

Simultaneous PLIF Imaging of OH and PLII Imaging of Soot for Studying the Late-Cycle Soot Oxidation in an Optical Heavy-Duty Diesel Engine

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ABSTRACT

The effects of injection pressure and swirl ratio on the in-cylinder soot oxidation are studied using simultaneous PLIF imaging of OH and LII imaging of soot in an optical diesel engine. Images are acquired after the end of injection in the recirculation zone between two adjacent diesel jets. Scalars are extracted from the images and compared with trends in engine-out soot emissions. The soot emissions decrease monotonically with increasing injection pressure but show a non-linear dependence on swirl ratio. The total amount of OH in the images is negatively correlated with the soot emissions, as is the spatial proximity between the OH and soot regions. This indicates that OH is an important soot oxidizer and that it needs to be located close to the soot to perform this function. The total amount of soot in the images shows no apparent correlation with the soot emissions, indicating that the amount of soot formed is a poor predictor of the emission trends.

CITATION: Lind, T., Li, Z., Micó, C., Olofsson, N. et al., "Simultaneous PLIF Imaging of OH and PLII Imaging of Soot for Studying the Late-Cycle Soot Oxidation in an Optical Heavy-Duty Diesel Engine," *SAE Int. J. Engines* 9(2):2016, doi:10.4271/2016-01-0723.

INTRODUCTION

Soot emissions from diesel engines are the net result of formation and oxidation of soot in the cylinder. Under conditions where the soot formation can be substantially suppressed it plays an important role for the soot emissions [1,2,3]. Under most conditions the soot formation cannot be suppressed, however, and the parameters associated with it then show negligible correlation with the soot emissions, while parameters associated with late cycle oxidation do correlate with the emissions [2,4,5]. At present, the general knowledge of the in-cylinder processes that govern the soot oxidation is limited.

Late-cycle soot oxidation has been studied in optical engines *e.g.* under variation of intake O₂ concentration [2,6] and in-cylinder flow parameters [7]. Most of these studies employ diagnostics detecting only soot and therefore provide no information about the interaction between soot and oxidizing species.

OH and O₂ are generally considered to be the most important soot oxidizers [8], where OH is likely to be dominant under fuel-rich and stoichiometric conditions while both OH and O₂ contribute under lean conditions [9]. The spatial relationship between OH and soot was studied by Dec and Kelly-Zion using quasi-simultaneous laser diagnostics during the late cycle in an optical diesel engine [10]. The

initial oxidation phase showed a large soot-containing region for each jet, surrounded by an OH region that overlapped minimally with the soot. The soot regions would later break up into smaller pockets separated by broader OH regions, suggesting that a diffusive combustion zone structure remains mostly intact during the soot oxidation process. Beyond this publication, direct studies of the late-cycle in-cylinder interaction between soot and oxidizer in diesel engines are sparse in the literature.

As the soot oxidation is largely mixing-controlled, the in-cylinder flow is of particular interest for understanding the limiting processes [11]. This is because the flow will affect the bulk transport of soot as well as the turbulent mixing between soot and oxidizer. The current study therefore focuses on how the injection pressure and swirl ratio affect the in-cylinder soot oxidation. These parameters are expected to affect both the bulk flow and the turbulence generation.

The presence of a diffusive combustion zone in the late cycle suggests that the oxidation takes place under near-stoichiometric conditions and OH should thereby be the dominant oxidizer. Planar laser-induced fluorescence (PLIF) measurements of OH are therefore carried out quasi-simultaneously with planar laser-induced

incandescence (PLII) measurements of soot in order to study the interaction between oxidizer and soot in the cylinder and its correlation with trends in engine-out emissions.

In particular, the analysis focuses on the local availability of oxidizer, as this is likely to be of central for an effective soot oxidation. For this reason, the physical proximity of soot and OH is studied in addition to the mere abundance of OH. The proximity is affected by the flow through bulk transport as well as through deformation of the soot-containing regions, since a large surface-to-volume ratio of the soot cloud would make a greater fraction of its soot particles accessible for oxidation. In this experiment the OH and soot are considered to be in proximity of each other if they are separated by less than 10 pixels, corresponding to 0.79 mm. Other variables connected with the availability of the oxidizer are also extracted from the imaging data and compared with measured soot emissions in a correlation analysis.

EXPERIMENT

Engine Specifications

The measurements were performed using an optical engine with a Scania D12 architecture. The engine was modified to have optical access to its first cylinder using a Bowditch design. The Bowditch design is the most common type of arrangement for providing optical access to the cylinder (see Figure 1). The idea is to lift the combustion chamber above the engine block by using a piston extension and supporting the cylinder head on extension supports. This allows enough room to place a slanted mirror (usually at 45 °) angle underneath the optical piston.

