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Overcoming Beam Attenuation Issues in OH-PLIF Diagnostics using an Aromatics-free, Low-Sooting Surrogate Fuel in an Optical Diesel Engine

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Abstract

Planar laser induced fluorescence of OH radicals (OH-PLIF) imaging diagnostics is a widely used technique to visualise high-temperature flames in optical diesel engines. However, strong fuel fluorescence from aromatics and high soot concentrations in diesel flames cause a serious beam attenuation issue, which could lead to misinterpretation of OH-PLIF images. This experimental study aims to demonstrate great advantages of using a fatty acid methyl ester surrogate fuel to avoid the beam attenuation issue owing to its no aromatics in fuel and low sooting propensity. Methyl decanoate, one of the extensively studied fatty acid methyl esters, is selected for this purpose and the results are compared to diesel. In an optically accessible light-duty diesel engine, total fuel energy input and main combustion event timings were matched between the two fuels. In addition to OH-PLIF imaging, a complementary diagnostic of excited OH (OH*) chemiluminescence imaging was performed during the high-temperature reaction phase. Planar laser induced incandescence (PLII) imaging was also performed to understand the spatial distributions of soot with respect to the OH-PLIF regions. The results show that methyl decanoate has a much higher OH radical coverage while having a much slower rate of dissipation resulting in strong OH signal persisting even during late crank angle timings. The overall distributions of OH* chemiluminescence and OH-PLIF signals appear to be very similar. By contrast, diesel fuel has a high intensity OH radical signal at the jet front while having very little signal behind the wall-jet head. The mismatch between the OH-PLIF images and the OH* images of diesel fuel suggested the serious beam attenuation, which raises a question on the interpretation of the OH-PLIF images. Therefore, it is necessary to use an aromatics-free, low-sooting fuel such as methyl decanoate for OH-PLIF imaging diagnostics to understand the true nature of the spatial and temporal development of flames in an optical diesel engine.

Introduction

Laser based imaging techniques are effective in identifying reaction species and understanding how their temporal and spatial development occurs during the combustion process. Two widely used laser based imaging techniques are planar laser induced fluorescence of hydroxyl radicals (OH-PLIF) and planar laser induced incandescence (PLII), which can be used to study the distributions of hydroxyl radicals and soot, respectively [5 - 7]. One of the major issues in applying these diagnostics to diesel combustion is beam attenuation of the excitation laser. This is when molecules within the fuel such as aromatics or combustion species such as soot particles cause reduction in excitation laser energy which could result in laser energy levels decreasing below the laser fluence threshold in certain regions of the viewing area [1, 2, 4]. This can lead to inaccurate signals and dark, uncertain areas within the resulting images and misinterpretation of their physical meanings.

One way to overcome this issue could be utilising a low-sooting surrogate fuel with no aromatics [2, 3]. Since aromatics is a known soot precursor [4], the lack of aromatics results in much lower soot production and thereby resolving the beam attenuation. Additionally, the lack of aromatics could minimise the amount of fuel fluorescence when using an excitation laser with a wavelength within the UV range [5], which can also reduce the beam attenuation.

In the present study, methyl decanoate has been selected as a fuel for OH-PLIF imaging as it is a biodiesel surrogate fuel which has similar combustion and soot formation properties as diesel while having very low amounts of soot generated due to the lack of aromatics and the presence of oxygen in its molecular structure [5]. The fuel is gaining popularity due to the detailed chemical kinetics model available in the literature [8]. In an optical diesel engine, we have performed OH-PLIF imaging for methyl decanoate and a conventional diesel fuel for a direct comparison of the significance of the beam attenuation issue. In addition, the line-of-sight integrated imaging of OH* chemiluminescence and PLII imaging were performed to provide complementary information to the OH-PLIF signals.

