Development and evaluation of an optical in-cylinder soot measurement method

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Extended Summary to the Presentation Slides

Radiation emitted from glowing soot particles in diffusion combustion is a well-known fact and has been investigated since the beginning of the 20th century. The soot radiation intensity in the combustion chamber can be measured via a glass fibre light conductor (Optical Light Probe, OLP). Three photodiodes with different filters provide a voltage signal to a crank angle resolved recording system. The post processing is based on the three colour pyrometry algorithm. Hottel & Broughton introduced in (Hottel and Broughton 1932) kL as a representing number for the soot density times the layer thickness in 1932 based on the general absorption law. In principle the viewed soot cloud itself behaves like a radiating body from which the absorptivity is unknown. For a limited range of wavelengths the connection to the absorptivity was approximated with a $\lambda^{-\alpha}$ approach. The constant α varies between 1 and 2 depending on fuel type.

First, the calibration of an OLP system defines the dependency of signal and intensity. The calibration is done with a standardised light source. Second the apparent black body temperatures at measured intensities were calculated with Plank's law. Third the equation for the soot temperature is solved. In the last step the kL factor can be determined using filter wavelength, apparent black body and soot temperature. In general the trace of the kL-factor during Diesel combustion starts with the beginning of the diffusion flame, rises to a maximum after the peak diffusion burn rate and decreases during the last part of the combustion process.

It is important to note that the measured intensity in this case is averaged information due to the wide angle view of 140°. Hence a certain gathered intensity can either be emitted by a homogeneous illuminated view field or by some spots with a higher intensity but both cases lead to the same apparent black body temperature.

Three different ways of calculating an end value of kL have been compared. The first approach was to integrate the kL evolution and find a value at a certain percentage (i.e. 95%). Another approach uses a light intensity threshold, which indicates the end of soot glowing. The according black body temperature of one wave length can be used to define kL_{end}. The concept of a limited oxidation below a certain soot temperature, which marks the end of kL, represents the third approach.

The results from (Barro, Vögelin et al. 2010) were carried out with the first method.

In this experiment, a Liebherr D924 and a Daimler OM642 were used to carry out the measurements.

The figure on slide 9 demonstrates despite no satisfactory information about the end value of kL, the kL evolution can provide information about soot formation and oxidation during a pilot injection. The figure shows an approximated injection rate (gray), the heat release rate (black) and the kL evolution (red). Comparing the time between the first injection and the first peak of the heat release rate with the second injection and the second heat release rate peak, one can observe a shorter ignition delay of the second pilot combustion. The small part of diffusion combustion caused by the short ignition delay forms soot, which can be observed in according the kL evolution. Using the OLP as tool to recognize soot formation, the diagram on slide 10 shows the heat release rate and kL evolution for three different pilot injection timings with a constant total injected fuel mass. An early pilot injection has no effect on the kL, as a consequence of pure lean premixed combustion. The smaller the ignition delay of the pilot combustion gets, the higher kL values are obtained, which indicates again diffusion combustion.

A similar investigation is shown on slide 11, where post injections have been studied. The graph shows a load point without post injection, with a 1.2 ms delayed 3 mm^3, a 2.5 ms delayed 3 mm^3 and a 2.5 ms delayed 6 mm^3 post injection. On the one hand a slight increase of the soot oxidation rate using small close post injection is observed. The far post injections, on the other hand, especially the 6 mm^3, seem to decelerate the oxidation rate significantly which can also be reported in the soot tail pipe emissions. Also this experiment has been repeated with the Liebherr engine. On slide 12 the effects of a varying post injection delay are shown. If the post injection starts late a significant increased kL evolution during the last phase of the heat release rate is formed which causes higher exhaust soot emissions. The total injected fuel mass was held constant. Also visible, comparing the slides 11 and 12, the heat release rate peak relative to the according peak of the kL are different for the two engines. One of the differences in the two load points was, beside the different engines, the EGR-rate, which has an effect of this relative temporal displacement of the kL peak to the heat release rate peak (reported on slide 13).

