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Investigation of late-cycle soot oxidation using laser extinction and in-cylinder gas sampling at varying inlet oxygen concentrations in diesel engines

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HIGHLIGHTS

- Optical and in-cylinder sampling data show a slower soot oxidation when inlet oxygen is reduced.
- Reduced intake O_2 lowers the maximum adiabatic flame temperature limiting OH production.
- The results point towards OH being the dominant oxidizer under diesel combustion.

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ABSTRACT

This study focuses on the relative importance of O_2 and OH as oxidizers of soot during the late cycle in diesel engines, where the soot oxidation is characterized in an optically accessible engine using laser extinction measurements. These are combined with in-cylinder gas sampling data from a single-cylinder engine fitted with a fast gas-sampling valve. Both measurements confirm that the in-cylinder soot oxidation slows down when the inlet concentration of O_2 is reduced. A 38% decrease in intake O_2 concentration reduces the soot oxidation rate by 83%, a non-linearity suggesting that O_2 in itself is not the main soot oxidizing species. Chemical kinetics simulations of OH concentrations in the oxidation zone and estimates of the OH-soot oxidation rates point towards OH being the dominant oxidizer.

1. Introduction

Diesel engines are favored by high efficiencies but are challenged by high emissions of nitrous oxides (NO_x) and particulate matter (PM), if not coupled with adequate exhaust aftertreatment technologies such as NO_x adsorbers and diesel particulate filters (DPF). Diluting the charge by Exhaust Gas Recirculation (EGR) is a widespread method for reducing the NO_x emissions by decreasing the combustion temperature. On the other hand, EGR generally increases PM emissions due to deteriorating in-cylinder soot oxidation rates [1,2]. Previous studies indicate that, under most conditions applicable to diesel engines, this oxidation has a dominating influence on the soot emission levels [2–5].

EGR reduces the intake oxygen concentration. This has a number of potential effects on the soot oxidation process. First, it will decrease the availability of oxygen during the late cycle, which could limit the oxidation rate. It also lowers the flame temperature, slowing the chemical kinetics of the oxidation process as well as decreasing the formation of hydroxyl radicals (OH) [6], which is believed to be the main oxidizing species [7–11]. A few experimental studies have studied the impact of EGR on the soot oxidation during diesel combustion in the cylinder. For example, Payri et al. measured the PM mass, size, and number density in the exhaust gases while varying intake O_2 between 9% and 13%. Though the study was concerning low temperature combustion (LTC) strategies, they could highlight the poor oxidation affecting

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the emissions before the inhibited formation dominated the emission trends at lower O_2 inlet concentration [12]. Using the same methodology to characterize the oxidation process, Gallo et al. [2] used the decay of the optical thickness (*KL*) of the extinction signal whereas Lopez et al. [13] used the *KL* from two-color pyrometry measurements. Both studies reached the conclusion that a reduction of inlet O_2 leads to a slower soot oxidation rate. Also using two-color pyrometry, a study by Huestis et al. showed that decreasing the intake O_2 from 21% to 9% decreased the late cycle soot oxidation rates monotonically, and that the emissions followed the late cycle trends in in-cylinder soot mass [14]. While this last study pointed out the importance temperature on the oxidation process, none of these studies proposed an explanation for the mechanisms behind the reduction of oxidation rate observed at lower O_2 availabilities in the cylinder.

The purpose of this study is to cast light on the relative importance of O_2 and OH as soot oxidizers during the late cycle. It is based on data from optical measurements and in-cylinder gas sampling. The optical measurements are made using laser extinction in an optically accessible single-cylinder engine fitted with a Bowditch-type piston extender [15]. The gas sampling data are acquired from a single-cylinder engine without optical access, fitted with a fast gas sampling valve. The analysis is complemented with a simulation of OH availability in the flame using a zero-dimensional (0-D) reactor model.

2. Terminology

Different terms for soot are used in different communities. These include particulate matter (PM), soot, and black carbon (BC). PM is the generic term describing the particles contained in an aerosol. In the engine community, PM is defined as the constituents of the diluted exhaust gases that are adsorbed on a filter in a gravimetric test. In such a test, the exhausts are drawn through an efficient filter, which is weighed before and after the test. The difference in mass (due to both solid and liquid particles) is the PM mass. A soot particle is an agglomerate of roughly spherical primary particles consisting primarily of carbon. Soot is by far the dominating constituent of PM. Black carbon is roughly equivalent to soot, i.e. light-absorbing carbonaceous particles originating from combustion sources. As it is measured optically, its name derives from its optical properties. BC is a term more commonly encountered in environmental contexts like aerosol physics, atmospheric chemistry or geophysical fields. As engine-out PM mostly consists of combustion-generated soot particles, it is an accepted approximation in the automotive and combustion engineering fields to use the terms PM, soot and BC more or less interchangeably.