Experimental Setup and Diagnostics

Engine and Fuel Parameters

Experiments were performed using a single cylinder light-duty optical diesel engine as shown in figure 1. The engine specification and operating conditions are summarised in table 1. The engine has a 497.5 cm^3 displacement volume with a bore of 83 mm, a stroke of 92 mm and a compression ratio of 15.5 (geometric). Optical access is permitted though a quartz window on the piston top allowing bottom view images of the combustion chamber to be taken. This view is directed into an ICCD camera via a 45º mirror located within a hollowed section of the piston body. Laser access is made through a quartz window located in the cylinder liner which allows views of the region just below the cylinder head. To prevent the laser from being obstructed at timings close to TDC, a 35-mm wide portion of the piston bowl rim was removed as illustrate in figure 1. The engine head houses two intake valves, two exhaust vales, a piezoelectric pressure transducer and a centrally mounted common-rail injector (Bosch CP3) modified from a seven-hole nozzle to a single-hole nozzle by laser-welding the unused holes. For stable engine operations with warmed-up conditions, a water heater/circulator (ThermalCare Aquatherm RA series) was used, which kept the wall temperature at 363 K. The intake temperature was measured at 303 K throughout the experiments. The engine was motored at 1200 rpm with an AC motor connected to the flywheel on the crank case. In this optical engine, a skip firing mode was used with firing cycles occurring once only in every tenth cycle. This was mainly to ensure that residual exhaust gases from previous firing cycles were not present, which also helped minimise the thermal stress and fatigue on the quartz windows. The images in this experiment were captured using an ICCD camera with a UV enhanced lens.

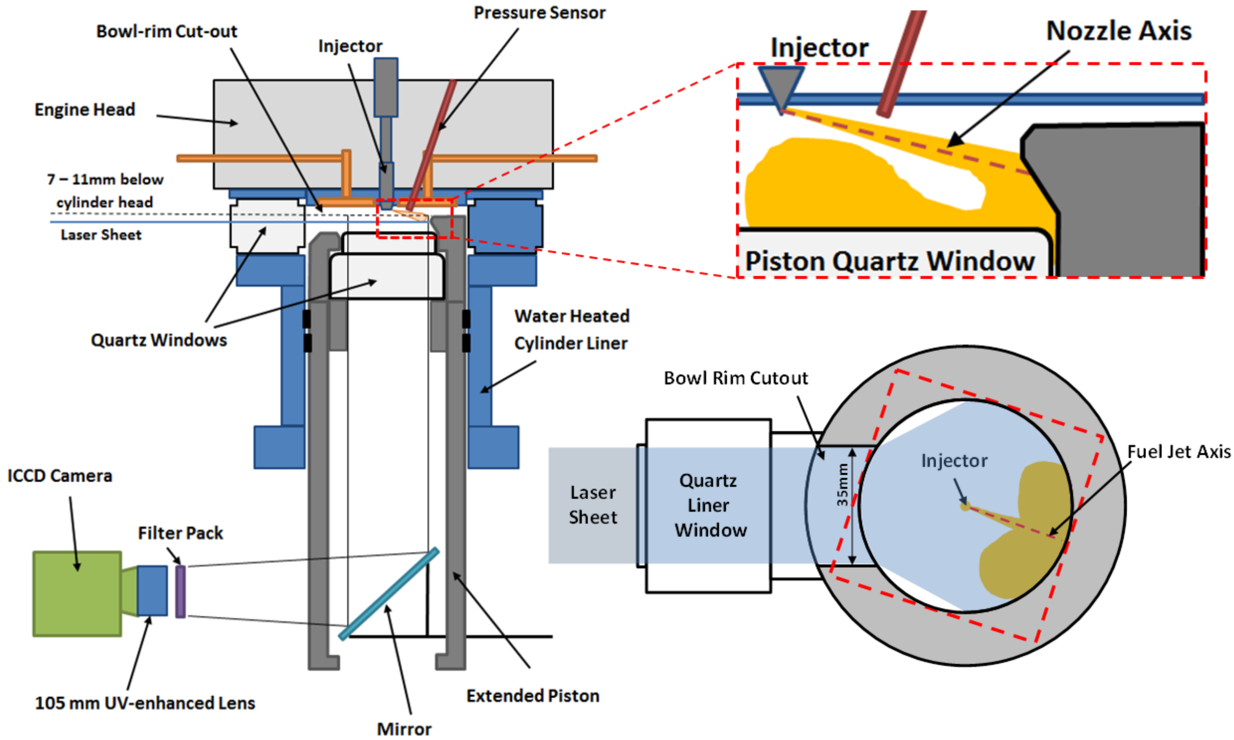

Figure 1. Schematic showing the optical engine configuration and laser-based planar imaging setup

