

Injection Pressure Effects on the Flame Development in a Light-Duty Optical Diesel Engine

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ABSTRACT

The impact of fuel injection pressure on the development of diesel flames has been studied in a light-duty optical engine. Planer laser-induced fluorescence imaging of fuel (fuel-PLIF) and hydroxyl radicals (OH-PLIF) as well as line-of-sight integrated chemiluminescence imaging of cool-flame and OH* were performed for three different common-rail pressures including 70, 100, and 130 MPa. The injection timing and injected fuel mass were held constant resulting in earlier end of injection for higher injection pressure. The in-cylinder pressure was also measured to understand bulk-gas combustion conditions through the analysis of apparent heat release rate. From the cool-flame images, it is found that the low-temperature reaction starts to occur in the wall-interacting jet head region where the fuel-air mixing could be enhanced due to a turbulent ring-vortex formed during jet-wall interactions. Also, the cool-flame images together with the apparent heat release rate suggest that the low-temperature reaction becomes stronger with increasing injection pressure. The influence of in-cylinder swirl flow on the OH* chemiluminescence signals was observed such that the high-temperature reaction on the down-swirl side of the jet is earlier than that on the up-swirl side of the jet regardless of the injection pressure. Moreover, the second-stage ignition on the down-swirl side of the jet is found to be stronger than the up-swirl side of the jet. This is consistent with higher fuel penetration and more intense fuel fluorescence signals observed on the down-swirl side of the jet, suggesting that relatively richer mixtures caused stronger high-temperature reactions. As the injection pressure increases, however, the spread and magnitude of the up-swirl OH* chemiluminescence signals become comparable to the down-swirl signals due to the increased injection momentum overcoming the swirl flow. On account of the unavoidable laser beam attenuation, the OH-PLIF signals on the up-swirl side could not be observed clearly. The down-swirl OH-PLIF signals, however, display interesting behaviour of the wall-interacting jet head such that the OH-PLIF region expands drastically in the turbulent ring-vortex region where the cool-flame signals were detected at earlier timings. The expansion of wall-jet head OH signals shows an increasing trend with increasing injection pressure, which is explained by a stronger ring-vortex due to the increased injection momentum.

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INTRODUCTION

Benefitting from high-pressure fuel injection independent of engine load and speed, common-rail diesel engines are widely used in passenger car and light-duty truck applications [1, 2]. The common-rail fuel injection system enables constantly high fuel pressure that improves the air/fuel mixing and combustion significantly. For example, the high-pressure injection up to 200 MPa [3] induces high injection momentum, leading to longer vapour penetration [4, 5], enhanced ambient gas entrainment, and thus better air-fuel mixing [6, 7, 8]. Also, the increased injection pressure leads to the increased lift-off length [6, 9] which, coupled with a small-hole nozzle, helps reduce the soot formation [3, 7, 9]. This is achieved through the reduced equivalence ratio at the flame base for fixed injection mass [8, 9] and the decreased soot residence time [6]. The earlier end of injection at higher injection pressure conditions also contributes to the reduced soot formation because for the fixed fuel mass, the pre-combustion mixing time is extended and thereby increasing premixed burn phase of diesel combustion [9, 10]. Some studies also reported decreased fuel consumption as well as reduced engine-out

emissions of products of incomplete combustion such as unburned hydrocarbon (uHC) and carbon monoxide (CO) [11, 12, 13] as the advantages of high pressure injection.