3. Experimental facilities

3.1. Engine setup

The engine used for the optical study is a heavy-duty direct-injection diesel engine based on a Scania D12, operated as a single-cylinder engine. A single-cylinder version of a Scania D13 is used for the in-cylinder gas sampling measurements. These engines are henceforth referred to as the optical and the all-metal engine. In order to produce as similar conditions as possible, both configurations employ the same cylinder head leading to identical swirl levels and the same injector for identical fuel flows. A Scania XPI common-rail fuel injection system capable of fuel pressures up to 2500 bar is used. The injector is a stock item with eight nozzle holes. The fuel used is Swedish MK1 diesel. Specifications of the engines, fuel system and fuel are given in Table 1.

Table 1
Engine and fuel specifications.

Engine base type	Scania D12 DI diesel	Scania D13 DI diesel
Bore	127 mm	130 mm
Stroke	154 mm	160 mm
Comp. ratio	15.6	16
Swirl	1.6	
Displacement	1.95 L	2.12 L
EGR	External	Internal
Injection system	XPI common rail	
Nozzle flow number	2174 cm^3/min	
Number of holes	8	
Firedeck angle	17°	
Hole diameter	0.175 mm	
Fuel type	MK1 diesel	
Cetane number	51	
Density	815 kg/m^3	
Lower heating value	42.9 MJ/kg	
Carbon-to-hydrogen ratio	0.53	

The two setups use different sources of EGR. On the optical engine, exhaust gases are produced using a diesel furnace operating at stoichiometric conditions. These are mixed with fresh air, heated and compressed to the desired inlet conditions in order to achieve a stable external source of "EGR". On the all-metal engine, exhaust gases are taken from the exhaust manifold and fed to the intake manifold, using flow and back pressure valves to control the flow. The intake O_2 concentration is used to measure the EGR rate. In the optical engine, it is measured during engine operation without injection by a lambda sensor located in the exhaust. For the all-metal engine, the concentration of inlet O_2 is calculated as:

$$O_{2,in} = \frac{CO_{2,in}}{CO_{2,ex}}(O_{2,ex} - O_{2,amb}). \tag{1}$$

where $O_{2,ex}$ is the exhaust O_2 concentration measured by a lambda sensor, $O_{2,amb}$ is the ambient O_2 concentration set at 20.95%. $CO_{2,in}$ and $CO_{2,ex}$ are the CO_2 concentrations of inlet and exhaust both measured using an infrared detector in an AVL AMA i60 emission system.

Another difference between the setups is the shape of the piston bowl. In the D12 engine, the bottom of the bowl is flat in order to facilitate the optical access, while the D13 engine has a slightly conical bowl bottom. As shown in Fig. 1, both configurations had open combustion chambers. These differences could cause variations in the in-cylinder flow that could affect the late-cycle mixing process. This may lead to different soot oxidation rates and, thus, different average soot emissions from the two engines. It should be noted, however, that the experiment consists in a variation in the intake oxygen concentration. This variation is the same in both engines and affects chemical aspects of the soot oxidation rather than the flow. For this reason, the trends in soot oxidation rates that result from the intake O_2 variation are expected to be the same in both engines.

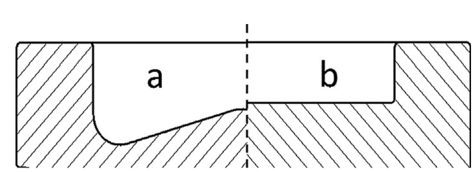

Fig. 1. Profile of the metal piston used in the D13 engine (a) and of the quartz piston used in the D12 engine (b).

3.2. Operating conditions

The engines are operated at a speed of 1200 rpm and a load of 6 bar $IMEP_g$. The EGR rate is varied in order to obtain various inlet O_2 concentrations (13%, 15% and 21%). The cylinder pressure is monitored using a side-mounted Kistler 6125C transducer coupled to a Kistler 5011B10 charge amplifier. A crank angle encoder giving 1800 pulses per revolution is used, resulting in one pulse per 0.2 CAD. The injection pressure is kept constant as well as the duration of injection (650 µs). The start of injection is adjusted in order to maintain CA50 at approximately 9 CAD ATDC. A summary of the operating conditions is given in Table 2.

