Probing the Evolution of Soot Characteristics during Soot Formation, Soot Oxidation and in the Exhaust of a Modern CI Engine Equipped with EGR

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Conclusions

Soot particle aerosol mass spectrometry on in-cylinder diesel soot:

- Helps us understand rapid soot transformation in diesel engines
- Shows how exhaust gas recirculation (EGR) may:

→ lower soot formation and oxidation rates

→ result in a slower soot maturation process

→ alter the chemical composition of the soot core and coating

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Introduction

Exhaust gas recirculation (EGR) lowers the available O_2 concentration during combustion which reduces flame temperatures and results in a slower NO_x production rate but also influence soot formation and oxidation rates as well as soot characteristics in a poorly known manner.

Objective

- Investigate soot emissions as a function of EGR level using four different fuels in a modern CI-engine
- Apply a new technique based on novel combination of a cylinder gas extraction technique and chemical characterization of aerosol particles to probe the evolution of diesel soot during combustion with high and low EGR in a modern heavy-duty diesel engine.
- Investgate the coupling between combustion conditions and physicochemical properties of in-cylinder soot.

Method

Soot emissions from different fuels

A heavy duty Scania D13 engine was operated at low load (6 bars IMEPg) and 1200 rpm. Black carbon (BC) emissions were quantified using an AVL Micro Soot Sensor as function of EGR (9-21% O_2) using four fuels: Diesel (MK1), Gasoline (RON 87 & 69) and Ethanol

Extracting in-cylinder soot

In-cylinder soot was extracted for the diesel fuel using a fast gas-sampling valve (resolution ~0.5 ms; Shen et al. 2015).

Chemical characterization

Extracted particles were diluted and probed with a soot particle aerosol mass spectrometer (SP-AMS) [1]. Refractory BC (rBC) was detected by IR laser vaporization and non-refractory species by flash vaporization (873 K), followed by electron ionization (70 eV) and detection in a HR-ToF-MS (Fig.1).

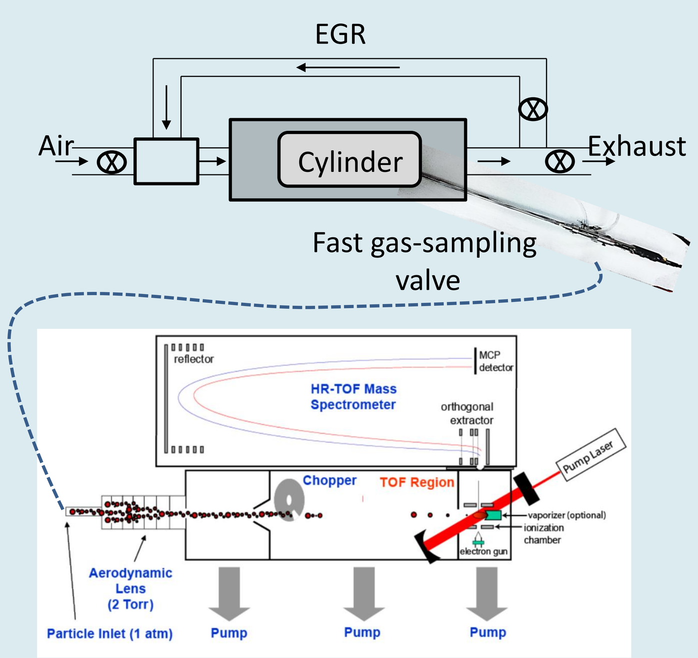

Figure 1: Set-up showing engine with EGR, the fast gas-sampling valve for particle sampling and the SP-AMS for particle characterization.