The high injection pressure also makes a significant impact on the diesel jet development inside the engine cylinder. In a diesel engine, particularly in small-bore diesels, jet-wall interactions cause marked variations in mixture formation, temperature distribution, and pollutants formation [14, 15, 16, 17, 18, 19]. The higher injection pressure would enhance the jet-wall interaction due to higher injection momentum which could increase an overall mixing rate [14]. This is explained by a turbulent ring-vortex created in the wall-jet head region during the jet-wall interaction [14, 16, 20]. This head-vortex is known to increase the local mixing which cancels out the limited mixing near the wall impingement region [14]. The higher jet momentum would intensify the head vortex while keeping the wall-impingement region small and thus increase the overall mixing and suppress the soot formation [21, 22]. The use of higher injection pressure could also reduce the entrainment of hot combustion

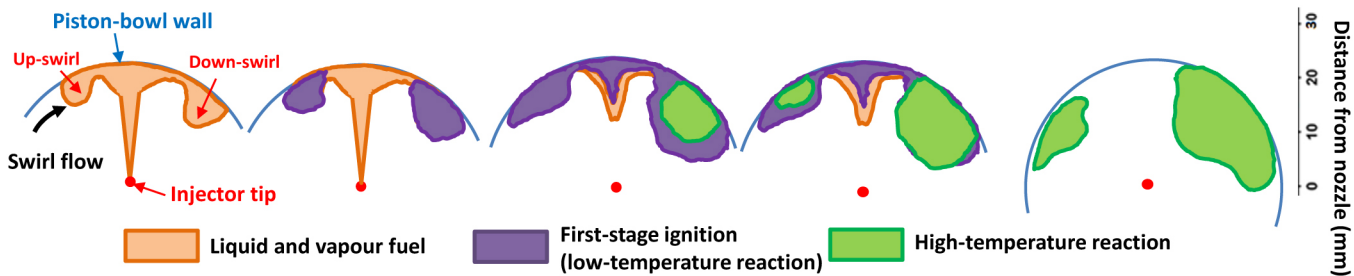


Figure 1. Illustration of a wall-interacting fuel jet in a small-bore diesel engine: adapted from Ref. [20]. The images are arranged in an increasing temporal order from left to right.

products that are directed back towards the incoming jet (i.e. re-entrainment). The re-entrainment is problematic as it would decrease the lift-off-length and thereby increasing soot formation [11, 18, 23, 24, 25]. While higher injection momentum would increase the chances of re-entrainment, the soot formation is effectively suppressed as the injection duration (and thus the re-entrainment period) is reduced for fixed fuel mass [9].

There are many fine papers providing a clear picture of a diesel flame development in both light-duty [26] and heavy-duty engines [27, 28]. However, there is a research gap about how a wall-interacting diesel jet is affected by variations in injection pressure. In our previous study [20], the development of a reacting fuel jet in a light-duty diesel engine was investigated in detail using various optical/laser-based imaging diagnostics. The major findings were summarised by illustrating the temporal and spatial evolution of fuel, cool-flame, and hydroxyl (OH) distributions of a single diesel jet, similar to Refs. [26, 27, 28]. The illustration is presented in Fig. 1. More details are found in Ref. [20] but three major aspects of this illustration are summarised as follows:

1. The low-temperature reaction of a wall-interacting diesel jet occurs in the jet head region where a turbulent ring-vortex is formed upon the jet impingement on the wall. The high-temperature reaction starts from the same wall-jet head region.
2. The swirl flow causes asymmetric flame structures such that the high-temperature reaction occurs earlier and is stronger on the down-swirl side of the jet due to the swirl-induced richer mixture.
3. During the premixed burn phase, the expansion of high-temperature reaction zone occurs in the same wall-jet head region of low-temperature reactions where the turbulent ring-vortex is expected.

The primary aim of the present study is to understand how the injection pressure impacts this concept developed for low injection pressure conditions. To this end, we performed line-of-sight integrated imaging of cool flame and excited OH (OH*) as well as planar laser induced fluorescence (PLIF) imaging of fuel and OH in a light-duty optical diesel engine. These images were used to illustrate the structural variation of the reacting diesel jet with increasing injection pressure.

