

Optical Studies about the Influence of Diesel Engine Operating Parameters on the Physicochemical Properties of Emitted Soot Particles

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ABSTRACT

This paper describes the influence of diesel engine operating parameters not only on the properties of the emitted soot particles but also on the whole engine chain of events, which was visualized by optical measurement techniques.

The vapor and liquid phase of the injected diesel spray was observed simultaneously by laser-induced exciplex fluorescence (LIEF) to analyze mixture formation up to the visible start of combustion. The soot formation and oxidation process was evaluated by detecting a spectral range of the soot luminescence and the OH radical. The electrical mobility particle diameter as well as the primary particle size of the emitted soot particles were analyzed by a Scanning Mobility Particle Sizer (SMPS) and by High-Resolution Transmission Electron Microscopy (HR-TEM). Finally, the results were combined to examine the influence of injection pressure, injection timing, boost pressure and engine speed on mixture formation, combustion and the properties of the engine out soot particles. All measurements were carried out on an optically accessible single-cylinder diesel engine.

The study shows a strong influence of injection pressure, injection timing and boost pressure as well as of engine speed on combustion, soot formation and oxidation and in particular on properties of the emitted diesel soot particles. Advanced injection and boost pressures as well as higher engine speeds lead to smaller primary particles and to smaller electrical mobility particle diameters and lower particle numbers. This is caused by the enhanced mixture formation resulting in a different soot formation and soot oxidation process during combustion. Different intensities of soot oxidation tends to affect smaller primary particle sizes for a SOI next to the TDC and cause smaller electrical mobility particle diameters and lower particle numbers for early injection events.

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INTRODUCTION

In view of the new European emission standard EURO 6 diesel engines have to meet strong emission limit values for particulate mass as well as for particulate number. These regulations will be achieved on the one hand by optimizing the in-cylinder process and on the other hand by exhaust aftertreatment systems like diesel particulate filters (DPF), which remove particulate matter (PM) very efficiently from the exhaust gas. The trapped PM in the DPF has to be removed by the so called regeneration process, where the soot is oxidized mostly into CO₂.

According to recent studies, the physical and chemical properties of the emitted diesel soot particles, which change

with engine operating conditions [1,2,3,4,5], affect the reaction behavior in the DPF during the regeneration process [6,7,8]. An earlier emission study [9] shows that with increasing injection and boost pressure the diameter of the emitted primary particles and their agglomerates decreases. Furthermore, thermogravimetric analysis reveals a decreasing oxidation temperature for smaller primary particles. Many publications point out that all processes in the engine chain of events, which affect the in-cylinder mixture formation and combustion, have an impact on the soot formation and oxidation process [2,5,10,11,12,13,14]. Hence the focus of the following study is to reveal how engine parameters (injection pressure, injection timing, boost pressure and engine speed) influence properties of the emitted soot

particles and how the changes correlate with in-cylinder mixture formation and combustion.

Laser-induced exciplex fluorescence (LIEF) was used to visualize simultaneously the vapor and the liquid phase of the injected spray. From LIEF images local air-fuel ratios (AFR) in the cylinder of the engine were derived to quantify the evaporating fuel spray. The combustion process was visualized by simultaneous imaging of the OH radical (OH*) and a spectral range of soot luminescence, which allows the analysis of the soot formation and oxidation process. Changes in physical properties of the emitted particles were examined by a Scanning Mobility Particle Sizer (SMPS) and by High-Resolution Transmission Electron Microscopy (HR-TEM). The measurements were carried out on an optically accessible single-cylinder diesel engine.

EXPERIMENTAL DISCRIPTION

The following section presents the optically accessible single-cylinder diesel engine as well as the various measurement techniques.

Experimental Setup and Operating Parameters

Optically accessible single-cylinder diesel engine

Table 1. Technical data of the single-cylinder engine

Displacement	500 cm ³
Engine speed	0–1250 rpm
Boost pressure	0.095–0.3 MPa
Boost temperature	293–363 K
Compression ratio	14:1
Bowl shape	Omega
Injection system	Common rail up to 165 MPa
Injector type	Bosch, solenoid, 6-hole, cone angle 135°
Exhaust gas recirculation (EGR)	Adjustable; 4 gases (air, N ₂ , CO ₂ , ...) plus water vapor

The single-cylinder diesel engine specified in [Table 1](#) offers optical access from several sides, as shown in [Figure 1](#). The quartz glass piston with an omega-shaped bowl gives access through the bottom of the piston bowl and into the combustion chamber. Additionally, there are two side windows in the cylinder wall to get side view into the cylinder or to guide a laser light sheet through the combustion chamber. The diesel engine has no catalytic aftertreatment devices in the tailpipe. The engine operates in skip-fire mode with one out of ten cycles being fired. This operating mode, which is typical and necessary for optically accessible engines, results in increased heat losses of the exhaust gas. To

take the exhaust gas temperature into account, the particles are sampled close to the outlet valve. A Common rail system provides constant injection pressures up to 165 MPa. The solenoid injector with a six hole nozzle (Bosch) has a spray cone angle of 135° and is mounted in the center of the cylinder head.