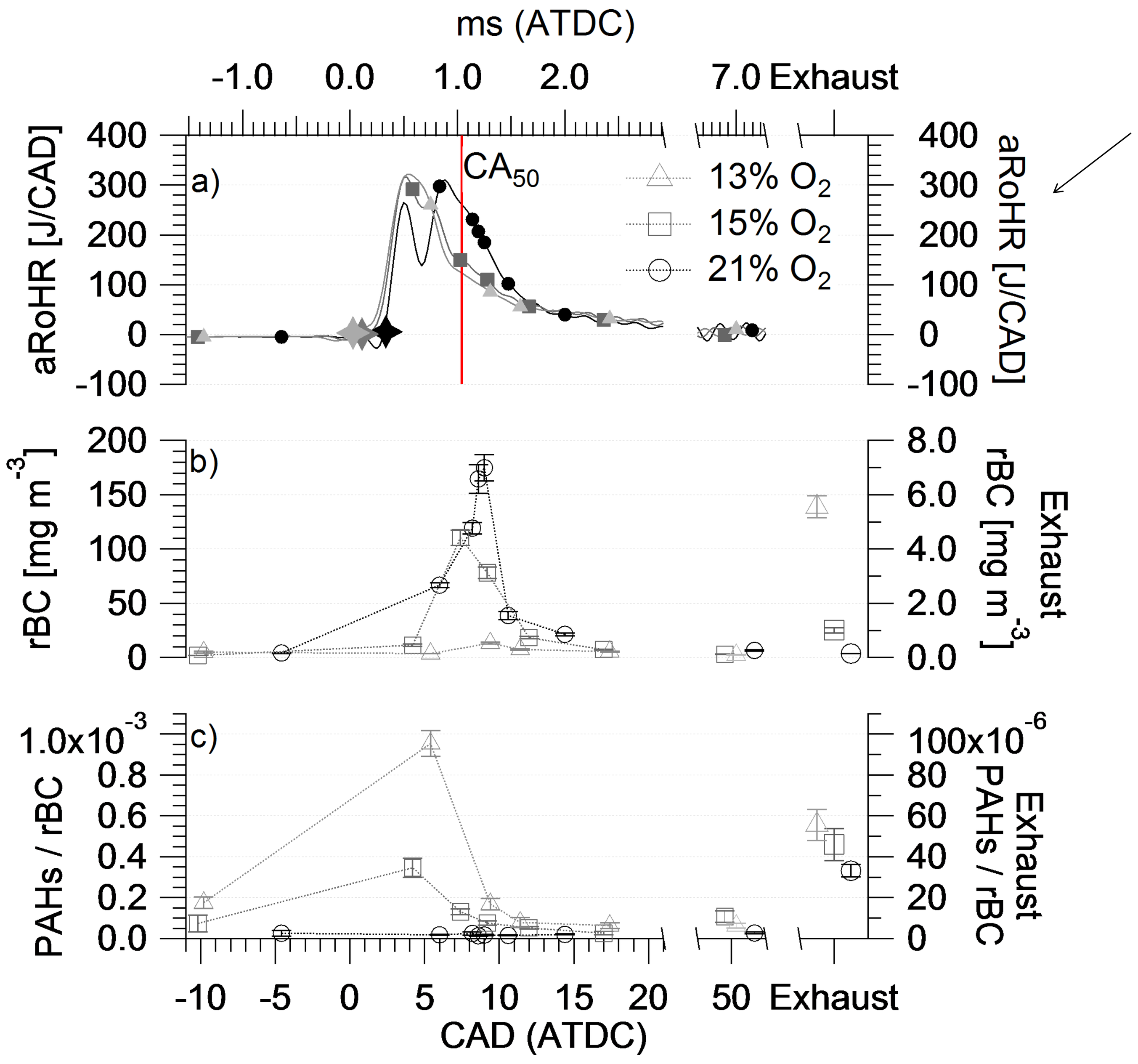

Figure 3: Figure 1: In-cylinder heat release rates (a), SP-AMS rBC (soot) mass concentration (b) and the relative concentration of PAHs to rBC as function of the combustion cycle (c). The timing in the combustion cycle is shown in milliseconds (ms, top) and crank angle degrees (CAD, bottom) after top dead center (ATDC) which is located at 0. Injection pressure 2000 bar.