EXPERIMENTAL SETUP AND DIAGNOSTICS

Engine Setup and Operating Conditions

The experiments were carried out in a light-duty, single-cylinder optical diesel engine. Figure 2 shows a schematic of the engine and imaging diagnostics setup. The engine specifications and operating conditions are summarised in Table 1. The engine had 83 mm bore and 92 mm stroke, resulting in a displacement volume of 497.5 cm³. The combustion chamber was bounded by a cylinder liner, a cylindrical-bowl piston top (55 mm in diameter), and a flat fire-deck where a centrally mounted injector nozzle, two intake valves and two exhaust valves were located. The optical access was achieved through the quartz window in the piston top and a 45° mirror placed in the hollow space of the extended piston body, as well as quartz cylinder liner windows. As illustrated in Fig. 2, a portion of the bowl rim (33 mm wide) was removed to ensure that a laser beam can enter the combustion chamber even when the piston was at a top dead centre (TDC) position. This piston modification resulted in a geometric compression ratio of 15.2 which is still relevant to diesel engines available in the current market. The quartz piston-top provided a field-of-view of 43 mm in diameter, slightly smaller than the piston-bowl diameter. The engine was naturally aspirated and had a swirl ratio of 1.4. The wall temperature of cylinder head, liner, and engine block was held constant at 363 K using a heated-water circulation system to simulate warmed-up operating conditions. The intake air temperature was measured at 303 K throughout the experiments. A second-generation Bosch common-rail system was used for the injection of conventional ultra-low sulphur diesel (ULSD) fuel with cetane number of 51. The original injector nozzle had seven 134-μm (nominal diameter) holes with 150° included angle, which was modified in the present study for a single-hole nozzle by blocking six holes. A laser-welding technique was used for this purpose. The single-hole nozzle was preferred for long injection duration (> 2 ms) to simulate that of a high-load operating condition while keeping the peak in-cylinder pressure below the burst pressure of the quartz windows used in this study. Moreover, the single-hole injector isolates the jet of interest from complex jet-jet interactions. The engine was operated at a 10 skip-firing mode with the injection occurring every 10th cycle (i.e. 9 motoring cycles and 1 firing cycle). This was to reduce the thermal loading on the quartz windows for the safety as well as to expel the residual gases from previous firing cycles. The engine speed was held constant at 1200 rpm using a 37-kW AC motor.

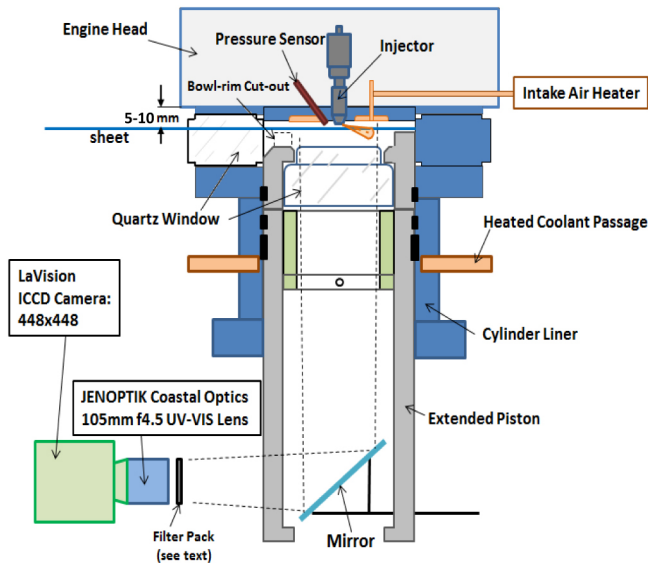


Figure 2. Schematic diagram of the optical diesel engine and laser diagnostic setup

Table 2 displays the fuel injection conditions tested in the present study. Three different common-rail (or injection) pressure of 70, 100 and 130 MPa were investigated. The fuel mass was fixed at 10 mg per injection which resulted in reduced injection duration and earlier end of injection (EOI) for higher injection pressure conditions. It was noted that this injection mass could be translated into 70 mg if all seven holes were used, well exceeding the high-load range in light-duty diesel engines. The fuelling rate was measured for all injection pressures tested using a Bosch-tube-type injection rate meter. The start of injection was fixed at 7 crank angle degrees before TDC ($^{\circ}\text{CA bTDC}$).

