be captured from early combustion products such as CH, CO and HCHO radicals. The aHRR starts to increase at a much higher rate from 4°CA aTDC, suggesting the second-stage ignition and high-temperature reaction [33] – i.e. start of combustion. The mixture prepared during the ignition delay period combusts quickly during this premixed burn phase [10], emitting strong signals from OH radicals. Therefore, the offline/online OH-PLIF imaging together with the OH* chemiluminescence and PLII imaging was performed from this main combustion stage. The aHRR peaks at 7.5°CA aTDC and declines as quickly as it rises until 10°CA aTDC. It was noted that the injection ends in the middle of the premixed burn phase at around 7.5°CA aTDC but the remaining fuel still combusts while being mixed with air in the following crank angles – i.e. mixing-controlled burn phase (including late-cycle burn-out). This is evidenced by the

slowdown of the aHRR decrease from 10°CA aTDC. The imaging diagnostics were performed up to 25°CA aTDC when the aHRR returns back to the level at the start of combustion at 4°CA aTDC.

3.2 Ignition delay period

Figure 8 displays the images corresponding to the ignition delay period. Shown in the top row are the fuel-PLIF images taken at 7 mm below the cylinder head for three different crank angles of -6, -4, and -2°CA aTDC. The signals are pseudo-coloured with blue for ease of identification. The red circle on each image illustrates the bowl wall as well as the field-of-view provided by the quartz window (i.e. the field-of-view covers the entire bowl). On the right side of the three images, the side-view illustration of fuel jet and laser sheet corresponding to the piston position at -2°CA aTDC is presented. The fuel-PLIF images show that the methyl decanoate jet penetrates freely upon the start of injection before it impinges on the bowl wall at -4°CA aTDC. After the wall-impingement, the fuel jet travels along not only the bowl wall but also along the bottom of the piston bowl as seen at -2°CA aTDC. Shown in the middle row of Fig. 8 are the fuel-PLIF images at the same 7 mm laser plane from TDC to 4°CA aTDC. Since Fig. 7 showed positive aHRR at these crank angles and thus reactions are expected, both online and offline OH-PLIF imaging were performed. When these images are combined using yellow for the offline signal and blue for the online OH-PLIF, however, they overlap in most of the jet area and appear in white colour. Therefore, the PLIF signals are interpreted as fuel-PLIF again. The images show that the fuel jet penetrates further along the bowl wall reaching half of the bowl circumference at 4°CA aTDC. At the same time, the fuel jet appears to bounce off the bowl wall and travels back towards the nozzle, which is shown as a downward movement of the wall-jet head in these bottom-view images. It was noted that this downward penetration occurred below the free jet trajectory, which was enhanced due to the curved lip design of the used piston. This means the wall-interacting fuel jet also travels along the bottom surface of the bowl.

In the bottom row of Fig. 8, the cool-flame chemiluminescence images corresponding to the fuel-PLIF images in the middle row are shown. It is seen that the cool-flame signals first appear near the jet axis and in the wall-jet head region at 2°CA aTDC when the aHRR becomes positive (Fig. 7). The cool-flame region grows quickly, matching the size of the fuel jet region in just two crank angles. It is noticeable that the cool-flame signals are stronger at the wall-jet head than those near the bowl wall. It was likely that the jet-wall interaction-induced turbulent ring-vortex caused the locally enhanced mixing in the wall-jet head region, which promoted the first-stage ignition [29]. From Fig. 8, it is interesting to note that the fuel-PLIF images show no strong influence of the in-cylinder swirl flow. It was in part due to relatively low swirl ratio of 1.4 in the present study. Moreover, the curved bowl-lip driven downward penetration of the jet was significant and therefore the swirl-induced jet asymmetry (e.g. [29, 51]) did not stand out clearly.