Displacement	497.5 cm^3	
Bore	83 mm	
Stroke	92 mm	
Compression ratio	15.5 (geometric)	
Engine speed	1200 rpm	
Swirl ratio	1.4	
Wall temperature	363 K	
Intake air temperature	303 K	
Injector type	Common-rail (Bosch CP3)	
Number of holes	1	
Nozzle type	Hydro-grounded, K1.5/0.86	
Nozzle diameter	134 µm	
Included angle	150º	
Rail pressure	100 MPa	
Fuel	Diesel	Methyl Decanoate
Lower heating value	43.3 MJ/kg	37.7 MJ/kg
Injected fuel mass per hole	10.0 mg	11.5 mg
Injection duration	1.1 ms	1.2 ms
Injection signal timing	9ºCA bTDC	11ºCA bTDC

Table 1. Engine setup and fuel operating parameters

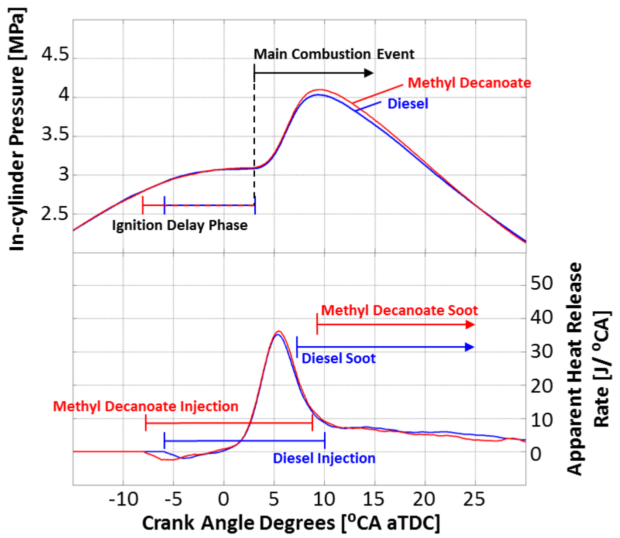

Figure 2. In-cylinder pressure and apparent heat release rate of methyl decanoate (red) and diesel (blue) fuels.

The two fuels used in this experiment were conventional diesel and methyl decanoate. The fuel parameters are listed in table. 1. For both methyl decanoate and diesel cases, a common-rail pressure of 100 MPa was used. To allow for a comparative study between the two fuel cases, the total energy input for both fuels was kept constant at 433 J per injection, which was given by 10 mg of diesel and 11.5 mg of methyl decanoate. Due to this fixed total energy input and similar ignition quality between the two fuels, the measured in-cylinder pressure and the apparent heat release rate curves were easily matched by adjusting the fuel injection timing slightly. The results are shown in figure 2, which confirms nearly identical in-cylinder conditions for the two fuels.

OH Planar Laser Induced Fluorescence (OH-PLIF) Imaging

An excitation laser sheet of 284 nm wavelength was projected into the combustion chamber through the quartz window on the cylinder liner. This laser sheet was used to excite ground-state OH radicals, along with other combustion species, within the combustion chamber. To isolate OH-PLIF signal in the 308 – 320 nm wavelength range, a set of optical filters were used in front of the lens. The filters include a 300-nm band pass filter (40-nm FWHM), WG-305 long pass filters and WG-295 long pass filters. The filtered signals were then captured by the ICCD camera. By adjusting the entrance height of the laser sheet, multiple planes were observed to depict the temporal and spatial development of OH.

Considering other fluorescence signals in the same emission range of OH (i.e. interference signals), another set of PLIF images were taken. Since OH excitation is very sensitive to 284 nm, the second set of images were obtained using 283.9 nm which would excite all other species besides OH. Combining the two sets of images together then allowed the signal from OH to be evaluated and identified. For this study, the images with all excited signals including OH (online) are coloured blue and the interference signals with no OH-PLIF (offline) are coloured yellow. In addition to OH-PLIF imaging, the line-of-sight integrated imaging of OH* chemiluminescence was also performed using the same optical filters (i.e. centred at 310 nm). For display purposes the OH* chemiluminescence images are processed to be aqua coloured.