Conclusions

The Optical light probe is a strong tool to investigate soot formation and oxidation in a crank angle resolved regime. Especially in engines with multiple injection strategies, with an OLP, one is able to distinguish the soot behaviour between the different injections. Moreover, changes in soot formation as well as soot oxidation rates can be observed during changes in EGR-rate.

But there is still no accurate and reliable kL_{end} evaluation method for different engines. Furthermore, the calibration of the intensity is difficult for wide series of load point, which seems to be a thermal issue of the tip of the sensor.

Barro, C., P. Vögelin, et al. (2010). Comparison of Soot Measurement Instruments during Transient and Steady State Operation. 14th ETH Conference on Combustion Generated Nanoparticles. ETH Zurich.

Hottel, H. C. and F. P. Broughton (1932). "Determination of True Temperature and Total Radiation from Luminous Gas Flames." Ind. Eng. Chem. Anal. Ed. **4**(2): 166-175.

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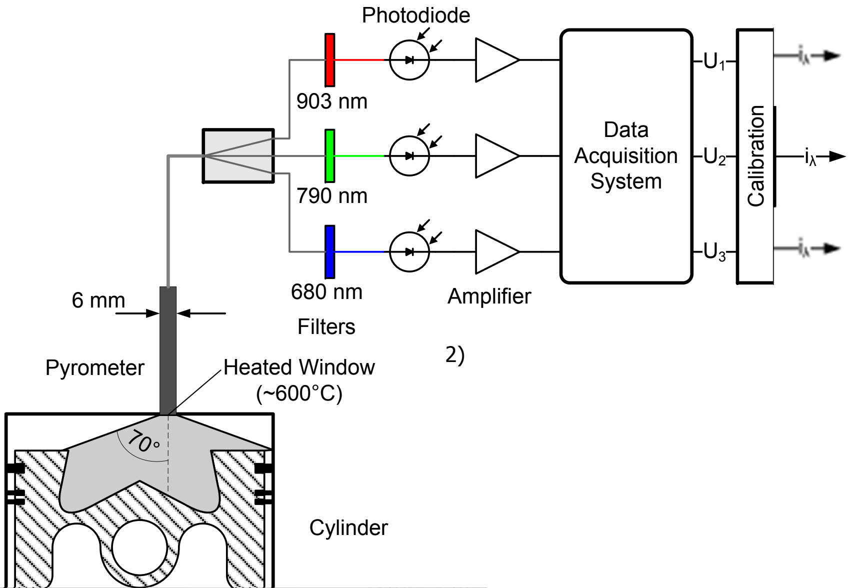
Outline

- Introduction
- Method
- Test facility
- Measurement Results
- Conclusions
- Outlook

Introduction



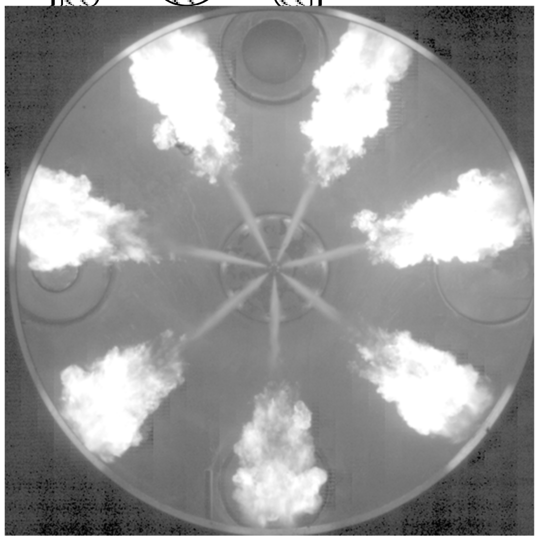
2)

$$i_{b,\lambda}(T) = \frac{2C_1}{\lambda^5\left(e^{\left(\frac{C_2}{\lambda T}\right)}-1\right)}$$

$T_{BB,1}$

$T_{BB,2}$

$T_{BB,3}$



1)

[1] Schneider 2003, [2] Kirchen 2008

Method

Wien's law according to [1)]

$$\frac{1}{T_{BB}} - \frac{1}{T_{Soot}} = \frac{\lambda}{C_2} \cdot \ln\left(p_\lambda\right) \quad (1)$$