3.3 Premixed burn phase

Figure 9 shows the OH* chemiluminescence images that are pseudo-coloured with light blue (top row) and the combined online/offline OH-PLIF images at 7 mm below the cylinder head (bottom row) for various crank angles of 5~9°CA aTDC. On each image, a vertical dash-dot line is drawn to illustrate the jet axis. The transition from the first-stage ignition to the second-stage ignition occurred very quickly. For comparison purposes, the cool-flame boundary at 4°CA aTDC is overlaid on the OH* chemiluminescence image taken at 5°CA aTDC and is shown at the top-left. It is seen that the first OH* signal appears within the cool-flame boundary and on the right to the jet axis, before they grow further in the radial direction. Interestingly, the growth on the right side occurs at a faster rate than that on the

left side. This was due to the effect of in-cylinder swirl flow. Although it made only a minor influence on the jet penetration and low-temperature reaction (Fig. 8), the opposing swirl flow caused the higher strain rate on the up-swirl side of the wall-jet leading to the higher scalar dissipation rate [52]. This led to the delayed second-stage ignition on the up-swirl side. The OH* chemiluminescence signals grow rapidly and by 7°CA aTDC, almost half of the bowl area is filled up with OH* signals and at 9°CA aTDC, OH* is found throughout the bowl area. It was noted that the growing OH* chemiluminescence region is consistent with the high aHRR seen in Fig. 7.

The OH* chemiluminescence signals are line-of-sight integrated and thus the information they carry is limited. For example, whether the first OH* signal observed at 5°CA aTDC is from the near nozzle region close to the cylinder head or the leading edge of the penetrating wall-jet below the cylinder head is unclear from the OH* signals. Therefore, the combined online/offline OH-PLIF images taken at 7 and 9 mm below the cylinder head are shown in Fig. 9. The PLIF image at 5°CA aTDC displays that the signals are mostly yellow (as on the far left) or white (as on the left to the jet axis) in both laser planes, suggesting that the fuel fluorescence is still dominant. However, from the 7 mm plane, it is noticeable that the signals on the right to the jet axis are blue dominant with minimal or no yellow, indicating that OH radicals develop in this region as the high-temperature reaction starts to occur. This then explains that the first detected OH* chemiluminescence signal was not from the near nozzle region but from the tip of the penetrating wall-jet. This is consistent with the location of first-stage ignition such that the high-temperature reaction was originated from the head vortex region where the mixing was locally enhanced. At later crank angles, signals from the fuel fluorescence (i.e. yellow and white) diminish quickly and by 9°CA aTDC, mostly OH signals are found. Once again, this is consistent with the high aHRR seen in Fig. 7. However, the yellow-coloured fuel region is still observed near the wall-impingement point at both 7 and 9 mm below the cylinder head. It was noted that the end of injection occurred at 7.5°CA aTDC (see Fig. 7) and thus the fuel fluorescence signals near the wall was likely from the last portion of the fuel injection where the injection rate declines. The low momentum fuel would induce slower penetration and due to the limited air entrainment near the wall-impingement point, the mixtures in this region could be relatively richer [53, 54].

3.4 *Mixing-controlled burn phase*

As the high-temperature reactions continue to occur, the fuel near the bowl wall seen in Fig. 9 is consumed quickly. This is clearly noticed in the OH-PLIF images at later crank angles of 10 to 17.5°CA aTDC, as shown in Fig. 10. In the top row, the online/offline combined OH-PLIF images taken at 7 mm below the cylinder head are presented, in which the signals are purely blue OH-PLIF. Since the injection ended at 7.5°CA aTDC and the aHRR continued to decline at this imaging time, it was identified as the mixing-controlled burn phase. An interesting trend observed from the OH-PLIF images in Fig. 10 is that strong OH signals persist for a long while. The downward penetration of reacting wall-jet continued until the OH signals are found near the opposite side of the bowl wall at 10°CA aTDC. Then, the overall flame structure based on OH distributions does not change much until 17.5°CA aTDC. By contrast, marked variations are found in soot distributions as shown in the PLII images taken at the same laser plane and at the same crank angles. The red-coloured images of PLII signals are presented in the middle row of Fig. 10. It was noted that the PLII imaging was performed at earlier crank angles but no signals were observed until the start of mixing-controlled burn at around 10°CA aTDC. The lack of soot formation during the premixed burn phase is different to conventional diesel combustion in a heavy-duty engine [6, 10]; however, it is widely found in highly-diluted low-sooting combustion regimes regardless of the engine size [11, 12, 55]. It should be considered that methyl decanoate

