

Soot Quantification of Single-Hole Diesel Sprays by Means of Extinction Imaging

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ABSTRACT

A radiation-based 2-color method (2C) and light extinction imaging (LEI) have been performed simultaneously to obtain two-dimensional soot distribution information within a diesel spray flame. All the measurements were conducted in an optically accessible two-stroke engine equipped with a single-hole injector. The fuel used here is a blend of 30% Decane and 70% Hexadecane (in mass). According to previous research, operating conditions with three different flame soot amounts were investigated.

The main purpose of this work is to evaluate the two soot diagnostics techniques, after proper conversion of soot-related values from both methods. All the KL extinction values are lower than the saturation limit. As expected, both techniques show sensitivity with the parametric variation. The soot amount increases with higher ambient gas temperature and lower injection pressure. However, the LEI technique presents more sensitivity to the soot quantity. Differences in the KL value on the spray axis between LEI and 2C increase with higher soot quantity.

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INTRODUCTION

Because of its outstanding power performance, fuel economy and reliability, the diesel engine is widely used in power systems around the world. However, particulate matter (PM) emissions formed in the combustion of diesel engine not only have negative impacts on human health and environment, but also make exhaust after treatment system necessary. Therefore, reducing PM emission to meet the strict regulations is a significant challenge for engine researchers. As the major contributor to PM emissions, soot formation and oxidation processes during combustion is still not well understood. In recent years, in order to have a better understanding of the soot processes in diesel combustion, optical diagnostics have been extensively applied.

One of the characteristics of diesel combustion is its high luminosity caused by the thermal radiation of soot particles at high temperature. Based upon radiation measurement, 2C has been developed and used to quantify the temporal and 2D spatial evolution of the soot distribution and corresponding temperature [1, 2, 3, 4, 5, 7, 8], although there is a high uncertainty for the KL factor of the soot with this method [5, 6].

Laser-induced incandescence (LII) is another 2D soot distribution diagnostic technique based on the soot thermal radiation. The soot particles are heated to a temperature well above the surrounding gas temperature due to the absorption of laser energy. The heated soot particles subsequently emit blackbody radiation corresponding to the

elevated soot particle temperature. LII is able to qualitatively visualize the soot spatial distribution [9, 10, 11, 12, 13]. However, the drawback of LII associated to hardware limitations of conventional measurement systems is that usually only one image per injection can be recorded, and accordingly information about the temporal evolution of soot during a single injection event is difficult to resolve, unless highly sophisticated laser sources and imaging systems are used [14].

Besides these techniques based on the thermal radiation of soot, another group of techniques are derived from the attenuation of light which is caused by absorption and scattering from the soot particles. Very often a point continuous laser is used in the so-called Laser-Extinction Method (LEM) [15, 16, 17]. After passing through the soot cloud, the laser beam is collected by an integrating sphere with a photodiode to measure the transmitted signal intensity. It is a simple and accurate way to measure soot process with a good time evolution. But it cannot get detailed information of the soot spatial distribution. However, with the availability of improved high speed cameras and light sources, a high-speed imaging extinction technique has been recently developed [18, 19]. Compared with LEM, the light source is supplied by a bundle of diffused rays which cover the whole spray area and the collection section is replaced by a high speed camera. Thanks to the wider illumination background, and especially to the fact that its diffuse nature allows reducing light steering effects [18, 19], both good spatial and time resolution can be achieved. This technique is called LEI (Light Extinction Imaging) in the present paper.

The objective of this work is to compare LEI and 2C performance when measuring soot amount both on temporal and spatial evolution under different operating conditions and find the advantages and limitations of each of them.

Including the present introduction, this document is composed of four sections. The experimental section presents the test rig, test matrix and optical setup applied in this research. A detailed description of the LEI method is elaborated in this section, and it is validated by LEM methods obtained in previous studies. Next, a KL temporal evolution of LEI together with the comparison between 2C and LEI techniques is presented in the results and discussions section. Finally, the last section summarizes some of the most important conclusions of this investigation.