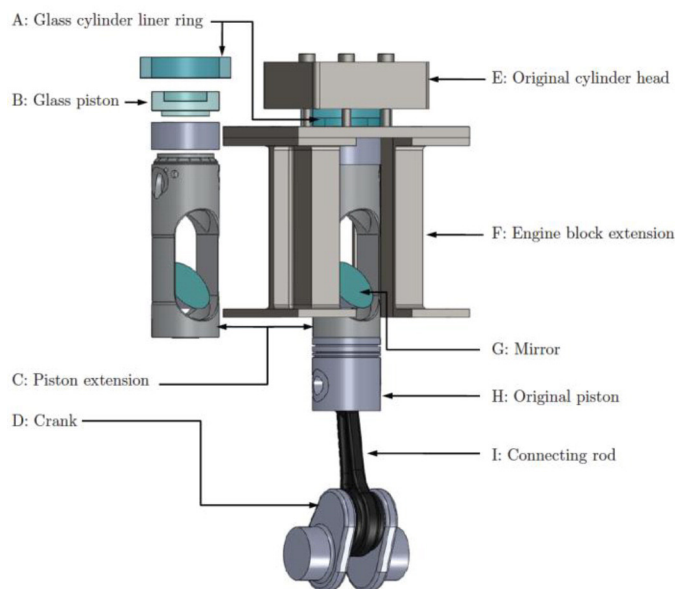


Figure 1. A sketch of the Bowditch design used in this experiment [12]

The other five cylinders are fitted with tungsten weights to compensate for the extra weight of the optical piston and the piston extension. By adding the tungsten weights a well-balanced engine

configuration was achieved. The engine is motored by an electric motor from ABB. Further details of the engine can be found in Table 1 and Table 2.

Table 1. Engine and Injection system specifications

Engine Type	Scania D12 DI Diesel
Bore	127 (mm)
Stroke	154 (mm)
Compression ratio	15 (-)
Displacement	1.95 dm ³

Table 2. Injector and Injection system specifications

Injection system	XPI common rail
Number of holes	8 (-)
Hole diameter	0.175 (mm)
Flow number	207 (pph)
Fire deck angle	17 (°)

Analysis grade *n*-heptane (>99 % purity) was used as fuel to minimize the potential background from fuel components that could otherwise fluoresce at the OH wavelengths. To further minimize this risk a stock Scania injector was modified for use with ethanol-like fuels to avoid contaminating elements, such as deposits from rubber gaskets that could otherwise be release into the fuel. The fuel was also mixed with 1.5 ml of Synfluid PAO 7 cSt and 1.5 ml of Synfluid PAO 9 cSt per litre of *n*-heptane, the specifications of which can be found in Table 3. The Synfluids were used only to increase the lubricity of the fuel in order to increase the lifetime of the fuel pump and similar parts. They do not share any fluorescing wavelengths with OH and will therefore not affect the images in any way.

Table 3. Fuel and additive specifications

Liquid	Density (kg/m ³)	Kinematic Viscosity @100 373 K (cSt)	Lower heating value (MJ/kg)
<i>n</i> -Heptane	0.68	0.51	44.6
Synfluid PAO 7	0.83	7	-
Synfluid PAO 9	0.84	8.9	-

The optical piston had a flat bowl design and was made out of Suprasil 2b grade quartz, which has been shown to exhibit very little fluorescence when illuminated with wavelengths down to 266 nm. Windows of the same quartz quality in the liner provided access for the laser sheets.

OH-PLIF

The laser setup used for the OH-PLIF consisted of a Continuum Powerlite DLS 9010 that was used to pump a dye laser. The laser wavelength of dye laser was tuned to 568 nm and frequency doubled to 284 nm. A Pellin-Broca prism was used to separate the 284 nm radiation from the residuals at 568 nm after the frequency doubling. The pulse length was 10 ns, the repetition rate was 10 Hz and the pulse energy was in the order of 20 mJ.

The wavelength of 284 nm is used to excite OH's Q1 (9) line of the $A^2\Sigma^+-X^2\Pi$ (0,1) system. The reason to use this line instead of the Q1 (8) is that its emission is stronger while still featuring only a moderate temperature dependency. The excited OH will relax back to the ground state through fluorescence in a wavelength band centred at roughly 310 nm.

The OH signal was detected using a PI-max 3 ICCD camera (Princeton Instr.) fitted with an achromatic B. Halle UV lens ($f=+100$ mm, $f\#2$). The OH-PLIF signal at 310 nm was separated from the PLII signal wavelength using a customized beam splitter with a reflection rate of 99.99 % in the wavelength band between 287 and 335 nm and 90 % transmission above 400 nm. A 300 nm long pass filter together with a UG11 filter was used to further decrease the amount of background signal detected. Further details on LIF can be found in [13].