used in the present study is a very low-sooting fuel, which contributed to the delayed soot formation despite no dilution conditions (i.e. no exhaust gas recirculation). The PLII images also show an interesting trend such that the soot signals first appear in the wall-impingement point of the jet. As mentioned previously, this is the region with limited mixing and thus locally rich mixtures are expected [21], explaining the high soot formation.

The soot signals near the wall-impingement point continues to grow between 10 and 13°CA aTDC with increasing numbers of soot pockets with various sizes and shapes. An interesting trend observed from the PLII image at 13°CA aTDC is that the signals take up larger space on the right side of the jet axis. This should be explained by the swirl flow in the clockwise direction such that relatively richer mixture on the down-swirl side led to higher soot formation than that in the leaner mixture formed on the up-swirl side due to the wall-jet travelling against the swirl flow. It is also noticeable that from 13 to 17.5°CA aTDC, the soot pockets appear to be divided into two groups with each flowing along the bowl wall in either up-swirl or down-swirl direction. At 15°CA aTDC, the soot signals are absent near the wall-impingement point and the soot pockets appear to shrink in size compared to those at 13°CA aTDC, suggesting that the soot oxidation occurs while the pockets flow along the bowl wall. To further discuss the soot oxidation, the OH-PLIF and PLII images are combined and presented in the bottom row of Fig. 10. The images clearly indicate that the soot pockets are surrounded by OH radicals at 10~13°CA aTDC. However, at 15°CA aTDC, the OH signals start to disappear from the wall-impingement region where the strong soot signals were found at earlier crank angles. This might suggest that the OH radicals were consumed in the oxidation of soot particles [6, 15, 16]. It is noticeable that at 17.5°CA aTDC, all the soot pockets developed on the right side of the jet axis completely disappeared, which once again is consistent with the weakening of OH-PLIF signals in that region. However, there is a small soot pocket remained in the 9 o'clock position. The cause for this persisting soot pocket is not entirely clear but it could be that the relatively slower development of OH region on the up-swirl side of the jet (see Fig. 9) led to a lower soot oxidation rate.

The combined OH-PLIF and PLII images from the other two planes of 9 and 11 mm below the cylinder head are presented in Fig. 11. For ease of interpretation, the 7 mm plane is also shown again in a three-dimensional configuration. The figure shows that the OH signals are initially stronger in the upper planes (e.g. 10~13°CA aTDC) but gradually become weaker while the signals increase in the lower planes (15~25°CA aTDC). This is consistent with the downward movement of piston in the expansion stroke. At 25°CA aTDC, the OH-PLIF in the 7 and 9 mm planes are very weak and only the 11 mm plane shows a measurable signal. In comparison, the PLII signals are found only in the 7 mm plane from 10 to 13°CA aTDC. This suggests that the initial soot formation occurred near the bowl-lip area as was illustrated in Fig. 10. The soot signals are not found in the lower planes until 15°CA aTDC. At 17.5°CA aTDC, the strong LII signals are observed in the 9 mm plane in the 9 o'clock position as well as in the centre of the bowl. These soot pockets persist for a long while, as shown in the images at 20 and 25°CA aTDC. Since the new soot formation at this late timing was unlikely, it was thought that the soot formed in the upper plane was transported into the centre of bowl due to the piston movement. Since the active OH radicals hardly exist at this late crank angle, it is hypothesised that these soot pockets cannot be oxidised but would exit through the exhaust.