EXPERIMENTAL SETUP

Test Rig

An optically accessible single cylinder two-stroke engine with three-liter displacement and low rotational speed has been used for these experiments, which is described in detail in [20]. A cylindrical combustion chamber is designed with a diameter of 45mm. This chamber has one upper access for the fuel injector, and four lateral orthogonal accesses. One of them is currently used for the pressure transducer whereas the other three are equipped with optical windows with geometrical dimensions of 88×37 mm and 28 mm thick. The Cross-sectional view of cylinder head is shown in Figure 1. During the engine operation, the block temperature is controlled by an external heating-cooling system while the in-cylinder thermodynamic conditions are regulated by the intake air temperature and pressure thanks to the electrical resistors and air compressor respectively. An injection takes place every 30 cycles, which guarantees that there is no remaining residual gas from previous combustion cycles and the ambient conditions in the chamber are kept constant between consecutive repetitions. A commercial common-rail piezoelectric injector equipped with a single-hole nozzle of 0.14 mm diameter has

been applied in this study. Thanks to the injector holder cooled with the engine and the low injection frequency during operation, the nozzle tip temperature can be considered constant.

Test Matrix

The fuel used in these tests is a two component blend of 30% Decane and 70% Hexadecane (percentages in mass). Considering that the object of this paper is to compare the two different optical diagnostic techniques, the test matrix includes 3 operating conditions that have been selected from a wider previous study [21] and have been denoted as High Soot (HS), Middle Soot (MS) and Low Soot (LS) conditions. Injection pressure and chamber temperature at the top dead center (TDC) have been modified while keeping constant in-cylinder pressure at TDC and oxygen concentration. It is well known from previous research [15,17,18] that soot formation will decrease with higher injection pressure and lower ambient temperature. The energizing time was set as 2ms, and the actual injection duration was approximately 4ms. For each operating condition, 20 injections have been recorded to reduce measurement uncertainties due to engine operating variability.

Table 1. Experimental conditions

Operating conditions	P_{inj} [bar]	P_{TDC} [bar]	T_{TDC} [K]	Oxygen Concentration
HS	500	53	870	21%
MS	1500	53	870	21%
LS	1500	53	782	21%

Optical System

The optical system has been designed so that simultaneous high speed 2C and LEI measurements can be realized. The arrangement of the optical setup is shown in Figure 2.