Table 1. Engine specifications and operating conditions.

Displacement (single-cylinder)	497.5 cm ³
Bore	83 mm
Stroke	92 mm
Compression ratio (geometric)	15.2
Swirl ratio	1.4
Wall (coolant) temperature	363 K
Intake air temperature	303 K
Fuel	ULSD (cetane number 51)
Injector type	Second-generation Bosch common-rail
Number of holes	1
Nozzle type	Hydro-grounded, K1.5/0.86
Nozzle hole diameter	134 μm
Included angle	150 $^{\circ}$
Engine speed	1200 rpm

Table 2. Fuel injection conditions

Rail pressure	70 MPa	100 MPa	130 MPa
Injected fuel mass	10 mg		
Injection timing	7.7 $^{\circ}\text{CA bTDC}$		
Injection duration	2.36 ms	2.24 ms	2.02 ms

Diagnostics

In-Cylinder Pressure and Apparent Heat Release Rate

As illustrated in Fig. 2, 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 (aHRR) based on a simple one-dimensional energy equation [29]. The aHRR was plotted to evaluate the in-cylinder conditions and to identify the combustion stage at the imaging time.

Cool Flame Chemiluminescence

During the first-stage, low-temperature ignition phase of diesel combustion, weak chemiluminescence signals are emitted from CH , CO and formaldehyde (HCHO) through the breakdown of ketohydroperoxide (KHP) species [26, 30]. 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. The lens was UV-enhanced, achieving over 85% transmission at 250 ~ 650 nm range, suitable for capturing the cool-flame chemiluminescence in a range of 360 ~ 560 nm [31, 32, 33]. This bottom-view imaging setup is shown in Fig. 2. To detect the weak cool-flame signals, the camera gain was set at a maximum value and long exposure time of 140 μs ($\sim 1^{\circ}\text{CA}$ at 1200 rpm) was applied without any optical filters placed in front of the lens. The cool flame chemiluminescence images were captured at various crank angle locations until the signal became a couple of orders of magnitude stronger with the start of high-temperature reactions. At each crank angle location, a total of 20 images were taken from twenty firing cycles.

OH* Chemiluminescence

Electronically-excited hydroxyl (OH^*) radicals are formed during high-temperature exothermic reactions of hydrocarbons at near stoichiometric conditions (e.g. $\text{CH} + \text{O}_2 \rightarrow \text{CO} + \text{OH}^*$) [31]. As the OH^* radicals return to their ground state (OH), the chemiluminescence signal is emitted in the 306 ~ 310 nm range [18, 34]. Therefore, the OH^* chemiluminescence images are a cost-effective and useful technique to identify high-temperature reaction zones in the flame [35, 36, 37]. Figure 2 shows that the same ICCD camera and UV-enhanced lens as in the cool-flame chemiluminescence imaging was used for OH^* chemiluminescence imaging. To isolate the emission range of the OH^* chemiluminescence signals, optical filters including a WG-305 glass filter and a 300-nm band-pass filter (FWHM: 40 nm) were placed in front the ICCD camera lens. The ICCD gate was set at 70 μs (half a crank angle at 1200 rpm) with the gain set at 25% of the maximum gain value. Consistent with other imaging diagnostics of this study, 20 OH^* images were captured at each selected crank angle.

Planar Laser-Induced Fluorescence of Hydroxyl (OH-PLIF)