4. Conclusions

To provide a fundamental understanding of the temporal and spatial development of a wall-interacting fuel jet, high-temperature reaction zone, and soot distribution, planar imaging of laser-induced fluorescence of fuel and OH (fuel- and OH-PLIF) as well as laser-induced incandescence (PLII) was performed in a small-bore optical diesel

engine. Line-of-sight integrated images of cool-flame chemiluminescence, OH^* chemiluminescence, and hot soot luminosity were also obtained to provide complementary information to the planar laser images. Methyl decanoate was selected as a low-sooting, oxygenated surrogate fuel for diagnostic purposes, given that the dynamics of the wall-jet development is similar with a conventional diesel fuel. A single-hole nozzle was used to simulate a high-load condition involving long injection duration for significant jet-wall interactions, which is however isolated from complex jet-jet interactions. The optical/laser-based imaging diagnostics were selectively performed for various combustion stages including the ignition delay period, premixed burn phase, and mixing-controlled burn phase. The major findings of this study for a given engine operating condition are summarised in Fig. 12 by illustrating the distributions of fuel (orange colour), low-temperature cool-flame zone (purple), high-temperature OH region (green), and soot (red) for each combustion stage.

- During the ignition delay period, the injected fuel initially travels as a free jet before impinging on the bowl wall to form a wall-interacting jet. Upon the wall-impingement, the fuel jet flows along the bowl wall while at the same time bounces off the bowl wall and travels back towards the nozzle. The latter movement occurs below the free jet trajectory and along the bottom surface of the bowl, which is enhanced due to the curved bowl-lip design used in this study. Similar behaviours are also reported in other studies using full geometry piston [12, 20]. The jet-wall interaction creates a turbulent ring-vortex in the wall-jet head region where the locally enhanced mixing causes earlier low-temperature reactions. The cool-flame region grows quickly, matching the size of the fuel jet in the head region.
- During the premixed burn phase, the transition from the low-temperature reaction to high-temperature reaction first occurs in the leading edge of the penetrating wall-jet. This also occurs earlier on the down-swirl side r due to the delayed second-stage ignition on the up-swirl side of the jet where higher scalar dissipation rate is expected. The high-temperature reaction then expands throughout the wall-jet head region when the peak rate of the apparent heat release is measured.
- As the injection ends in the middle of the premixed burn phase, the apparent heat release rate declines and the mixing-controlled burn commences. The soot formation first occurs at the start of mixing-controlled burn and from the fuel-rich region near the wall-impingement point, which is different to the high soot concentration measured in the head region of a free diesel jet [10] or a wall jet involving extended ignition dwell [11, 12].
- This soot region continues to grow with increasing numbers of soot pockets with various sizes and shapes and then flows along the bowl-wall in both up-swirl and down-swirl directions. The soot pockets shrink in size and eventually disappear as the OH radicals are consumed to oxidise soot particles. As the piston moves down late in the expansion stroke, the soot oxidation process due to OH radicals becomes inactive and the survived soot can exit through the exhaust.
- This study has investigated the structures and development of a single-jet diesel flame in a running engine with an emphasis on OH and soot. While the single-jet approach is justified for its capability to inject the fuel for long duration and isolate the target jet well away from other jets for diagnostics purposes, the interaction between two neighbouring jets occurring in more practical multi-hole injectors and its impact on the temporal and spatial development of OH and soot should not be underestimated. Also, the present study did not apply widely used emissions reduction technologies in modern diesel engines such as exhaust gas recirculation and intake air boosting, which affect the ambient gas conditions and ignition delay, and thus OH and soot.

Therefore, further investigations will be required to fully understand the OH and soot evolution in a small-bore diesel engine.

