

Parameters Influencing Soot Oxidation Rates in an Optical Diesel Engine

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ABSTRACT

Soot emissions from diesel engines are the net result of two competing processes: soot formation and soot oxidation. Previous studies have shown poor correlation between soot formation rates and the soot emissions. This article presents a systematic study of a number of parameters affecting soot oxidation rate and how it correlates with the soot emissions. An optical heavy-duty engine is used in conjunction with a laser extinction setup in order to collect time resolved data of the soot concentration in the cylinder during the expansion stroke. Laser extinction is measured using a red (685 nm) laser beam, which is sent vertically through the cylinder and modulated to produce 10 pulses per crank angle degree. Information is obtained about the amount of soot formed and the soot oxidation rate. The parameters studied are the motored density at top dead center (TDC), motored temperature at TDC, injection pressure, engine speed, swirl level and injector orifice diameter. A central composite design is employed to assess the importance of the parameters as well as identifying potential interaction effects. A single exponential decay function is fit to the extinction data to describe the oxidation process and the half-life of the decay is used as a measure of the oxidation rate. The half-lives are compared with engine out emissions and the importance of each parameter is studied using regression analysis. The results suggest that the injection pressure has the strongest effect on the late-cycle soot oxidation rate, while the temperature at TDC has the weakest effect of the parameters studied.

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INTRODUCTION

Diesel engines are widely used in the transport sector due to their high efficiencies, but they suffer from significant emissions of nitrogen oxides (NO_x) and particulate matter (PM). The latter mostly consists of combustion-generated soot [1,2] and is connected with respiratory and cardiovascular diseases [3]. As soot particles are efficient light absorbers, they are also identified as major short-lived climate forcers (SLCF) and may also affect the climate by acting as condensation nuclei for cloud formation [4]. Despite a strong mitigation of PM emissions by diesel particulate filter reducing soot emissions from engines still represents an important challenge for the automotive industry.

PM and NO_x are treated in tandem due to the fact that reducing emissions of one will often increase the emissions of the other [5,6,7]. In the cylinder, NO_x emissions can be reduced by lowering combustion temperatures [5,6]. PM emissions can be reduced by improving their oxidation during the combustion process. Previous studies have shown that reducing the formation of soot did not correlate with a reduction of soot emissions [8,9]. However, several studies have highlighted the importance of soot oxidation for the exhaust soot levels [10,11,12,13,14]. The late-cycle soot oxidation is expected to depend on a number of factors as described below.

Dilution with EGR strongly impacts the flame temperature [5,15]. The temperature has a strong effect on the soot oxidation, but also the reduced availability of oxidizers will inhibit the oxidation process. Gallo *et al.* showed that a reduction in intake oxygen concentration from 21 % to 9 % resulted in a gradually slower oxidation [10], which correlated well with a steady increase in soot emissions, at least until soot formation was severely inhibited by the reduced combustion temperature.

Temperature generally has a strong influence on chemical reaction rates. In the case of soot, the rate of soot oxidation will increase faster with temperature than the rate of formation [16,17]. In this study, the effect of the gas temperature at top dead center (TDC) is evaluated. It is expected to have a smaller impact on the flame temperature than the intake oxygen concentration, but could still affect the soot oxidation.

For a given oxygen concentration, the gas density should affect the soot oxidation by increasing the number of oxidizer molecules per unit volume. In order to separate the density effect from that of temperature, it is varied by changing the inlet pressure in this study.

Since the late-cycle soot oxidation is a mixing-controlled process it can be enhanced by increasing the turbulent kinetic energy in the bulk gases. This can be done by increasing the injection pressure, which will create more energetic bulk-flow structures in the cylinder [18]. It can also be achieved by increasing the engine speed, as the in-cylinder turbulence scales linearly with engine speed [5]. Yet another

way is to increase the swirl level [19,20]. A higher swirl level implies a fuel-air mixing improvement, nonetheless, this well-known effect can be mitigated by an excessive sprays interaction which leads to a particular rich equivalence ratio and therefore higher soot emissions [21,22].

In this study, in-cylinder soot oxidation rates are investigated using laser extinction measurements. The technique has been successfully used in a prior experiment where oxidation rates were studied during a sweep in intake oxygen concentration [10]. Here, the parameters discussed above are systematically varied using a central composite design (CCD) in order to identify their respective importance as well as potential interaction effects. The parameters are the motored gas density at TDC, the motored gas temperature at TDC, the injection pressure and the engine speed. The swirl and injector orifice diameter are also varied but are not included in the CCD. The objective is to identify the parameters that are most important for the soot oxidation rates and soot emissions. Fitting exponential decay functions to the extinction curves and extracting their half-lives gives a measure of the oxidation rates. These half-lives are then used to highlight how well oxidation rates correlate with exhaust soot levels.