In addition to the in-cylinder pressure measurement, cool flame and OH* chemiluminescence imaging, planar laser induced fluorescence imaging (PLIF) of OH was also performed at the same operating conditions. For OH-PLIF imaging, a Rhodamine-6G filled dye laser (Sirah Cobra-Stretch) was pumped by a frequency doubled beam (532 nm) from an Nd:YAG laser (Quanta-Ray PRO-230) 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. In front of the camera lens (Fig. 2), a series of optical filters were placed. The same optical filters as in the OH* chemiluminescence imaging was used to isolate the OH-PLIF emissions range (i.e. 305 ~ 320 nm) and to reject the scattering from the excitation wavelength. The emitted laser beam was converted to a 30-mm wide, 300- μ m thick laser sheet using a series of cylindrical lenses before being inserted into the combustion chamber through the cylinder liner quartz window [20]. It was noted that this liner window had the plano-concave shape which diverged the laser sheet horizontally. A mock-up test was conducted to evaluate the degree of this divergence and its effect on the laser coverage area as shown in Fig. 3 (top left). The laser sheet divergence marked by red dashed lines confirms that the expanded laser sheet covers the entire field-of-view provided by the piston-bowl window.

On the top-right corner of Fig. 3, the selected diesel jet (directing 2 o'clock) relative to the laser coverage, bowl-rim cut-out and piston-bowl window are illustrated, which suggests that the visualisation of

the selected diesel jet is possible. The rectangle bounded by the red dashed lines displays the region of interest and the orientation used in the following sections for presentation purposes. The OH-PLIF imaging was performed for various vertical distances from the cylinder head as shown in Fig. 3 (bottom-right). Three different laser planes were selected to cover the top, middle and bottom part of the cylinder bowl including 5, 7 and 10 mm below the cylinder head.

During the laser experiments, a beam attenuation issue was identified on the up-swirl side of the jet (i.e. the jet travelling against the swirl flow), particularly at high injection pressure conditions. This issue is illustrated on the bottom-left corner of Fig. 3. Higher injection pressure is expected to result in longer penetration length with reaction occurring further downstream [38, 39]. Therefore, the sooting flame penetrated along the wall and eventually the up-swirl jet was in the way of the incoming laser sheet, leading to the laser beam attenuation. This issue was unavoidable as a conventional diesel fuel with many aromatic hydrocarbons was used, which are well-known precursors to soot formation. Both soot particles and aromatic hydrocarbons are well-known sources of strong interference for the OH-PLIF signal. Therefore, the discussions about OH-PLIF images will be emphasized on the down-swirl side of the jet. In our future work, the diesel fuel will be replaced with a low-sooting surrogate fuel to reduce the beam attenuation. Further information on how these interferences are dealt with can be found in the following section.