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References

- [1] Rajalingam BV, Farrell PV. The effect of injection pressure on air entrainment into transient diesel sprays. SAE Paper 1999-01-0523; 1999.
- [2] Rusly A, Le MK, Kook S. Effect of injection pressure on transient behaviour of wall-interacting jet flame base in an automotive-size diesel engine. SAE Int J Fuels Lubr 2013;6:615-26.
- [3] Siebers DL, Pickett LM. Injection pressure and orifice diameter effects on soot in di diesel fuel jets. in: J.H. Whitelaw, F. Payri, C. Arcoumanis, J.M. Desantes (Eds.) Thermo- and Fluid Dynamic Processes in Diesel Engines 2, Springer Berlin Heidelberg, 2004, pp. 109-32.
- [4] Pickett LM, Siebers DL. Soot in diesel fuel jets: effects of ambient temperature, ambient density, and injection pressure. Combust Flame 2004;138:114-35.
- [5] Birch S. Delphi claims world-first for direct-acting diesel injection. SAE International [Internet]. 2008 Sep [cited 2015 April 10]. [about 1 p.]. Available from: <http://articles.sae.org/4200/>
- [6] Tree DR, Svensson KI. Soot processes in compression ignition engines. Prog Energ Combust 2007;33:272-309.
- [7] Siebers DL, Higgins B. Flame lift-off on direct-injection diesel sprays under quiescent conditions. SAE Paper 2001-01-0530; 2001.
- [8] Siebers DL, Higgins B, Pickett L. Flame lift-off on direct-injection diesel fuel jets: oxygen concentration effects. SAE Paper 2002-01-0890; 2002.
- [9] Pickett LM, Siebers DL. Soot formation in diesel fuel jets near the lift-off length. Int J Engine Res 2006;7:103-30.
- [10] Dec JE. A conceptual model of di diesel combustion based on laser-sheet imaging. SAE paper 970873; 1997.
- [11] Musculus MPB. Multiple simultaneous optical diagnostic imaging of early-injection low-temperature combustion in a heavy-duty diesel engine. SAE Paper 2006-01-0079; 2006.
- [12] Musculus MPB, Miles PC, Pickett LM. Conceptual models for partially premixed low-temperature diesel combustion. Prog Energ Combust 2013;39:246-83.
- [13] Aronsson U, Chartier C, Andersson Ö, Johansson B, Sjöholm J, Wellander R, Richter M, Alden M, Miles PC. Analysis of EGR effects on the soot distribution in a heavy duty diesel engine using time-resolved laser induced incandescence. SAE Int J Engines 2010;3:137-55.
- [14] Dec JE, Kelly-Zion PL. The effects of injection timing and diluent addition on late-combustion soot burnout in a DI diesel engine based on simultaneous 2-D imaging of OH and soot. SAE paper 2000-01-0238; 2000.
- [15] Stanmore BR, Brilhac JF, Gilot P. The oxidation of soot: a review of experiments, mechanisms and models. Carbon 2001;39:2247-68.
- [16] Puri R, Santoro RJ, Smyth KC. The oxidation of soot and carbon monoxide in hydrocarbon diffusion flames. Combust Flame 1994;97:125-44.