In order to compensate for the difference in compression ratio, the top dead center (TDC) conditions in temperature and density are matched between the engines. This is realized by applying adiabatic compression calculations, leading to the use of a substantially lower inlet pressure on the all-metal engine. A sample motored pressure trace at 15% inlet O_2 from the optical engine is compared with a motored one from the all-metal engine without EGR in Fig. 2a. The apparent heat release rate (AHRR) from a case with combustion at 15% O_2 is shown in Fig. 2b for the two engines. The differences in thermodynamic conditions at TDC and during combustion are minor, justifying the validity of the comparison between setups.

4. Soot measurement techniques

4.1. Laser extinction method

The laser extinction technique is a quantitative measurement technique for soot that has been applied successfully in combustion engines for several decades [2,3,16–18] as well as in spray vessels [19–21]. The intensity of a laser beam decreases as it passes an absorbing medium, *e.g.* containing soot. The initial and transmitted intensities, I_0 and I, are measured and, assuming that the in-cylinder combustion medium is optically thin, the Beer-Lambert law applies:

$$I = I_0 e^{-KL}. \tag{2}$$

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 decreases the initial laser intensity, and is thus a combination of absorption and scattering of light out of the beam path. For particles with sizes much smaller than the laser wavelength, the scattering is negligible in comparison with the absorption (i.e. the Rayleigh approximation), and K is then equal to the absorption coefficient [22]. Under this assumption, K can be related to the soot volume fraction, f_v, as

$$K = \frac{f_v 6\pi E(m)}{\lambda} \tag{3}$$

Table 2
Engines operating conditions.

Operating conditions		
Engine	Scania D12 DI diesel	Scania D13 DI diesel
Speed	1200 rpm	
Load	6 bar $IMEP_g$	
P_{inj}	2000	
CA50	8 CAD ATDC	
SOI	Adjusted to keep CA50 constant	
DOI	650 µs	
Inlet P	1.8 bar	1.65 bar
Inlet T	70 °C	
Fuel	MK1 Swedish diesel	
EGR rate	Variable (13%, 15% and 21% O_2)	

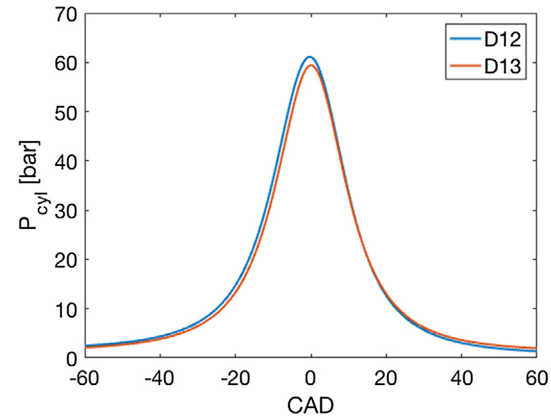

Fig. 2a. Sample motored trace for the 15% $[O_2]$ case. The D13 trace (all-metal engine) is recorded without EGR.

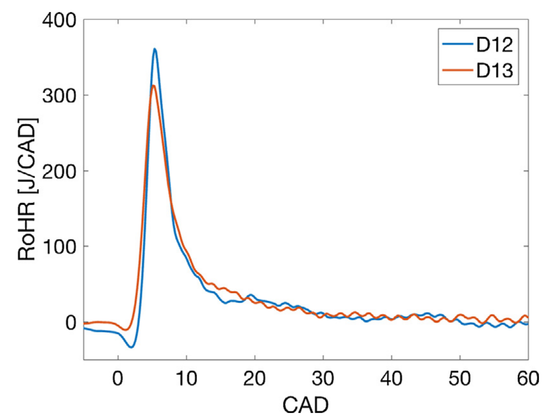

Fig. 2b. Sample AHRR for the 15% $[O_2]$ case.