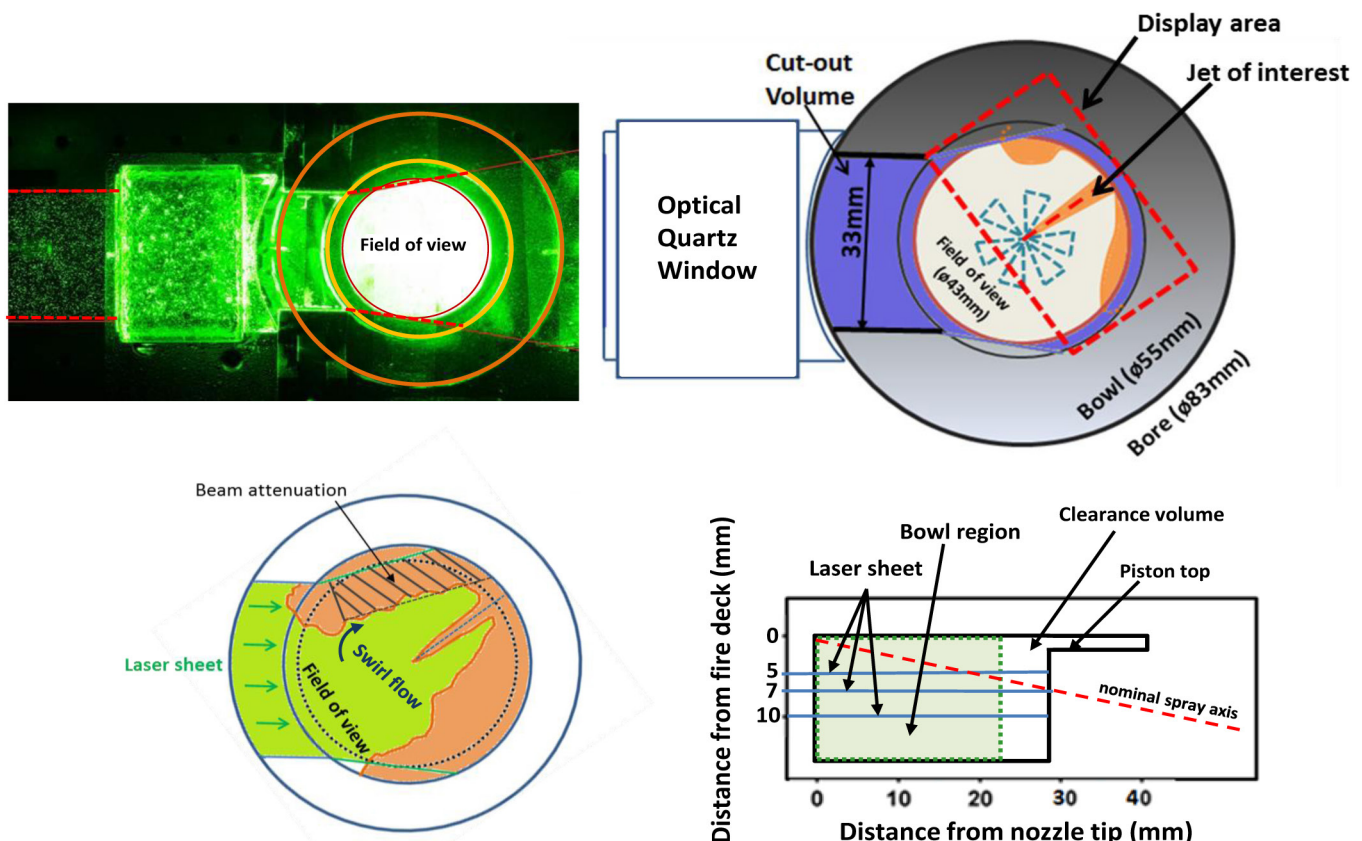


Figure 3. The laser beam pass and field of view of PLIF imaging in bottom view (top left) and illustration of the jet of interest relative to the piston geometry and laser-sheet orientation (top right). Also shown are the distance between the cylinder head and the laser beam for OH-PLIF imaging (bottom right) and the sketch of a laser attenuation issue (bottom left).

Another issue of OH-PLIF imaging was signal interferences in the 308 ~ 320 nm range due to the presence of polycyclic aromatic hydrocarbons (PAH) and soot luminosity. This issue was addressed by comparing OH-PLIF images obtained using a 284 nm “online” excitation wavelength and a 283.9 nm “offline” excitation wavelength, similar to Refs. [20, 27, 28, 40]. Due to the fine rotational and vibrational spectrum of OH, a slight shift of the excitation wavelength would result in significantly lower OH fluorescence signals, which could be interpreted mostly as interference signals. In this method, the online laser beam induces fluorescence of OH as well as other sources (interference) whereas the offline laser beam does not cause fluorescence of OH but other sources. An example is shown in Fig. 4 for the images taken at 10°CA aTDC and 100 MPa injection pressure when the peak aHRR was observed. Indeed, the offline OH-PLIF image on the left-hand side displays some signals near the piston-bowl wall at 2 and 3 o'clock directions, which is markedly different from the online OH-PLIF image shown on the right-hand side. For comparison purposes, the boundaries of the offline signals are overlaid on the online image. It is evident that PLIF signals in the online image cover much larger areas than those of the offline image, suggesting that the signals are predominantly OH in this online OH-PLIF image. The same method was repeated for all PLIF images taken at various crank angle locations and for various injection pressures. It should be noted that the online/offline images in Fig. 4 were not obtained simultaneously from the same engine cycle. However, one may find that the offline signal boundaries well represent the general behaviour of interference signals with respect to the online OH-PLIF signals. A potential impact of cyclic dispersion on comparing online and offline signal images will be discussed in the following sections.