Planar Laser Induced Incandescence (PLII)

A high energy laser was utilised to achieve high laser fluence of approximately 0.72 J/cm^2. This was so that the laser fluence threshold, where soot signal intensity does not change with laser energy, is exceeded in an attempt to minimise the effect of laser attenuation [2]. A 1064 nm wavelength laser sheet was used for 7 mm and 9 mm planes to understand the spatial distribution of soot and its variations with respect to OH regions. Optical filters composed of a 430 nm band-pass filter and a 450 nm short-pass filter were used to isolate incandescence signals at shorter wavelength ranges. For display purposes, the incandescence signals were coloured red.

Results and Discussion

Beam Attenuation from Fuel

Figure 3 shows the OH* chemiluminescence (top) and OH-PLIF (bottom) images from diesel fuel during the fuel injection event. This was the imaging timing corresponding to the start of combustion and the premixed burn phase (see Fig. 2) and therefore developing OH* and OH-PLIF signals were expected. From the OH* chemiluminescence images, it is clearly seen that high temperature reactions begin on the fuel jet axis and travel back towards the piston wall while spreading along the upper region of the piston bowl. This indicates that electronically excited OH radicals exist within the region between the injector and the wall impingement point. However, the OH-PLIF signals observed at 7 and 9 mm below the cylinder head do not match those of the OH* chemiluminescence signals. Signals from OH-PLIF images show a long thin front spanning across the piston bowl leaving a large dark region between the signal front and the bowl wall around the impingement point. Furthermore, the comparison between the online OH-PLIF signal (blue) and the offline OH-PLIF signal (yellow) exhibits an obvious overlap indicating that OH-PLIF signals from this crank angle timing are primarily due to interference signals. This overlap of signals continues well into later crank angle timings even when OH* signals fill up a large portion of the piston bowl.

The strong front at this timing was likely caused by fluorescence signals emitted by laser excited fuel molecules in diesel. The conventional diesel fuel used in the present study consists of approximately 25% of aromatics which plays a large part in fuel fluorescence [1]. The energy from the excitation laser entering the piston bowl was absorbed by the aromatics in diesel and used to emit strong fluorescence signal that outperformed OH-PLIF. In addition, diesel is known to have high levels of opacity for light on the UV wavelength [7]. The result is a massive reduction of laser energy at the fuel jet head, the point at which the excitation laser first makes contact with diesel fuel. This reduction in the laser beam energy led to limited emissions from OH-PLIF beyond this point, resulting in a large unknown dark region behind the wall-jet head. Figure 3 further supports this as the OH-PLIF signal front moves downward synchronised with the penetration of the fuel jet as it travels along the piston bowl floor.

The corresponding images for methyl decanoate show different results. Figure 4 shows the OH* chemiluminescence and OH-PLIF images during the injection event of methyl decanoate fuel. At this timing, the OH* chemiluminescence images depict an overall similar trend for high temperature combustion compared with diesel. The images indicate that high temperature reactions begin close to the fuel jet axis. Although the spread of high temperature reaction is faster compared to diesel, the overall distribution is similar with the high temperature reaction spreading towards the piston bowl wall.

However, when comparing the OH-PLIF and OH* chemiluminescence images, the methyl decanoate images show much greater consistency than diesel. Instead of forming a strong signal front at the fuel jet head, the OH-PLIF images for methyl decanoate illustrate a widespread signal that begins at the jet head and extends towards the bowl wall covering much of the area the fuel jet occupies. Initially, as the high temperature reaction begins there is much overlap between the interference signal and the overall signal indicating that the first column of images in figure 4 is interference dominant. However, as the high temperature reaction develops, the interference signals begin to disappear leaving little to no signal in the last image column indicating that the image is OH-PLIF dominant. The minimal interference signal is due to the lack of aromatics in methyl decanoate fuel. That is, the