- [17] Bruneaux G. Combustion structure of free and wall-impinging diesel jets by simultaneous laser-induced fluorescence of formaldehyde, poly-aromatic hydrocarbons, and hydroxides. *Int J Engine Res* 2008;9:249-65.
- [18] Haudiquert M, Cessou A, Stepowski D, Coppalle A. OH and soot concentration measurements in a high-temperature laminar diffusion flame. *Combust Flame* 1997;111:338-49.
- [19] Zhang J, Jing W, Fang T. High speed imaging of OH* chemiluminescence and natural luminosity of low temperature diesel spray combustion. *Fuel* 2012;99:226-34.
- [20] Miles PC, Collin R, Hildingsson L, Hultqvist A, Andersson Ö. Combined measurements of flow structure, partially oxidized fuel, and soot in a high-speed, direct-injection diesel engine. *P Combust Inst* 2007;31:2963-70.
- [21] Bruneaux G. Mixing process in high pressure diesel jets by normalized laser induced exciplex fluorescence part II: Wall impinging versus free jet. *SAE Paper* 2005-01-2097; 2005.
- [22] Polonowski CJ, Mueller CJ, Gehrke CR, Bazyn T, Martin GC, Lillo PM. An experimental investigation of low-soot and soot-free combustion strategies in a heavy-duty, single-cylinder, direct-injection, optical diesel engine. *SAE Int J Fuels Lubr* 2011;5:51-77.
- [23] Chartier C, Aronsson U, Andersson Ö, Egnell R, Johansson B. Influence of jet-jet interactions on the lift-off length in an optical heavy-duty DI diesel engine. *Fuel* 2013;112:311-8.
- [24] Menkiel B, Donkerbroek A, Uitz R, Cracknell R, Ganippa L. Combustion and soot processes of diesel and rapeseed methyl ester in an optical diesel engine. *Fuel* 2014;118:406-15.
- [25] Rusly AM, Le MK, Kook S, Hawkes ER. The shortening of lift-off length associated with jet-wall and jet-jet interaction in a small-bore optical diesel engine. *Fuel* 2014;125:1-14.
- [26] Pickett LM, López JJ. Jet-wall interaction effects on diesel combustion and soot formation. *SAE Paper* 2005-01-0921; 2005.
- [27] Genzale CL, Reitz RD, Musculus MPB. Effects of piston bowl geometry on mixture development and late-injection low-temperature combustion in a heavy-duty diesel engine. *SAE Int J Engines* 2008;1:913-37.
- [28] Pasunurthi SS, Hawkes ER, Joelsson T, Rusly AM, Kook S, Lucchini T, D'Errico G. Numerical study of a diesel engine under motored and combustion conditions. *Proceedings of the 9th Asia-Pacific Conference on Combustion*. Gyeongju, Korea, May 19-22, 2013.
- [29] Le MK, Kook S, Hawkes ER. The planar imaging of laser induced fluorescence of fuel and hydroxyl for a wall-interacting jet in a single-cylinder, automotive-size, optically accessible diesel engine. *Fuel* 2015;140:143-55.
- [30] Sarathy SM, Thomson MJ, Pitz WJ, Lu T. An experimental and kinetic modeling study of methyl decanoate combustion. *P Combust Inst* 2011;33:399-405.
- [31] Vaughn T, Hammill M, Harris M, Marchese AJ. Ignition delay of bio-ester fuel droplets. *SAE Paper* 2006-01-3302; 2006.
- [32] Yanowitz J RMA, McCormick R L, Taylor J D, Murphy M J. Compendium of experimental cetane numbers, 2014 Aug. Report No.: NREL/TP-5400-61693. Contract No.: DE-AC36-08GO28308.
- [33] Heywood JB, *Internal combustion engine fundamentals*. New York: McGraw-Hill, 1988; p. 509-10
- [34] O'Connor J, Musculus M. In-cylinder mechanisms of soot reduction by close-coupled post-injections as revealed by imaging of soot luminosity and planar laser-induced soot incandescence in a heavy-duty diesel engine. *SAE Int J Engines* 2014;7:673-93.
- [35] Dec JE, Espey C. Ignition and early soot formation in a DI diesel engine using multiple 2-D imaging diagnostics. *SAE Paper* 950456; 1995.