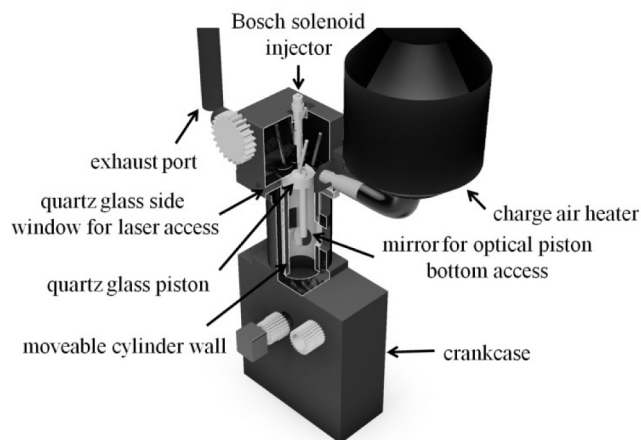


Figure 1. Design of the optically accessible single-cylinder engine

Engine operating parameters

As described in the introduction, changes in engine operating parameters have a significant influence on the properties of the emitted soot particles. However, there is less information about correlations between the in-cylinder diesel combustion, which changes with engine operating parameters (i.e. injection and boost pressure, injection timing), and the physicochemical properties of the emitted soot particles. Recent studies point out that injection parameters and the air-fuel ratios (AFR) have significant influence on particulate matter emissions [14, 15, 16]. Therefore the injection pressure p_i and the start of injection (SOI) as well as the boost pressure p_b have been selected for this study. It is well-known that thermodynamic conditions in the combustion chamber of the engine play an important role in the soot formation and oxidation process [17, 18]. As temperature and pressure in the cylinder change with crank angle (CA), engine speed n is also an important parameter here. [Table 2](#) shows the engine operating parameter variations.

Table 2. Engine operating parameters

Engine speed (n)	600, 800, 1000 rpm
Injection pressure (p_i)	80, 100, 130 MPa
Start of injection (SOI)	-10, -6, -3 °CA ATDC
Boost pressure (p_b)	0,105; 0,125; 0,145 MPa
EGR rate	0 %
Boost temperature	313 K
Injected fuel mass	17 mg

Measurement Techniques and Evaluation Methods

Laser-induced exciplex fluorescence (LIEF)

Liquid and vapor phase of injected sprays can be separately visualized by adding excited state complex (exciplex) tracers to the fuel. Laser-induced exciplex fluorescence was accomplished first on a cuvette by Melton [19] and was developed further to visualize and to quantify evaporating fuel sprays [20, 21]. LIEF was then applied to optically accessible engines for in-cylinder mixture formation studies [22, 23].

So far, a disadvantage of LIEF is the need to use substitute fuels instead of commercial diesel fuels (DIN EN590) with its many fluorescence-active species. With the aid of multicomponent substitute fuels some groups have come closer to rebuild EN590-like properties [24]. However, the evaporation process of a genuine fuel depends on the complex interactions of its many components.

In previous publications we have described the spectroscopic properties of a gas-to-liquid diesel (GTL), which is a specified and commonly available diesel fuel [25, 26]. Therefore GTL is an almost ideal substitute for EN590 evaporation measurements. For the mixture formation studies the exciplex tracers N,N,N',N'-tetramethyl-p-phenylendiamine (TMPD) and naphthalene were added to the GTL as they are approved for diesel engine applications [23, 27].