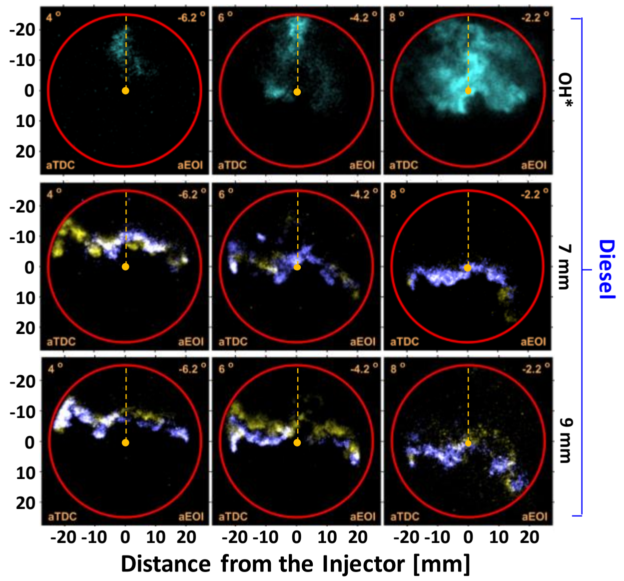

Figure 3. OH* chemiluminescence and OH-PLIF images at 7 mm and 9 mm planes for diesel combustion during the fuel injection event

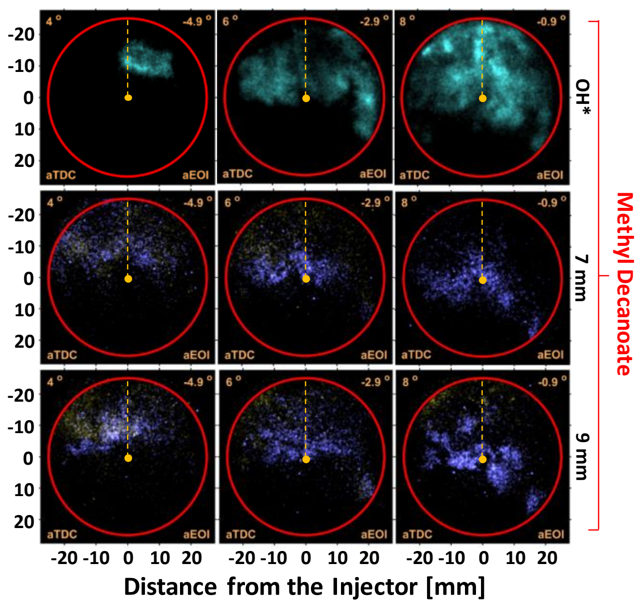

Figure. 4 OH* chemiluminescence and OH-PLIF images at 7 mm and 9 mm planes for methyl decanoate during the fuel injection event

clear depiction of OH is the result of the lack of fuel fluorescence absorbing the laser energy allowing high laser fluence levels to persist throughout the whole bowl.

Beam Attenuation from Soot

Soot is another combustion species that cause high levels of beam attenuation. The high density soot clouds absorb the excitation laser energy and use it to emit incandescence signals [1, 2, 5]. During the high temperature reaction phase as interference signals from fuel fluorescence begin to disappear, soot begins to form. In the case of diesel, there is a time overlap of fuel fluorescence disappearing and soot appearing. Figure 5 shows soot (red) forming in high quantities behind the OH-PLIF signal front during early stages of high temperature reaction. The location of the soot indicates that beam attenuation caused by soot clouds absorbing laser energy is occurring in the OH-PLIF images. Indeed, no OH-PLIF signals exist behind the high intensity soot cloud for all crank angle degrees.

The left column illustrates soot signals extended from behind the jet front towards the piston wall. However, later timings illustrate a thin soot front as opposed to a large soot cloud indicating that the laser power used in PLII imaging is not enough to penetrate the initial sooting front resulting in a large dark region behind, similar to that of the diesel OH-PLIF images. This is a problem since dark regions prevent the full understanding of the OH and soot distributions.