LASER EXTINCTION TECHNIQUE

The laser extinction technique is a quantitative measurement technique for soot that has been applied successfully for several decades in IC engines [10, 23,24,25] as well as in spray vessels [26,27,28]. The intensity of a laser beam decreases as it passes through a region containing soot. The initial and transmitted intensities, I_0 and I , are measured and, assuming that the in-cylinder soot is an optically thin medium, the Beer-Lambert law applies:

$$I = I_0 e^{-KL}, \quad (1)$$

Here, K is the extinction coefficient and L is the length of the absorbing medium, in this case the vertical extent of the combustion chamber. Extinction is any process that prevents the initial intensity from reaching the detector, and is thus a combination of absorption and scattering of light out of the beam path. In the Rayleigh limit, where the particle sizes are much smaller than the laser wavelength, the scattering is assumed to be negligible and $K \approx K_{abs}$ [29]. Under this assumption, the extinction coefficient is a function of the soot volume fraction, f_v , according to:

$$K = \frac{f_v 6\pi E(m)}{\lambda}, \quad (2)$$

where λ is the laser wavelength and $E(m)$ is the refractive index function, representing the imaginary part of $(m^2-1)/(m^2+2)$, in which m is the complex refractive index of the soot particles, see for example [30]. Throughout this paper, the soot concentration is presented as KL . This product is directly related to the average soot concentration through the cylinder, and is derived directly from the relative transmission measurement. Hence this product has a certain value for a specific soot concentration in the cylinder even during

piston movement (assuming constant soot concentration along the diode-laser beam path). The decrease of KL under these assumptions can be related to net oxidation of the soot in the cylinder.

A diode-laser wavelength of 685 nm is chosen. This wavelength is in the visible spectral region (400-700 nm) facilitating alignment of the laser and detection system. The choice of a long wavelength in this region, close to 700 nm, is two-fold. Firstly, it minimizes influence from polycyclic aromatic hydrocarbons (PAHs), which are known to absorb radiation in both the ultraviolet and visible spectra regions [30,31,32]. Secondly, a longer wavelength also minimizes potential scattering contribution from the soot to the extinction measurements.

Due to the size of typical soot particles from diesel engines, the assumption that the extinction coefficient is equal to the absorption coefficient might not be entirely safe. However, given the uncertainties in the measurements and assumptions, potential scattering contribution will not influence the conclusions from this work.

EXPERIMENTAL SETUP

The engine used for this study is a heavy-duty direct-injection diesel engine based on a Scania D12 operated as a single-cylinder engine. A Scania XPI common-rail fuel injection system capable of injection pressures up to 2500 bars is used. Two injectors are used, including a stock injector with eight nozzle holes and a prototype injector with smaller holes. The fuel used is Swedish MK1 diesel. The base swirl level is 1.6 and a second swirl level of 5.9 is studied by adding flow plates to the inlet manifold which obstruct the 2 inlet ports, one fully and one partially. The engine, fuel system and fuel specifications are given in Table 1.

Table 1. Engine, fuel system and fuel specifications

Engine base type	Scania D12 DI diesel	
Bore	127 mm	
Stroke	154 mm	
Comp. Ratio	16	
Swirl	1.6	5.9
Displacement	1.95 l	
Injection system	XPI common rail	
Nozzle flow number	207 pph	70 pph
Number of holes	8	
Firedeck angle	17 °	16 °
Hole diameter	0.175 mm	0.1 mm
Fuel type	MK1 Diesel	
Cetane number	51	
Density	815 kg/m ³	
Lower Heating Value	42.9 MJ/kg	
Carbon/Hydrogen	0.53	

The inlet air is conditioned in terms of pressure and temperature using a two-stage compressor and an inlet heater. A diesel furnace operated at stoichiometric conditions is used as a stable external source of EGR. The exhaust soot levels are measured using a gas particle sensor [33].

The cylinder pressure is recorded through a 5 mm long duct leading to the combustion chamber roof with a side-mounted Kistler 6125C transducer. For each point of operation the duration of injection is adjusted to match the accumulated heat released. In order to maintain comparable in-cylinder conditions the start of injection is adjusted in order to keep the combustion phasing constant. A more detailed overview of the operating conditions is developed in the Experimental design part and is summarized in [table 2](#) and [3](#).

The engine has Bowditch-type optical access [34]. The piston extension has a full quartz piston top and a 45° mirror in a fixed position below it. An insert containing an angled window is used in lieu of one of the exhaust valves, providing optical access from the top of the cylinder. The angle of the window compensates for the angle of the optical access and makes it possible to obtain a vertical beam path through the cylinder. A cross-section of this optical access is given in [Figure 1](#). The absence of one exhaust valve does not substantially affect the combustion process since the engine is running relatively slowly at a maximum of 1200 rpm, allowing for effective gas scavenging.