where λ is the laser wavelength. $E(m)$ is the refractive index function, representing the imaginary part of $(m^2-1)/(m^2+2)$, where m is the complex refractive index of the soot particles, see *e.g.* [23]. In the present work the laser wavelength 685 nm was used, which is rather long in order to better fulfill the Rayleigh scattering approximation and avoidance of PAH absorption, as well as to facilitate laser beam alignment using a visible laser wavelength. Throughout this paper, the product KL is used as a measure of the soot in the cylinder, and it is directly related to the amount of soot in the beam path and obtained directly from the relative transmission measurement. This product KL thus remains constant if the soot content in the beam path remains constant, even if the piston moves, under assumptions of negligible beam steering and non-varying optical properties of the soot. Assuming that no net transport of soot occurs out of the beam path (i.e. that transport out of the beam path is balanced by transport into it), a decrease in KL after the end of injection (EOI) can thereby be attributed to net oxidation of the soot in the cylinder. This is a fair assumption when measuring close to the bowl periphery in a swirl-supported combustion system, since the soot quickly becomes evenly distributed in the azimuthal direction after the end of injection, and since the swirling flow sets up a quasi-steady flow through the beam path. To obtain a high temporal resolution, the photodiode laser beam is modulated at a frequency of 72 kHz using an acousto-optic modulator (AOM), giving 10 laser pulses per CAD at an engine speed of 1200 rpm.

A schematic representation of the setup is shown in Fig. 3. The Bowditch piston extension has a full quartz piston top and a 45° mirror in a fixed position below it. An insert containing an angled

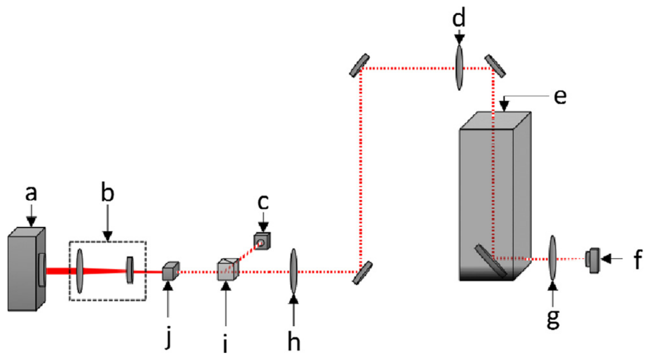

Fig. 3. The parts of the laser extinction setup. Diode laser (a), telescope lenses (b), photodiode for the reference signal (c), re-collimation lens (d), schematic of engine (e), photodiode (f), collection lens (g), re-collimation lens (h), cubic beam splitter (i), and AOM (j).

window is used in place 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 insert and makes it possible to obtain a vertical beam path through the cylinder. A cross-section of this optical access is given in Fig. 4. The absence of one exhaust valve does not substantially affect the combustion process since the engine is running at a relatively low speed of 1200 rpm, allowing for effective gas scavenging. A more detailed presentation of the setup and method of measurement can be found in [2].

4.2. In-cylinder gas sampling

In-cylinder gas sampling was performed on the all-metal engine, fitted with the same cylinder head as used in the optical measurements. In the all-metal engine, the quartz window in the insert (yellow detail in Fig. 4) was replaced with a fast-acting gas-sampling valve [24]. During operation a solenoid hammer actuates the valve by hitting the top of the valve stem. The hammer is controlled by the valve driver, itself driven by a TTL (Transistor-Transistor Logic) signal from a computer program and triggered on crank angle basis. With these features the gas flow through the valve can be controlled in a wide range, with respect to sampling timing, sampling rate and sampling duration. In this study, the undiluted gas flow rate sampled from the cylinder was kept constant at 1 L per minute (at ambient atmospheric pressure and temperature) for each sampling point. This volume corresponds to approximately 0.05% of the total cylinder volume. For the sampling settings used to achieve this flow rate, the minimum step-by-step sampling resolution, i.e. the duration between the valve opening and closing, can be less than 3.5 crank angle degrees CAD at high in-cylinder pressures [25].

Fig. 5 presents the dilution and gas analyzing system. The gases are diluted with nitrogen (N_2) during the first step (D1) in order to prevent further oxidation of the particles. The following steps (D2 and D3) reduce the amount of particles to a level suitable for the aethalometer (Model AE33, Magee Scientific), used to measure the BC concentration.

The aethalometer is based on measurement of the extinction of particles deposited on a filter substrate. Seven different wavelengths are used, ranging from 370 nm to 950 nm. These allow determination of the optical properties of the soot particles. In this study, the BC concentration is obtained as the average of the measurements at the two highest wavelengths (880 nm and 950 nm) in order to reduce interferences from organics or polycyclic aromatic hydrocarbons (PAHs) that absorb in and near the ultraviolet region [24].