The GTL/excipient system was applied to the optically accessible single-cylinder diesel engine to visualize and examine the influence of different engine operating parameters on mixture formation (Figure 2). A laser light sheet of $0.5 \text{ mm} \times 45 \text{ mm}$ was guided through the combustion chamber via the cylinder side windows. The two-dimensional fluorescence signal was captured through the piston bowl window by an intensified charged coupled device (ICCD) camera (LaVision) with an image-doubler for simultaneous liquid and vapor phase recording. A notch filter removed scattered laser light (355 nm). With interference filters the vapor phase signal (400 nm, with full width at half maximum (FWHM) 17 nm) and the liquid phase signal (515 nm, FWHM 8 nm) were spectrally separated. For a first quantification of the fluorescence signal of the evaporating fuel sprays, the engine was operated with a nitrogen atmosphere to avoid oxygen quenching. Furthermore, the signal was corrected to laser light sheet intensity and residual crosstalk of the exciplex signal. To calculate the air-fuel ratio a calibration image of a homogeneous GTL/tracer mixture at $\text{AFR} = 14.8$ for all particular thermodynamic conditions was acquired prior to the measurements. Figure 3 shows the averaged image of three injection events for the vapor and liquid phase as well as the calculated air-fuel ratio (AFR) map shortly before the visible start of combustion (VSOC).

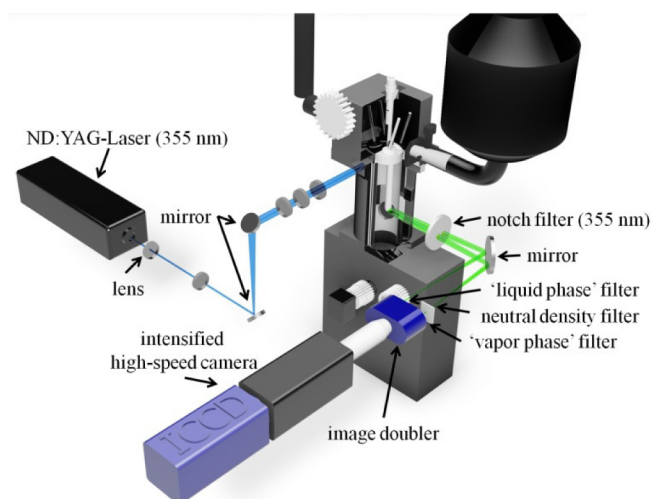


Figure 2. Setup for the simultaneous imaging of vapor and liquid phase in an optically accessible single-cylinder diesel engine

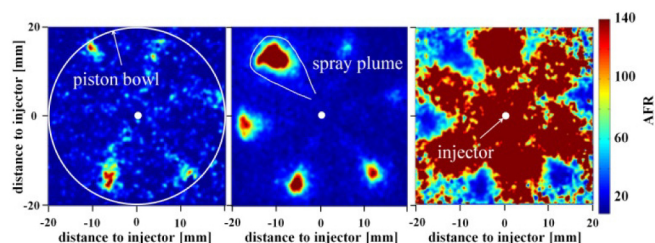


Figure 3. Liquid (left) and vapor (middle) signal and calculated air-fuel ratio (AFR), view through the quartz glass piston bowl

Combustion spectroscopy

By soot imaging the local start as well as the time- and spatially-resolved soot formation can be observed [28, 29]. The OH radical plays an important role in the soot oxidation process and gives also information about the local self-ignition process as well as about the local main oxidation zones [30, 31]. The soot formation and oxidation process can be evaluated by simultaneous imaging of these two wavelengths.

Therefore the combustion process was recorded by chemiluminescence imaging of the OH radical at a significant emission wavelength through the piston bowl window using an ICCD camera (Figure 4). The camera with a recording rate of 10 kHz was started by the electrical injection signal. For the simultaneous imaging of the OH radical and soot an image doubler and two band pass filters (OH*: 308 nm, soot: 490 nm, FWHM 10 nm) were applied to the optically accessible single-cylinder diesel engine. In addition, a neutral density filter was placed in front of the 490 nm band pass filter due to the extremely elevated intensity of the soot radiation compared to the OH* chemiluminescence. Thus the

camera could operate with a higher sensitivity to detect weak OH* chemiluminescence as well.

Figure 5 shows an example for simultaneously recorded OH* and soot luminescence with view through the bottom of the piston bowl. The images demonstrate OH* (left) and soot (right) distributions, which are accumulated over time.

The images of OH* (308 nm) and soot (490 nm) were recorded with a time-resolution of 100 μ s and were spatially integrated. The resulting history of the relative OH* to soot intensity ratio illustrates the diesel combustion phases (premixed, diffusive and post-combustion).