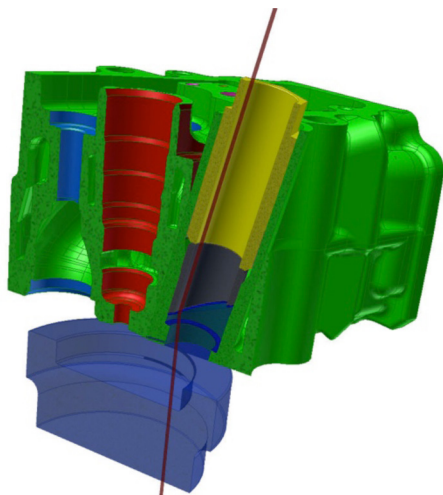


Figure 1. Cross section of the optical cylinder head and piston. In red is the location of the injector, the yellow and gray part is the optical insert replacing one exhaust valve.

The laser-extinction setup is schematically shown in [Figure 2](#). The laser beam from a 50 mW continuous laser diode operating at 685 nm (Roithner LaserTechnik, QL68J6S-A/B/C) is collimated using an aspheric lens with focal length 4.51 mm, directly mounted on the temperature-controlled laser diode mount (Thorlabs TCLDM9). This provided an approximately collimated laser beam with a beam width and height of 4 and 2 mm, respectively. The laser mount is connected to controllers for diode case temperature (Thorlabs TED200) and driver current (Thorlabs LDC205C).

To obtain crank-angle resolved data the laser is intensity-modulated using an acousto-optic modulator (AOM) from AA Opto-Electronics (MT80 - A1.5), controlled using a driver from the same

manufacturer (MODA80-1). The engine's crank angle encoder sends a signal every 0.2 CAD and by using a Pulse Generator (Berkeley Nucleonics model 575) producing two pulses for each trigger input, an approximate resolution of 0.1 CAD is achieved. For the engine running from 900 to 1200 rpm this translates into a laser modulation frequency of 54 to 72 kHz.

The laser beam is divided into two beams with a beam splitter prior to entering the engine and after the AOM. By using two photodiodes (Thorlabs PDA100A-EC), one measuring the attenuated signal and one a reference signal, the effect of laser intensity variation could be minimized. This is possible by measuring a calibration constant, making the reference beam intensity proportional to the incident laser light intensity. The constant is measured during an engine cycle without injection in close proximity to the injection cycle where the soot measurement is taken, giving an individual calibration value for each 0.1 CAD (i.e. every laser pulse measured). It also ensures that variations in the transmission characteristics e.g. due to flame luminosity and window fouling during the engine cycle are taken into account. Nevertheless, to minimize the effects of background radiation, three filters are mounted on the photodiode measuring the transmitted laser beam; one short pass filter with cut-off wavelength 700 nm (Thorlabs, FES0700) and two long pass-filter with cut-on wavelength of 650 nm (Thorlabs, FEL0650) and 665 nm (Schott, RG 665). This created a relatively narrow bandpass between 665 and 700 nm that did not fully suppress the background radiation. The remaining background contribution is removed during post processing, making use of the sequential background measurement points between the laser pulses. Further details about the setup as well as assessments of inaccuracy due to beam steering can be found in [10].

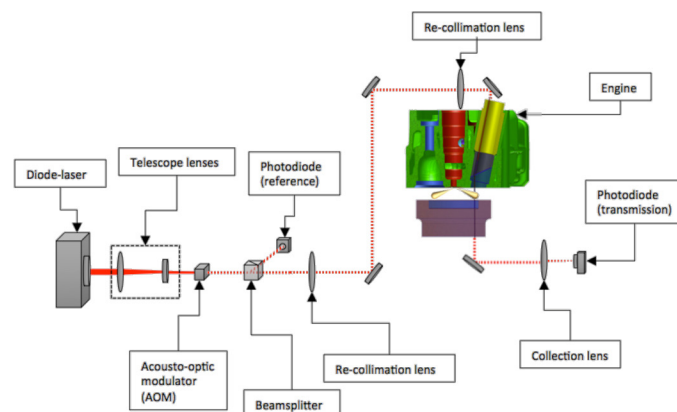


Figure 2. Optical setup for laser extinction measurements.

[Figure 3](#) shows one image from a high-speed video taken during this experiment. In the image, NL is recorded. The white circle represents the piston bowl wall and the red dot roughly shows the laser location during the experiments.