The two techniques used in this study present fundamental differences. The extinction measurements are non-intrusive and 1-D along the beam path. On the other hand, the sampling measurements are intrusive and probe in a 3-D region located close to the sampling valve inlet. The data from the two different techniques will be analyzed and compared.

4.3. Simulation tools

The availability of OH in the flame is evaluated using a Φ-T map, a concept first introduced by Kamimoto and Bae [26]. The Φ-T map of OH mass fraction is constructed using a 0-D reactor, from LOGEsoft [27], with constant pressure, temperature and equivalence ratio. The MK1 Diesel was modeled by a surrogate fuel with 70% *n*-heptane together with 30% toluene. Lars Seidel's chemical mechanism for *n*-heptane could then be applied in the simulations [28]. The addition of toluene is used to mimic the sooting behavior of diesel, which *n*-heptane alone cannot. Such surrogate for diesel fuel has been commonly used in diesel combustion studies [29,30] and ascertained in [31]. The map consists of a grid of nodes at different Φ and T conditions (the pressure is constant for all nodes). One simulation is performed at every node and the Φ-T map shows the OH yield after 2 ms.

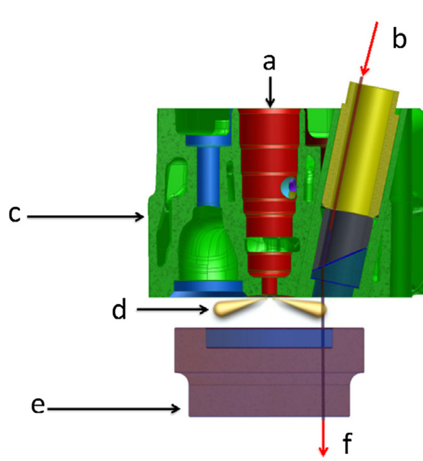

Fig. 4. Section through the cylinder head used in the extinction setup. Injector location (a), laser entrance (b), cylinderhead (c), burning sprays (d), optical piston (e), and laser exit (f).

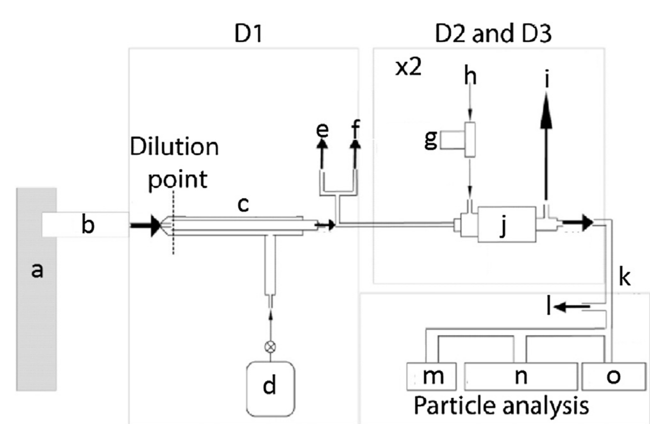

Fig. 5. Diagram of dilution and gas analyzing system [24]. D1, D2 and D3 are dilution steps. Engine (a), fast sampling valve (b), dilution probe (c), N_2 bottle (d), NO_x measurement (e), flow reading (f), pressure regulator (g), air (h), diluted sample (i, not used), ejector diluter (j), diluted sample (k), NO_x measurement (l), SMPS (m, not used in this article), aethalometer (n), and SP-AMS (o, not used in this study).

5. Dependency of the soot oxidation rate on O_2 and OH availability

Gallo et al. observed a constant degradation of the soot oxidation rate with reduced intake O_2 level, leading to increased soot emissions [2]. This was accompanied with an increase in the engine-out emissions of soot. Fig. 6a shows the optical thickness, *KL*, in the cylinder for three intake O_2 levels. As previously mentioned, *KL* is proportional to the soot amount in the beam path. The curves show a marked late-cycle decay due to soot oxidation. Fig. 6b shows aethalometer data from the all-metal engine. The curves represent the content of BC in samples drawn from the cylinder at different crank angle positions during the cycle. In both these figures it can be seen that the 21% O_2 data set represents the steepest decay and the 13% O_2 case the slowest. The two measurement setups independently show that a global effect of the reduction in inlet O_2 concentration is a reduction in the rate of soot oxidation.