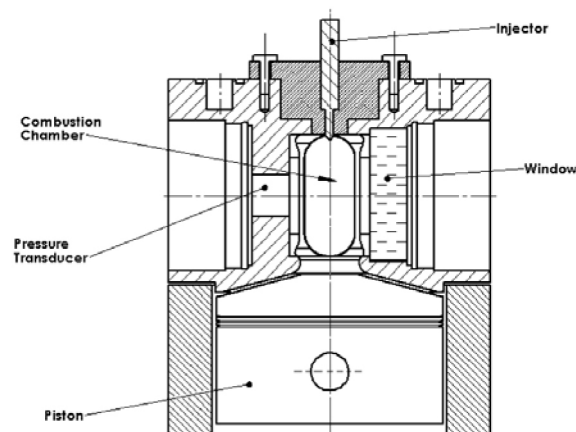


Figure 1. Cross-sectional view of cylinder head

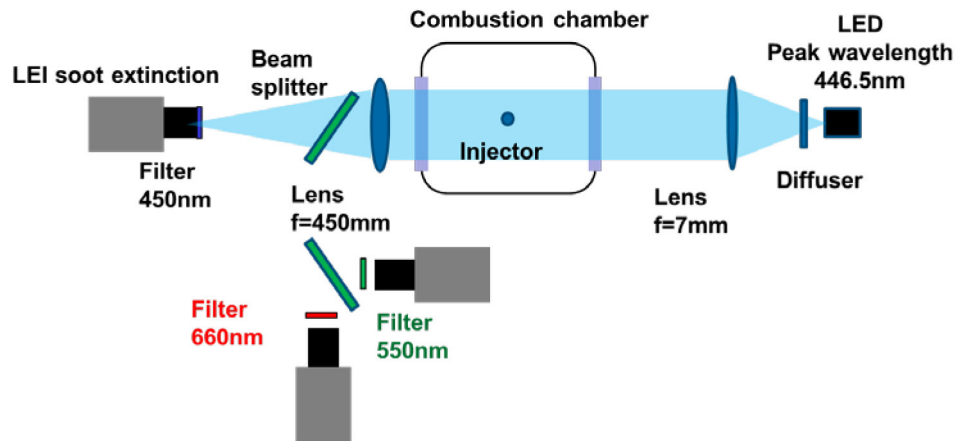


Figure 2. Schematic of the optical setup

2-Color Method

The 2C was realized using two high-speed CMOS cameras and two bandpass filters (centered at 550 nm and 660 nm, both with 10 nm FWHM). After passing through a collecting spherical lens ($f=450\text{mm}$), the light emitted by the soot cloud crossed the first beam splitter, which transmits 50% of the intensity to the LEI camera, while the other 50% is reflected into the 2-Color system. Then, another beam splitter (50%/50%) is applied to distribute the remaining soot radiation equally into the two CMOS cameras. In order to make a comparison between LEI and 2C results at the same time during the same injection, all three cameras need to be synchronized. To ensure a better synchronization, all cameras employed here are identical (Photron SA-5), running with the same frequency at 20 kHz. One of the 2-Color cameras was set as the master camera while the other one and the LEI camera were set as slave cameras.

The 2C assumes that the flame radiation (with uniform spatial temperature and soot distributions) depends on the wavelength, the temperature and the amount of soot. The soot radiance I_{soot} can be expressed as follows:

$$I_{soot} = \varepsilon \cdot I_b \quad (1)$$

where the black-body radiance I_b can be written from Planck's law:

$$I_b(\lambda, T) = \frac{1}{\lambda^5} \frac{c_1}{\left[\exp\left(\frac{c_2}{\lambda T}\right) - 1 \right]} \quad (2)$$

and the emissivity ε can be obtained using the empirical correlation developed by Hottel and Broughton (1932):

$$\varepsilon(KL, \lambda) = 1 - \exp\left(\frac{-KL}{\lambda^\alpha}\right) \quad (3)$$

where c_1 and c_2 are constants, the KL is the optical thickness calculated from 2-color method.

In order to transform grey levels into radiance values, calibration curves have been obtained by means of a tungsten-ribbon calibration lamp (Osram W17G), which was located at the same distance from the 2-Color cameras as the distance between the cameras and flame in the combustion chamber.

LEI Method

The LEI optical setup can be divided in two different sections, which are referred to as the illumination and collection sides. On the illumination side, a high-output blue LED with a Peak wavelength 450nm was applied here as the light source. A LED pulse duration of 0.9us was used here to “freeze” the soot fields within high velocity fuel jet. The light passed through a diffuser to create a diffused Lambertian intensity profiles. Behind the diffuser, a Fresnel lens ($f=7\text{mm}$) was mounted to magnify the visualization area so that it can cover the whole optical access window.

On the collection side, the transmitted light of the LED and the thermal radiation from the combustion are collected by means of a spherical lens ($f=450\text{mm}$) to make sure the size of the images focused on the lens of the camera is smaller than the lens. What's more, it also can reduce the effects of beam steering. After going through the beam splitter as mentioned above, the light was finally collected by a high-speed CMOS camera (Photron SA-5, recording at 20kHz) equipped with a bandpass filter (450nm, 10 FWHM). The exposure time of the camera was set to 6.96us with 416×896 pixels image resolution and the pixel/mm ratio is 10.

The light intensity detected by the camera includes two parts: the transmitted LED light intensity and the flame intensity. Due to the use of an interference filter, the crosstalk of flame radiation into the LEI camera is minimized in the visible wavelength range. However, the flashing frequency of the LED was set as half of the camera frame rate to capture an image between every two successive LED pulses, so that flame luminosity can be quantified and this information used to get the correct transmitted LED light. The schematic of LED synchronization is shown in Figure 3.