Extended Summary to the Poster

Influence of engine parameters on physical properties of emitted diesel soot particles

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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 into carbon monoxide and carbon dioxide. According to recent studies the physical and chemical properties of the emitted diesel soot particles, which change with engine operating conditions [1, 2], affect the reaction behavior in the DPF during the regeneration process [3, 4]. An earlier emission study [5] shows that with increasing injection and boost pressure the diameter of the emitted primary particles and their agglomerates decrease. Furthermore, the publication points out that those changes in injection and boost pressure affect the in-cylinder combustion process and thus the properties of emitted soot particles.

Hence the focus of the following study is to reveal how the physical properties of the emitted soot particles change with further engine parameters (injection timing, engine speed) and how these changes correlate with the in-cylinder combustion process.

Optical measurements of combustion and engine out soot particles on an optically accessible single-cylinder diesel engine

The measurements were carried out on a single-cylinder diesel engine with optical access from several sides. The quartz glass piston with an omega-shaped bowl gives access into the combustion chamber. The engine has no catalytic aftertreatment system and works in skip-fire mode with one out of ten cycles being fired. A common rail system provides constant injection pressures up to 165 MPa. A solenoid injector from Bosch with a six hole nozzle has a spray cone angle of 135° and is mounted in the center of the cylinder head.

Three different engine speeds (600, 800, 1000 rpm) were varied under constant injection pressure (80 MPa), boost pressure (0.105 MPa) and injection timing (-6 °CA aTDC). The variations in start of injection (-10, -6, -3 °CA aTDC) were carried out at p_b = 0.145 MPa, p_i = 100MPa and n = 600rpm.

A specific wavelength of the soot luminescence (490 nm) as well as the OH radical at 308nm can be recorded simultaneously by an ICCD camera and an image-doubler. The time-resolved OH* / soot ratio gives information about the different diesel combustion phases (premixed, diffusive and post combustion). The premixed combustion takes place with a high intensity of the OH*. In the diffusive combustion phase the most soot is produced. In the third phase (post combustion) most of the soot in the cylinder is oxidized.

For the SMPS-measurements a constant volume sample out of the tailpipe of the single-cylinder diesel engine was conditioned by a Rotating Disc diluter and a thermodenuder. The measurements provided a Gaussian-shaped concentration of the electrical mobility particle diameter as well as the particle number and mass. The emitted particles were analyzed by High-Resolution Transmission Electron Microscopy as well. For the HR-TEM imaging soot particles were directly sampled on TEM copper grids (lacey-carbon-film coated) out of the tailpipe.

Conclusion and future work

Combining the results of combustion spectroscopy and the engine out soot emissions the following conclusions can be drawn for the engine speed and start of injection variations:

- With increasing engine speeds the soot formation intensity during diffusive combustion is nearly constant while soot oxidation is intensified. This results in smaller primary particle sizes and smaller mean electrical mobility particle diameters as well as lower particle number and mass at advanced engine speeds.
- Early injection events cause a similar intensity of soot formation. Differences in the soot oxidation intensities yield smaller primary particle sizes for a start of injection near the top dead center and result in smaller electrical mobility particle diameters and lower particle number and mass for early injection events.

In the future, results of mixture formation will be combined with the results of the combustion process and of the engine out soot emissions.

References:

[1] Mathis U, Mohr M, Kaegi R, Bertola A, Boulouchos K: Influence of Diesel Engine Combustion Parameters on Primary Soot Particle Diameter. *Environ Sci Technol* 2005, 39:1887–1892.

[2] Srivastava DK: Effect of Engine Load on Size and Number Distribution of Particulate Matter Emitted from a Direct Injection Compression Ignition Engine. *Aerosol Air Qual Res* 2011.

[3] Müller J-O, Su DS, Jentoft RE, Wild U, Schlögl R: Diesel engine exhaust emission: oxidative behavior and microstructure of black smoke soot particulate. *Environ Sci Technol* 2006, 40:1231–1236.

[4] Lamharess N, Millet C-N, Starck L, Jeudy E, Lavy J, Da Costa P: Catalysed diesel particulate filter: Study of the reactivity of soot arising from biodiesel combustion. *Catal.Today* 2011.

[5] Leidenberger U, Mühlbauer W, Lorenz S, Lehmann S, Brüggemann D: Experimental Studies on the Influence of Diesel Engine Operating Parameters on Properties of Emitted Soot Particles. *Combust Sci. Technol.* 2012, 184:1–15.

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MOTIVATION

Background

- Strong emission limit values for particulate mass and number (Euro 6)
- Compliance of regulations by optimizing in-cylinder combustion process and by exhaust aftertreatment systems like diesel particulate filters
- Removing of the trapped particulate matter by active regeneration
- Influence of physicochemical properties of emitted soot particles on the reaction behavior of trapped PM in the DPF
- Physicochemical properties of the emitted particles dependent on the in-cylinder combustion process

Aim:

- Influence of diesel engine operating parameters (injection timing, engine speed) on the in-cylinder combustion process and on the physical properties of emitted soot particles (injection timing, engine speed)

Technical data of the engine and operating parameters

Technical data of the optically accessible single-cylinder diesel engine

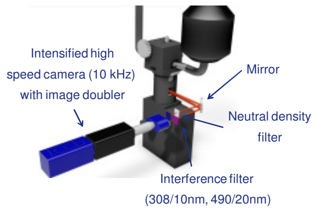
Displacement	500 cm³
Engine speed	0-1250 rpm
Injection pressure	Up to 160 MPa
Boost pressure	0.105 MPa – 0.30 MPa
Boost temperature	293-363 K
Compression ratio	14:1
Piston bowl shape	Omega
Injector type	Bosch, solenoid, 6-hole, cone angle 135°
Injection system	Common rail
Exhaust gas recirculation	Adjustable with different gases (air, N_2, CO_2,…)