There are several potential ways to quantify these soot oxidation rates. One method is to fit an exponential decay function to the extinction curves and extracting the half-life (HL) [2,3]. Although the 13% O_2-case in Fig. 6a is not perfectly described by an exponential, the half-lives extracted from the curves still give a useful estimate of the overall oxidation rates. When decreasing the inlet O_2 concentration from 21% to 13%, *i.e.* by a factor of less than two (−38%), the oxidation half-lives in Fig. 6a display a sixfold increase (translating to an 83% decrease of the oxidation rate). This indicates that the availability of O_2 in itself is not governing the oxidation rate. A linear dependence of the oxidation rate on the intake O_2 concentration is not expected, however, as the O_2 concentration affects other aspects of the oxidation chemistry by affecting the flame temperature. This will be discussed below.

O_2 and OH are both important soot oxidizers [9]. According to Bartok and Sarofim [7], both OH and O_2 play a role under lean conditions while OH is likely to be dominating under fuel-rich and stoichiometric conditions [7]. Since the late-cycle soot oxidation is a mixing-controlled combustion process, it is expected to take place near stoichiometric conditions, and OH is thereby expected to be the main soot oxidizer under diesel conditions. About 10–20% of all OH collisions with soot are effective at gasifying a carbon atom [8,11]. Moreover, Guo et al. have shown that soot oxidation by OH has negligible activation energy and they point out that, for premixed and diffusion flames, optimized models indicate that soot oxidation by OH dominates over O_2 [11].

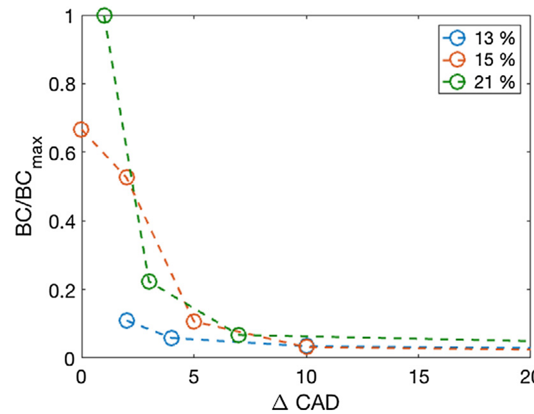

Fig. 6b. Evolution of BC from the in-cylinder sampling measurements shown from the start of decay.

While dilution with EGR affects the availability of O_2, it has an even greater impact on the flame temperature. The flame temperature, in turn, has a strong effect on the availability of OH. Fig. 7 represents *Φ*-*T* maps obtained using the 0-D reactor model. The colored iso-fields represent the OH concentration and the white, green and red curves represent the adiabatic flame temperatures at the different O_2 concentrations using an initial temperature of 900 K. The maximum adiabatic flame temperature is 2744 K at 21% O_2, and drops to 2196 K for the 15% O_2 case.

Fig. 8 shows normalized number densities of OH extracted from Fig. 7, plotted against the soot oxidation half-lives displayed in Fig. 6a. Since the soot oxidation is expected to occur at stoichiometric conditions, the OH mass fractions are extracted at the maximum flame temperature. As expected, the oxidation rate increases with the OH concentration in the flame. It can be noted that the six-fold decrease in half-life previously mentioned is accompanied by a roughly six-fold increase in OH availability.

Besides the availability of OH, the local temperature could be expected to affect the soot oxidation rate. In Seidel's mechanism, however, the activation energy for OH-soot reactions is zero, yielding a dependence on OH concentration and the soot area-to-volume ratio, but not on temperature. This is motivated by OH being a very reactive species. The current study provides no data on soot morphology but, assuming that the area-to-volume ratio

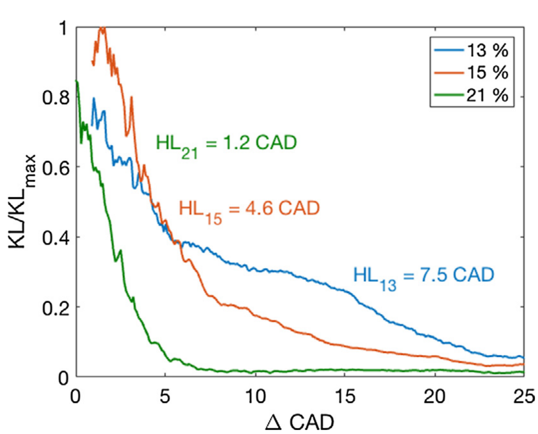

Fig. 6a. Evolution of KL (relative to the peak KL at 15% O_2) in the optical measurements shown from the start of decay. The half-life extracted from the exponential approximation is shown in CAD.