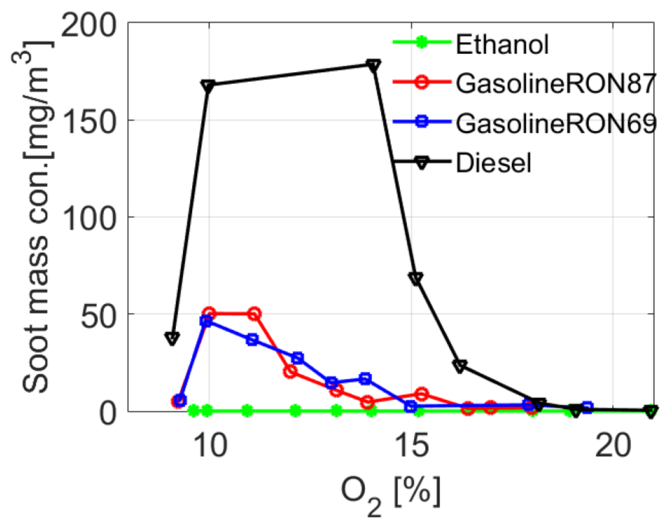

Figure 2: Black Carbon engine out emissions measured with a Micro Soot Sensor as a function of EGR level using four different fuels in the CI engine. The EGR level is given as inlet oxygen concentration. Injection pressure 1200 bar..

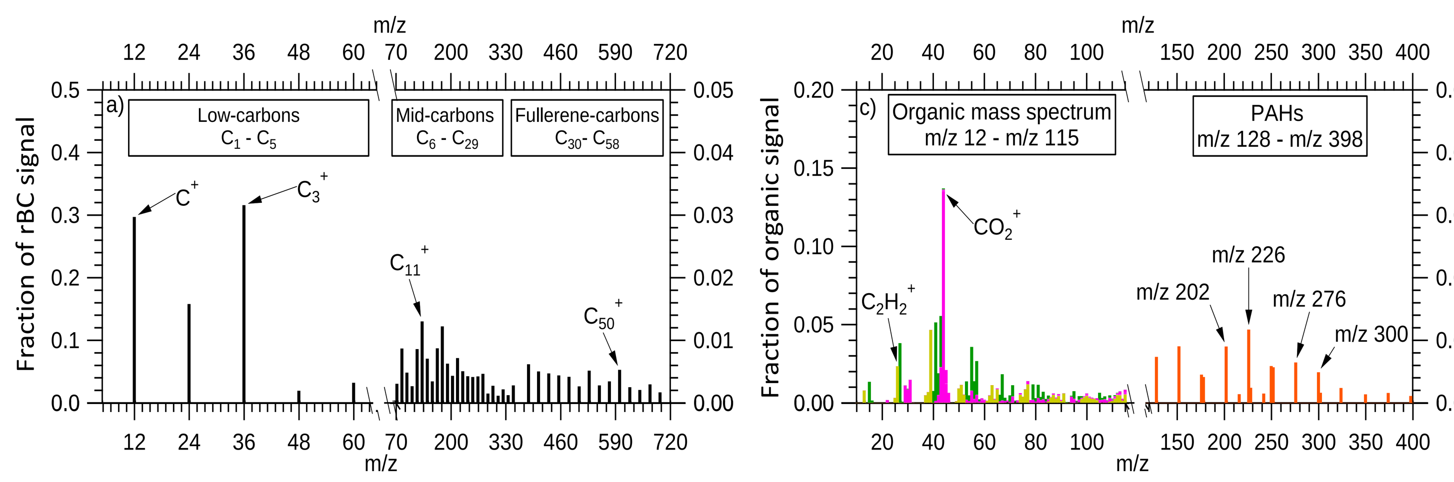

Figure 4: Refractory carbon cluster ion distribution and organic ion fragments at 13% inlet O_2 concentration during intense soot formation at ~5 CAD (ATDC). Organic ion fragments: aliphatic fragments ($C_xH_{y>x}$), aromatic/unsaturated fragments ($C_xH_{y\leq x}$), oxidized organic fragments ($C_xH_yO_z$) shown on left axis and PAHs, shown on the right axis.