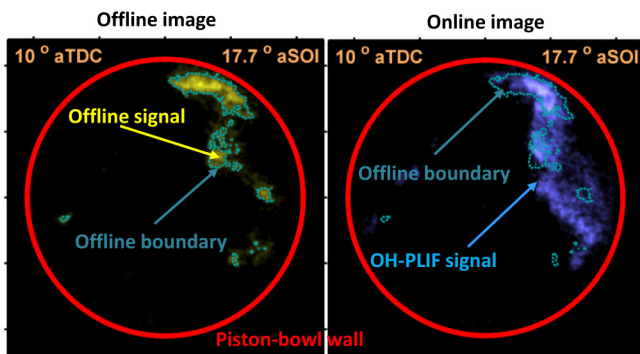


Figure 4. The boundary detection of offline OH-PLIF signals (left) and the offline signal boundaries overlaid on the online OH-PLIF image (right). Shown at the top-left and top-right of each image are a corresponding crank angle position (°CA aTDC) and crank angle degrees after the start of fuel injection (°CA aSOI), respectively.

Fuel Planar Laser-Induced Fluorescence (Fuel PLIF)

Using the same setup of OH-PLIF diagnostics as in Fig. 3, fuel-PLIF imaging was also performed. The conventional diesel fuel used in this

study contained many aromatic hydrocarbons and additives (e.g. naphthalene and alkyl benzenes) that are known to produce strong fluorescence signals due to UV excitation [41]. The fluorescence spectrum of aromatics does not display the fine-scale structure of OH-PLIF, resulting in broadband emissions. Therefore, the OH-PLIF signal using 284 nm would overlap with the fuel-PLIF emission range [28, 42] meaning that the fuel-PLIF is interference to OH-PLIF signals. However, the fuel-PLIF can provide valuable information on the vaporising diesel jet development if the images are taken prior to the start of combustion. In this study, the PLIF signals detected before the start of high-temperature reaction were interpreted as fuel-PLIF and were used to discuss the vaporising jet penetration.

Cyclic Variations

Reacting diesel jets inside the engine cylinder are highly turbulent with irregular mixture and temperature distributions, leading to cyclic variations. To minimise the cyclic dispersion, the optical diesel engine used in this study was operated at fixed wall (coolant) temperature, intake air temperature, and engine speed. The skip-firing also helped reduce the cyclic variations caused by residual gases from previous firing cycles. However, some cyclic variations were unavoidable.

Cycle-to-Cycle Variations in In-Cylinder Pressure

Figure 5 shows in-cylinder pressure traces (top) and corresponding aHRR (bottom) for fixed operating conditions of Table 1 and at selected injection pressure of 130 MPa. All the in-cylinder pressure traces recorded from 20 firing cycles (black lines) are plotted together with their ensemble-averaged trace (red). The figure shows that the individual traces are very consistent before the combustion starts at around 5°CA aTDC, suggesting stable thermal and ambient gas conditions of the engine. However, as the combustion-induced heat release occurs and thus the in-cylinder pressure increases drastically, some variations are found in the in-cylinder pressure traces. For example, the start of combustion (identified by the drastic pressure rise) occurs at various crank angle locations ranging from 6 to 8°CA aTDC and the peak in-cylinder pressure fluctuates between 3.7 and 4 MPa. However, in this study, these in-cylinder pressure variations are smaller than the differences caused by the variations in injection pressure as will be shown in the following sections. The aHRR of individual cycles (black lines) and their cycle-averaged value (red line) are also shown at the bottom of Fig. 5, which also suggest a similar degree of cyclic variations. Although the peak value fluctuates, it is noted that the rise of aHRR at around 7°CA aTDC are very similar among all the instantaneous cycles. Also, a small peak in aHRR is observed consistently at about 5°CA aTDC for all the cycles. This suggests the first-stage, low-temperature ignition occurring prior to the second-stage, high-temperature ignition, during which cool-flame chemiluminescence signals are expected [28, 32].