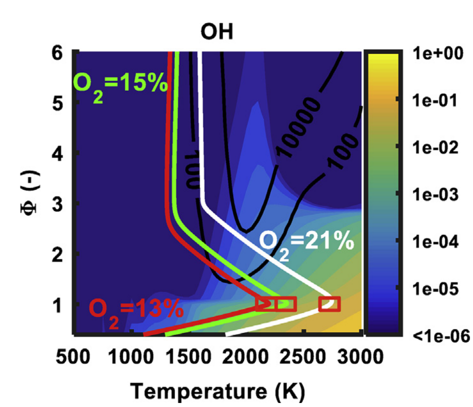

Fig. 7. *Φ*-*T* map of OH mass fraction constructed using a 0-D reactor with constant pressure, temperature and equivalence ratio. The three red squares highlight the maximum adiabatic flame temperature corresponding to the three cases (13, 15 and 21% O_2). The scale on the right represents the mass fraction of OH species. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

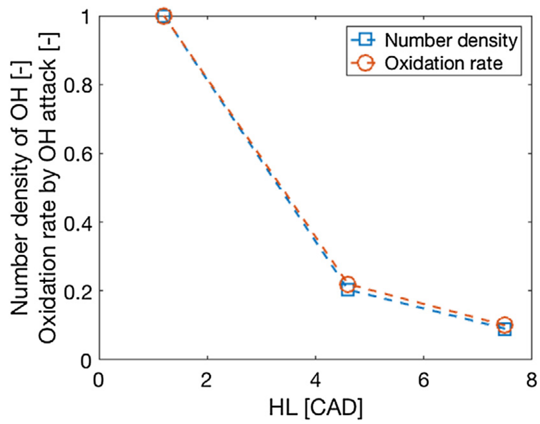

Fig. 8. Variation of the relative number density of OH (blue curve) and soot oxidation rate according to Neoh et al. [31] (red curve) at the 3 cases studied, versus the variation of the oxidation half-life.

remains constant, the temperature dependence of the OH-soot reactions can be estimated using the model of Neoh et al. [32]

$$\omega_{OH} = \gamma_{OH}\frac{3n_{OH}}{N_A}\left(\frac{8RT}{\pi M_{OH}}\right)^{1/2}. \tag{4}$$

Here, ω_{OH} is the soot oxidation rate, n_{OH} and M_{OH} are the number density and the molar mass of OH, R is the general gas constant and N_A is Avogadro's number. γ_{OH} is the collisional frequency between OH and the soot surface and is assigned a value of 0.13 by Neoh et al. [32]. Inserting the OH concentrations and the peak adiabatic flame temperatures from the simulations into this model yields the oxidation rates presented in Fig. 8 alongside the OH number density. Both the number densities and the rates are normalized to facilitate comparison. Although the temperature drops by 25%, the estimated oxidation rate drops at the same rate as the OH concentration. This supports both the assumption that the OH-soot reactions do not have a strong temperature dependence and rather follow the OH availability, as well as the claim that OH is the dominant soot oxidizer.

6. Conclusions

The in-cylinder soot oxidation slows down when the inlet concentration of O_2 is reduced. This observation has been confirmed through measurements using two techniques on two different engine setups. Decreasing the intake O_2 concentration by 38% reduces the soot oxidation rate by 83%. The non-linear impact of O_2 on the soot oxidation indicates that O_2 availability is not limiting the soot oxidizing process in itself.

The reduction of inlet O_2 concentration has a strong impact on the adiabatic flame temperature. It is hypothesized that the temperature affects the soot oxidation rate mainly through its effect on the mass fraction of OH during combustion. When the maximum flame temperature drops from 2700 K to 2400 K, the OH concentration drops roughly six times. This corresponds well to the drop in the oxidation rate. Both the chemical mechanism used for the OH simulations and the soot oxidation model by Neoh et al. state that the temperature dependence of soot oxidation due to OH is negligible, due to the high reactivity of OH radicals. In combination, these findings indicate that OH is the dominant oxidizer under diesel conditions.

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