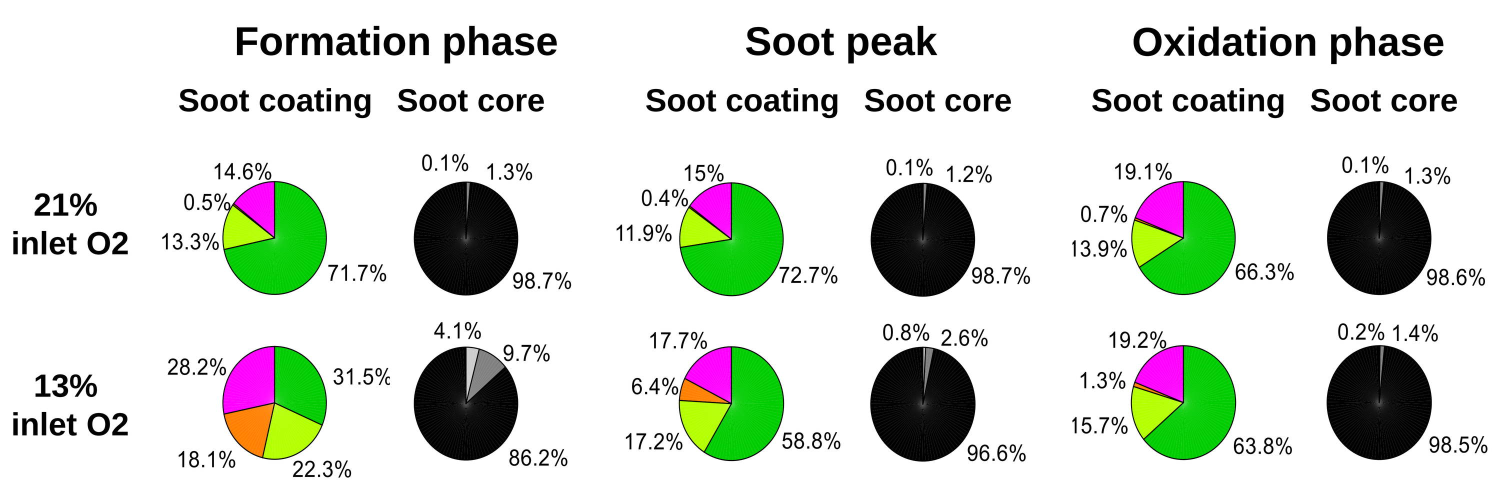

Figure 5: Evolution of soot chemical composition from the soot formation phase (left; ~5 CAD ATDC) to the soot oxidation phase (right; ~15 CAD ATDC). Refractory (Soot core) composition represented by rBC (low-carbon, black; mid-carbon, dark grey; fullerene-carbon, light grey). Non-refractory (coating) composition ´divided into major fragment families (CxHy, dark green; CxHy<x, light green; CxHyOz, magenta; PAHs, orange).

Results

When EGR was introduced:

- The chemical composition of the soot core and coating displayed large variations with the combustion cycle
- EGR ➔ slower soot formation ➔ build up of PAH concentrations ➔ increased PAH emissions
- EGR ➔ reduced soot formation rates but even more reduced oxidation rates ➔ increased BC emissions
- Mid- and fullerene-carbon ions detected in soot formation phase but not in soot oxidation phase
- PAHs, oxidized fragments and fragments from unsaturated compounds elevated during soot formation

Slower soot maturation

We interpret the decay in fullerene-carbon ion signal (Fig.4) as resulting from changes in the soot nanostructure and indicative of a much slower soot maturation process when high EGR is introduced.

Implications for method

The combination of in-cylinder particle extraction with on-line SP-AMS measurements enables direct studies of rapid soot processes providing detailed information on the coupling between combustion conditions and physicochemical properties of the soot.

Acknowledgements

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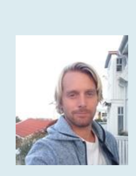

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