PLII

Laser-induced incandescence is a technique for measuring soot concentrations, based on the detection of the thermal emission induced by heating soot particles with a laser pulse [14]. The LII signal is roughly proportional to the soot concentration [15], and the technique is often used for two-dimensional imaging, so-called Planar LII (PLII).

A Quantel Brilliant B Nd:YAG laser was used for the PLII measurements. Using the fundamental wavelength (1064 nm) instead of the frequency-doubled wavelength (532 nm) largely avoided absorption and background fluorescence from PAH molecules, which could otherwise potentially interfere with the LII signal. The pulse energy was <200 mJ and the dimensions of the laser sheet were ~ 0.5 mm thick and ~ 20 mm wide. This was experimentally verified to provide high enough irradiance to reach the so-called plateau region, where the LII signal becomes independent of the pulse energy [9]. By choosing a laser irradiance slightly above the threshold to the plateau region, some absorption of the laser pulse energy by the soot can be accepted without losing LII signal, hence leading to two-dimensional soot images with minor influence from absorption along the laser beam propagation direction.

The LII signal was detected using a PI-max II camera (Princeton Instr.) and to suppress the natural background flame luminosity and chemiluminescence a 425 nm short pass filter was placed in front of the CCD camera.

Combining PLIF and PLII

The 284 nm OH-LIF and the 1064 nm LII laser sheets were formed using a +1000 mm cylindrical lens after which a telescope setup of optics were used to create laser sheets of 20 mm width and 0.5 mm thickness. The laser sheets were superimposed using a dichroic mirror and the horizontal imaging plane was positioned 17 mm below the firing deck in the engine. Figure 2 shows an overview of the optical setup used in this experiment.

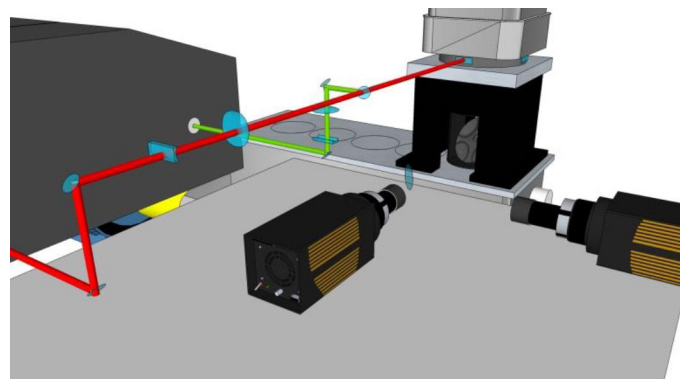


Figure 2. An overview of the optical setup used in the experiment.

When the engine stabilized at 1200 rpm, both lasers were synchronized with the engine at 10 Hz. Since the LII laser pulse is more invasive than the OH-LIF laser pulse, and since the LII signal has a longer duration, the PLII laser was triggered 1 μ s later than the OH-PLIF laser, as can be seen in Figure 3. This delay is sufficient to avoid overlap with the short-lived OH-LIF signal, and still short enough for the measurements to be considered quasi-simultaneous. The cameras were only operated in the fired cycles. Both the PLII camera and the OH-PLIF camera were triggered by the two laser Q-switches and had exposure times of 50 ns and 70 ns, respectively.

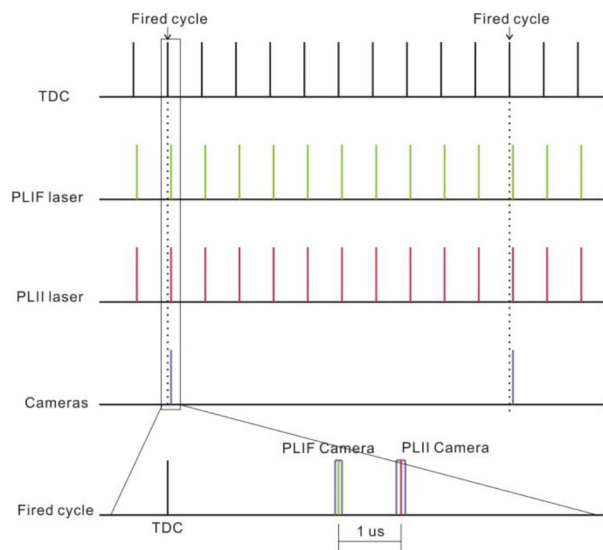


Figure 3. The synchronization scheme used for the optical measurements.