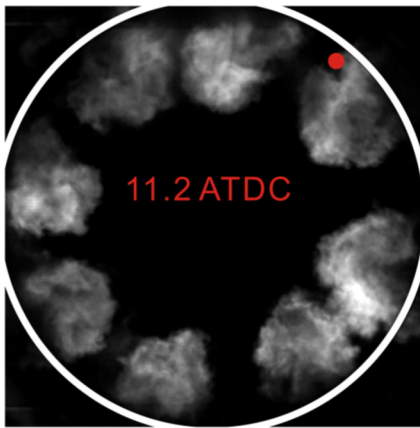


Figure 3. Natural luminosity image at 11.2 CAD ATDC was taken through the optical access. The white circle represents the piston bowl wall and the red dot is the position of laser.

Soot is first transported into the beam by the spray. It is then transported along the floor towards the center (out of path). Due to the centrifugal force and reverse squish flow it is then transported upwards outwards towards the squish region. Some of the parameters studied could affect the trends because of transport of PM out of the laser beam by affecting the radial fluid flows such as the injection pressure variation. Other parameters like temperature or density at TDC do not affect the radial flow. However, the trends observed are coherent to an oxidation process. And the clear correlation between oxidation rate and exhaust PM highlighted in this study further strengthen this assumption. Further discussions about the limitations of the technique can be found in [35].

EXPERIMENTAL DESIGN

To ensure the integrity of the optical parts, the engine is operated at a low load of 5 bars IMEP_g. The start of injection (SOI) is adjusted to keep the combustion phasing (CA50) constant for all points of operation at 9 CAD after top dead center (ATDC). CA50 is the crank angle position where 50% of the total heat has been released. Due to some limitations of the injection control system, The CA50 can vary around the target value. The start of injection (SOI) is carefully chosen to have the CA50 as close as possible to 9CAD ATDC. The duration of injection (DOI) is adjusted for each measurement in order to obtain the same cumulative heat release (CHR) of 1700 joules (J). In order to produce sufficient amounts of soot for the purposes of the experiment, the EGR is adjusted to obtain an intake O₂ concentration of 15 %. Swedish Diesel (MK1) is used for all measurements as well as in the furnace used as an external source of EGR. The standard swirl level of the engine is 1.6. One point of operation is measured with a swirl level of 5.9. The standard injector for this study has a nozzle of 0.175 mm. A measurement is also made with a smaller nozzle (0.1 mm). A summary of the general operating conditions can be found in the [table 2](#).

Table 2. Summary of generic operating conditions. The values between parenthesis for swirl and injector nozzle correspond to extra measurements.

Operating conditions	
Load	5 bars IMEP _g
CA50	9 CAD ATDC
SOI	Adjusted to keep CA50 @ 9 CAD ATDC
DOI	Adjusted to keep ARoHR @ 1700J
EGR rate	15% O ₂
Fuel	MK1 Swedish Diesel
Swirl	1.6 (5.9)
Injector nozzle	0.175 mm (0.1mm)

The study of the most relevant parameters is conducted using a central composite design (CCD). The interest of such a design is that it supports fitting a quadratic model to the data while separating the effects of each parameter as well as identifying potential interactions between them [36]. This design of experiment revolves on the symmetrical variation of various parameters around a center point. In coded values “-1”, “0” and “+1” where “-1” represents the lower variation of the parameter, “+1” the higher variation and “0” is halfway through as reference base value. From this design of experiment, three sets of data are typically recorded. The first one is the set comprised of the corner points where all parameters are varied following their extreme values (“-1” and “+1”). The second set is the central point where all parameters are set to their base value (“0”). The third and final set is the axial points, where a single parameter is varied while the others are kept at their base value.

The engine speed is varied from 900 rpm up to 1200 rpm by steps of 75 rpm. The modulation frequency of the laser is adjusted accordingly in order to keep a temporal resolution of 0.1 CAD. The injection pressure is varied from 1000 bars up to 2000 bars by steps of 250 bars. Temperature and density at TDC represent the conditions of the gases without injection and combustion processes. The temperature at TDC is swept independently of density by adjusting inlet temperature and pressure. The values are obtained using the ideal gas law and adiabatic compression estimations. The inlet temperature is varied between 80°C and 160°C. Finally, the density at TDC is varied from 15.2 up to 22.8 kg/m³ independently of the temperature by adjusting the inlet pressure following the same method of estimation as for temperature.

A summary of the CCD can be found in [table 3](#). The CCD will allow a linear regression analysis. To be able to compare the effects of the factors the data are subjected to unit-variance scaling before fitting the regression model. This means that all factors are rescaled to have mean zero and range from -1 to 1. Thereby the actual unit of the factor does not affect the size of its coefficient in the model. Without unit-variance scaling, a given variation in injection pressure, for instance, would yield a different coefficient if the pressure were measured in Pa instead of bars.