Variations in engine speed (n) and start of injection (SOI)

Engine speed (n)	600, 800, 1000 rpm
Injection pressure (p_{inj})	80, 100 MPa
Start of injection (SOI)	-3, -6, -10 °CA aTDC
Boost pressure (p_b)	0.105, 0.145 MPa
Exhaust gas recirculation (EGR)- rate	0 %
Injected fuel mass	17 mg
Fuel	Diesel DIN EN 590:2010

Measurement techniques and evaluation methods

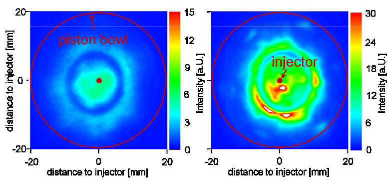
Simultaneous detection of the OH radical (308 nm) and soot (490 nm)

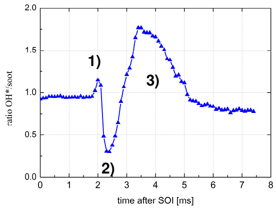


- Time-resolved detection of the OH*/soot ratio:

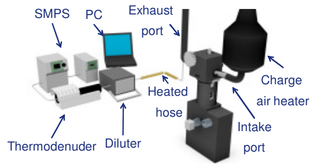
Diesel combustion phases:

1) Premixed combustion: high OH* intensity (first peak)
2) Diffusive combustion: maximum of soot formation (first minimum)
3) Post-combustion: highest soot oxidation (second maximum)

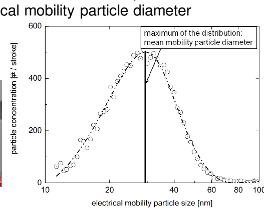




Engine out particle measurements (Scanning Mobility Particle Sizer and Microscopy)

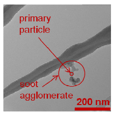


- Scanning Mobility Particle Sizer (SMPS, constant volume sample flow out of the tailpipe)
→Distribution of the electrical mobility particle diameter (SMPS-measurements)
→Mean electrical mobility particle diameter



- High-Resolution Transmission Electron Microscopy (HR-TEM, directly sampled)

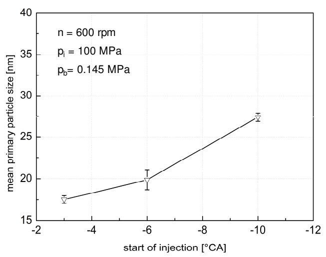
→Distribution of the primary particle size
→Mean primary particle size



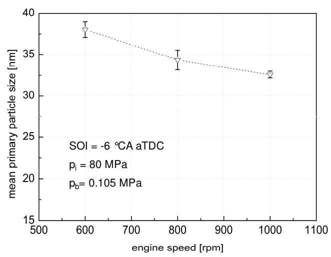
Results

Engine out soot emissions

- Mean primary particle size

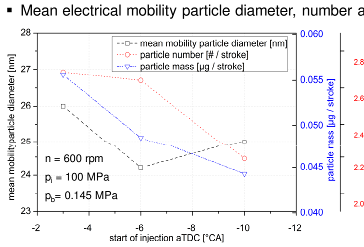


→ Smaller primary particle sizes with injection timing next to top dead center (TDC)

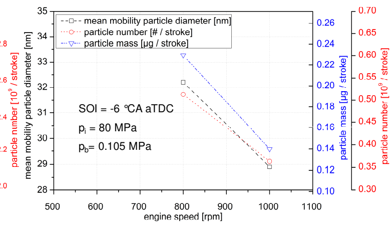


→ Smaller primary particle sizes with increasing engine speeds

- Mean electrical mobility particle diameter, number and mass

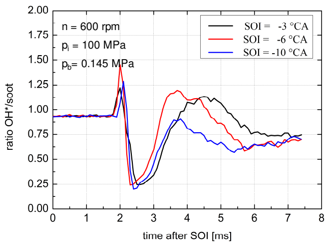


→ Smaller electrical mobility particle diameter, lower particle number and mass with earlier injection timings

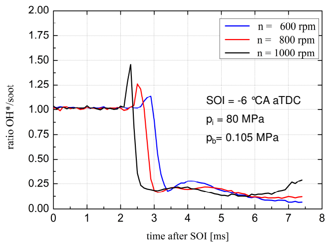


→ Smaller electrical mobility particle diameter, lower particle number and mass with increasing engine speeds

Visualizing the soot formation and oxidation process



→ Ignition delay constant for SOIs next to TDC
→ Soot formation intensity almost constant
→ SOI = -6 °CA soot oxidation slightly higher and starts earlier



→ Lower ignition delay and intensified premixed combustion at higher engine speeds
→ Soot formation intensity almost constant
→ Soot oxidation slightly intensified

Conclusions

- Influence of engine speed (n) and start of injection (SOI) on the in-cylinder soot formation and oxidation process and on the physical properties of the emitted particles.
- Early injection events (SOI = -10 °CA) result in a similar degree of soot formation.
- For a late SOI different intensities of soot oxidation cause smaller primary particle sizes but larger mobility particle diameters and a higher particle number and mass.
- Higher engine speeds lead to similar soot formation intensities and to slight different oxidation behaviors.
- Higher engine speeds tend to result in smaller primary particle sizes, smaller electrical mobility particle diameters and a lower particle number and mass.

Future Work

- Analyzing the mixture formation process by laser-induced exciplex fluorescence.
- Combining the results of the analysis of mixture formation, combustion and the engine out soot emissions.
- Transient operating conditions.

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