- [36] Mancaruso E, Vaglieco BM. Spectroscopic measurements of premixed combustion in diesel engine. *Fuel* 2011;90:511-20.
- [37] Dec JE, Espey C. Chemiluminescence imaging of autoignition in a DI diesel engine. SAE paper 982685; 1998.
- [38] Pickett LM, Kook S, Williams TC. Visualization of diesel spray penetration, cool-flame, ignition, high-temperature combustion, and soot formation using high-speed imaging. *SAE Int J Engines* 2009;2:439-59.
- [39] Kuti OA, Zhu J, Nishida K, Wang X, Huang Z. Characterization of spray and combustion processes of biodiesel fuel injected by diesel engine common rail system. *Fuel* 2013;104:838-46.
- [40] Dec JE, Coy EB. OH radical imaging in a DI diesel engine and the structure of the early diffusion flame. SAE paper 960831; 1996.
- [41] Donkerbroek AJ, van Vliet AP, Somers LMT, Dam NJ, ter Meulen JJ. Relation between hydroxyl and formaldehyde in a direct-injection heavy-duty diesel engine. *Combust Flame* 2011;158:564-72.
- [42] Kashdan JT, Docquier N, Bruneaux G. Mixture preparation and combustion via LIEF and LIF of combustion radicals in a direct-injection, HCCI diesel engine. SAE Paper 2004-01-2945; 2004.
- [43] McManus K, Yip B, Candel S. Emission and laser-induced fluorescence imaging methods in experimental combustion. *Exp Therm Fluid Sci* 1995;10:486-502.
- [44] Dieke GH, Crosswhite HM. The ultraviolet bands of OH Fundamental data. *J Quant Spectrosc Ra* 1962;2:97-199.
- [45] Singh S, Musculus MPB, Reitz RD. Mixing and flame structures inferred from OH-PLIF for conventional and low-temperature diesel engine combustion. *Combust Flame* 2009;156:1898-908.
- [46] Schulz C, Kock BF, Hofmann M, Michelsen H, Will S, Bougie B, et al. Laser-induced incandescence: recent trends and current questions. *Appl Phys B* 2006;83:333-54.
- [47] Bobba MK, Musculus MPB. Laser diagnostics of soot precursors in a heavy-duty diesel engine at low-temperature combustion conditions. *Combust Flame* 2012;159:832-43.
- [48] Vander Wal RL. Laser-induced incandescence: excitation and detection conditions, material transformations and calibration. *Appl Phys B* 2009;96:601-11.
- [49] Vander Wal RL, Weiland KJ. Laser-induced incandescence: Development and characterization towards a measurement of soot-volume fraction. *Appl Phys B* 1994;59:445-52.
- [50] Zhao H, Ladommatos N. Optical diagnostics for soot and temperature measurement in diesel engines. *Prog Energ Combust* 1998;24:221-55.
- [51] Le MK, Kook S. Injection pressure effects on the flame development in a light-duty optical diesel engine. *SA Int J Engines*, 2015;8:609-24
- [52] Liu S, Hewson JC, Chen JH, Pitsch H. Effects of strain rate on high-pressure nonpremixed n-heptane autoignition in counterflow. *Combust Flame* 2004;137:320-39.
- [53] Musculus MPB. Entrainment waves in decelerating transient turbulent jets. *Journal of Fluid Mechanics* 638, pp. 117-140, 2009.
- [54] Kook S, Pickett LM, Musculus MPB, and Gehmlich RK, Influence of diesel injection parameters on end-of-injection liquid length recession. *SAE International Journal of Engines* 2(1):1194-1210, 2009.
- [55] Kook S, Bae C, Miles P, Choi D et al. The Influence of charge dilution and injection timing on low-temperature diesel combustion and emissions. SAE Technical Paper 2005-01-3837, 2005

Table 1 Engine specifications and operating conditions

Displacement (single-cylinder)	497.5 cm ³
Bore	83 mm
Stroke	92 mm
Compression ratio	15.5 (geometric)
Swirl ratio	1.4
Wall (coolant) temperature	363 K
Intake air temperature	303 K
Fuel	Methyl decanoate
Lower heating value	37.7 MJ/kg
Kinematic viscosity at 40°C	1.71 mm ² /s
Density at 15°C	0.871 g/ml
Cetane number	52
Injector type	Bosch common-rail
Number of holes	1
Nozzle type	Hydro-grounded, K1.5/0.86
Nozzle diameter (nominal)	134 µm
Included angle	150°
Injected fuel mass per hole	10 mg
Rail pressure	100 MPa
Injection duration	2.24 ms
Injection timing and in-cylinder air conditions	7°CA bTDC 858 K and 11.16 kg/m ³
Engine speed	1200 rpm