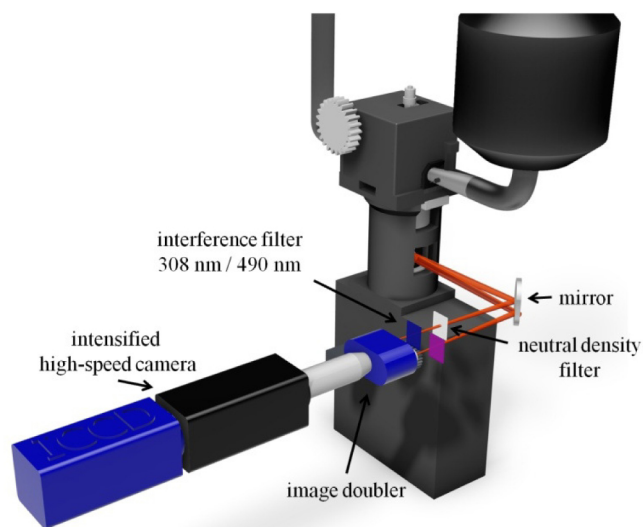


Figure 4. Setup for the simultaneous imaging of OH* (308 nm) and soot (490 nm)

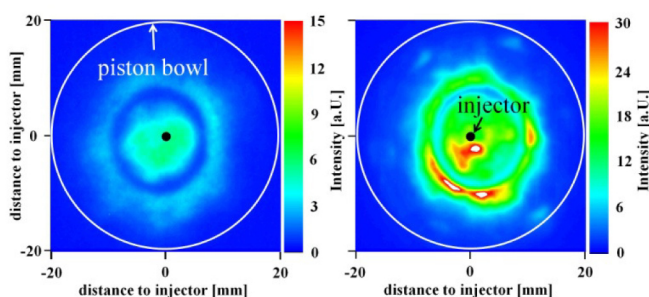


Figure 5. Time-integrated images of OH* at 308 nm (left) and soot at 490 nm (right)

Physical characterization of engine out soot particles

Scanning mobility particle sizer (SMPS)

For obtaining an overview of the emitted soot particle size distribution, a constant volume sample flow out of the tailpipe was conditioned by a Rotating Disc Diluter MD 19-3E (Matter-Engineering AG), which works according to the international Particle Measurement Program (PMP) regulations [32,33,34]. A thermodenuder (TSI 3065) was

used to avoid nucleation at operating points with high volatile hydrocarbon fraction in the exhaust. The diluted and conditioned sample exhaust gas flow (dilution ratio 1:36, hot dilution at 150 °C with filtered air, thermodenuder temperature at 200 °C) was analyzed by a Scanning Mobility Particle Sizer (SMPS) consisting of an Electrostatic Classifier (EC 3080, TSI), a Differential Mobility Analyzer (DMA 3081, TSI) and a Condensation Particle Counter (CPC 3022, TSI). The SMPS measurements provided a Gaussian-shaped concentration of the respective electrical mobility diameter of the emitted soot particles. The maximum of the curve was defined as the mean electrical mobility particle diameter (Figure 6).

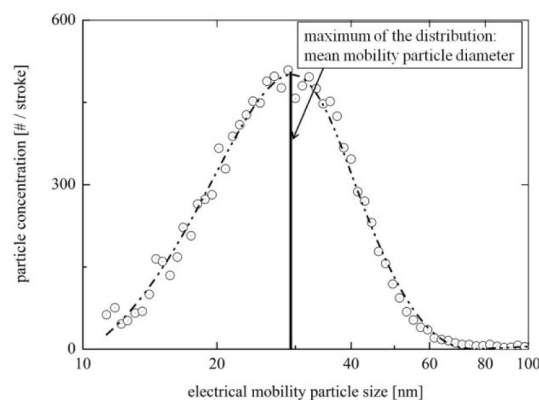


Figure 6. Typical distribution of the electrical mobility particle diameters (SOI = -6 °CA, $p_b = 0.145$ MPa, $p_i = 80$ MPa)

High-resolution transmission electron microscopy (HR-TEM)

Engine-out soot particles have been further analyzed by High-Resolution Transmission Electron Microscopy (HR-TEM; Zeiss Libra 200FE). With a magnification up to 10^6 primary particles and morphological details of the soot particles can be studied [6,35,36,37]. For the HR-TEM imaging soot particles have been directly sampled out of exhaust gas on TEM copper grids (lacey-carbon-film coated). The grid has been put into the tailpipe by a self-designed grid holder, which kept the opening for the samples closed to the outside, to guarantee constant operating conditions without any pressure loss in the tailpipe. Before the grid has been held perpendicularly to the exhaust gas flow, it had been conditioned at 373 K. The particles were sampled on the TEM grid over ten fired combustion cycles.

Allowing statistical representative results, the primary particle diameters of 15 soot agglomerates, which were sampled on TEM grids, have been measured with a 40,000-fold magnification. The evaluation of the HR-TEM images has been conducted by the open-source microscopy software ImageJ. Figure 7 shows a HR-TEM image of a soot