Methyl decanoate is an oxygenated fuel with low sooting propensities, which can be used to overcome beam attenuation issues that persist in diesel. Figure 6 shows the soot formation during the high temperature reaction phase of methyl decanoate combustion. Although the soot forms in a similar location to diesel soot, the size and intensity of the resulting soot cloud is much less. As a result, small pockets of methyl decanoate soot cloud could be visualised close to the piston bowl wall even after the soot signals develop across the jet head. This indicates that the beam attenuation is minimised allowing a high energy laser to penetrate the initial layer of soot. This lack of beam attenuation is also shown in the OH-PLIF images as there are non-overlapping OH signals appearing behind the soot front

Conclusion

Diesel is subjected to significant beam attenuation issues when diagnosed with laser based imaging techniques such as OH-PLIF.

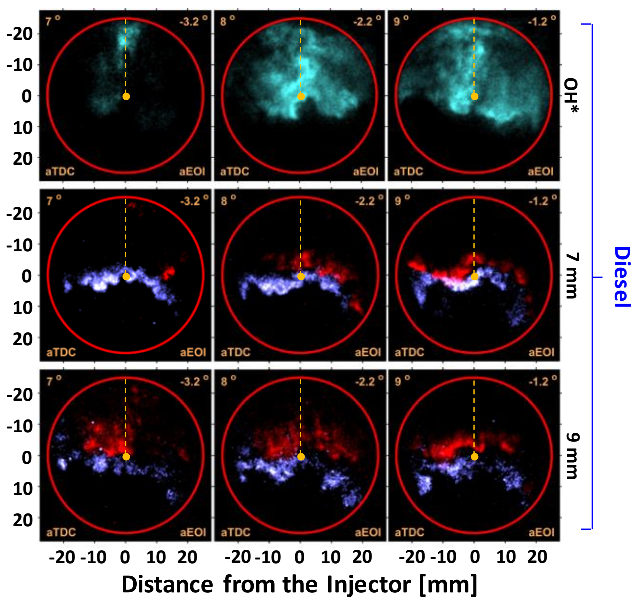

Figure 5. OH* chemiluminescence and OH-PLIF/PLII images at 7 mm and 9 mm planes for diesel combustion at the start of soot formation

During the fuel injection event liquid and vapour fuel in addition to aromatics absorb the laser energy resulting in a high intensity thin signal front at the jet head location. In later stages soot presence absorbs the laser energy further increasing the attenuation issue. These two main factors together prevent accurate representative images of diesel combustion from being taken with OH-PLIF. Methyl decanoate, while having similar combustion properties, do not have aromatics and is a low sooting fuel. This means that methyl decanoate does not suffer from beam attenuation allowing images using OH-PLIF to accurately represent the combustion event.

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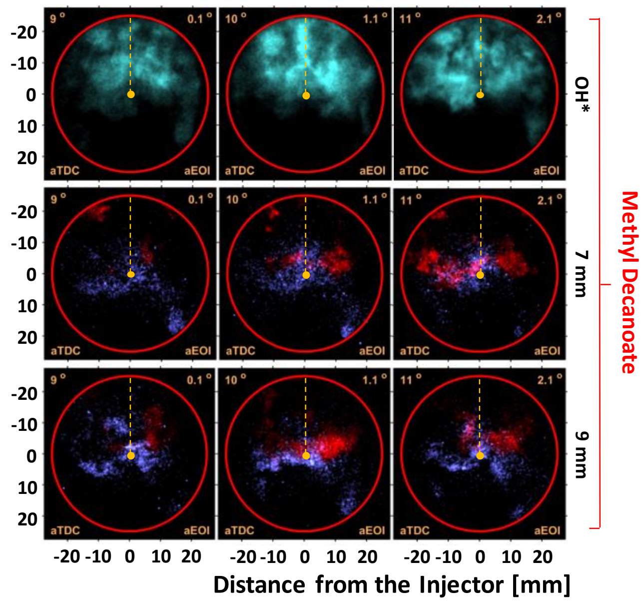

Figure 6. OH* chemiluminescence and OH-PLIF/PLII images at 7 mm and 9 mm planes for methyl decanoate combustion at the start of soot formation