Figure 1 Schematic diagram of the optical diesel engine and laser diagnostics setup

Figure 2 Still images from high-speed movies of hot soot luminosity for a selected cycle of diesel (top) and methyl decanoate fuel (bottom)

Figure 3 Illustration of the laser sheet with respect to the piston bowl and fuel jet in the bottom view (top) and side view (bottom-left). Also shown on the bottom-right corner is an example image of laser-induced fuel fluorescence obtained at 7 mm below the cylinder head.

Figure 4 (a) Offline OH-PLIF (top-left) and online OH-PLIF signals (top-right) pseudo-coloured in yellow and blue, respectively, and their combined image (bottom) and (b) Soot PLII (top-left) and OH-PLIF signals (top-right) pseudo-coloured in red and blue, respectively, and their combined image (bottom). On the combined images, the corresponding imaging times are denoted in crank angle degrees after top dead centre ($^{\circ}$ aTDC) and after the start of fuel injection ($^{\circ}$ aSOI). All images were obtained 7 mm below the cylinder head.

Figure 5 In-cylinder pressure traces of 20 instantaneous cycles and their ensemble average (top). Shown at the bottom are the corresponding traces of apparent heat release rate.

Figure 6 Individual soot PLII images of 20 engine cycles at 12°CA aTDC . The representative PLII image of the 20-image set is shown at the top-right. All images were taken at 7 mm below the cylinder head.

Figure 7 Averaged in-cylinder pressure (top) and the apparent heat release rate (aHRR) traces (bottom) for the selected engine operating conditions. Also shown in the aHRR plot is the measured injection rate profile. The laser-based imaging times are illustrated on both the in-cylinder pressure and aHRR traces using circles/squares for the ignition delay phase, triangles for the premixed burn phase, and diamonds for the mixing-controlled burn phase.

Figure 8 Planar laser induced fluorescence (PLIF) signals and cool-flame chemiluminescence signals during the ignition delay period. Shown on the first two rows are the development of a non-reacting fuel jet during jet-wall interaction. Also shown on the bottom row are the cool-flame signals corresponding to the images on the middle row. Illustrations at the right show the used laser sheet position (7 mm below the cylinder head) with respect to the piston position at a given crank angle location and the postulated fuel jet development.

Figure 9 OH* chemiluminescence images (top) and corresponding planar laser induced fluorescence (PLIF) signals of OH (online/offline combined) at 7 mm (middle) and 9 mm (bottom) below the cylinder head during the premixed burn phase. The vertical dashed-dot line indicates the fuel jet trajectory. Illustration at the right shows the used laser sheet position with respect to the piston position at a given crank angle and the postulated fuel jet development.

Figure 10 Planar laser induced fluorescence (PLIF) signals of OH (online/offline combined, top), planar laser-induced incandescence (PLII, middle) of soot, and the combined image (bottom) during the mixing-controlled burn phase. The vertical dashed-dot line indicates the fuel jet trajectory. Illustration at the right shows the used laser sheet position (7 mm below the cylinder head) with respect to the piston position at a given crank angle location and the postulated fuel jet development.

Figure 11 The combined images of OH-PLIF signals (online/offline combined) and PLII signals during the mixing-controlled combustion phase. The images were taken at 7, 9, and 11 mm below the cylinder head. Illustration at the right shows the used laser sheet positions with respect to the piston position at a given crank angle location and the postulated fuel jet development.

Figure 12 Illustration of the development of fuel, low-temperature reaction, high-temperature reaction, and soot of a single fuel jet in a small-bore diesel engine