With the absorptivity, f(λ) [1)]
(also called: black body coefficient)

$$p_\lambda = 1 - e^{-kL/\lambda^\alpha} \quad (2)$$

1 and 2 combined [1)]

$$\frac{1}{T_{BB}} - \frac{1}{T_{Soot}} = \frac{\lambda}{C_2} \cdot \ln\left(1 - e^{-kL/\lambda^\alpha}\right) \quad (3)$$

α experimentally set to 1.39,
kL ~ f_v (Soot volume fraction)[2)]

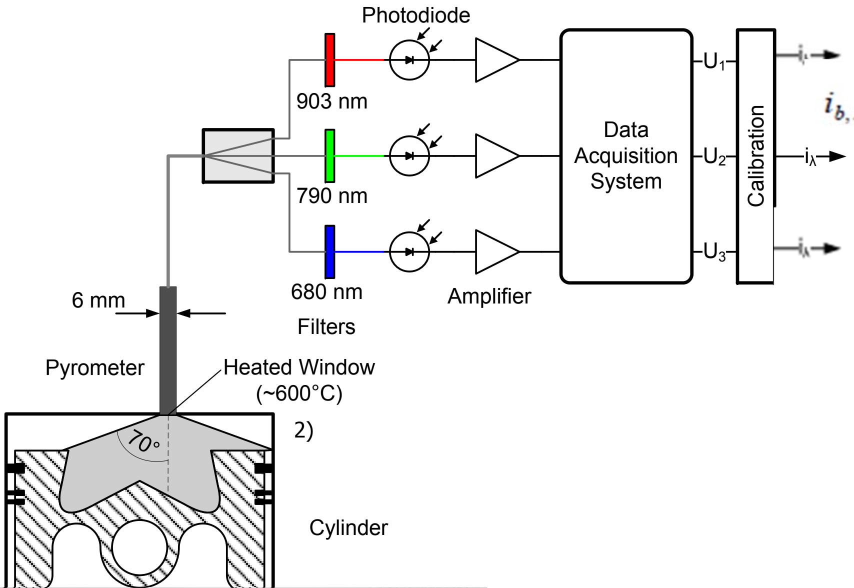
$$kL = -\lambda^\alpha \ln\left[1 - \left(\frac{e^{\frac{C_2}{\lambda T_{Soot}}} - 1}{e^{\frac{C_2}{\lambda T_{BB}}} - 1}\right)\right] \sim f_v \quad (4)$$

Iterative solvable equation for the soot temperature T_{Soot}

$$\left[1 - \left(\frac{e^{\frac{C_2}{\lambda_1 T_{Soot}}} - 1}{e^{\frac{C_2}{\lambda_1 T_{BB,1}}} - 1}\right)\right]^{\lambda_1^\alpha} = \left[1 - \left(\frac{e^{\frac{C_2}{\lambda_2 T_{Soot}}} - 1}{e^{\frac{C_2}{\lambda_2 T_{BB,2}}} - 1}\right)\right]^{\lambda_2^\alpha} \quad (5)$$

[1)] Hottel and Broughton 1932 [2)] Schubiger 2001

Method



2)

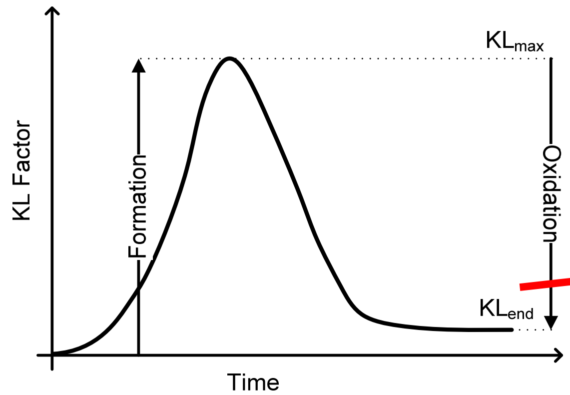
$$i_{b,\lambda}(T) = \frac{2C_1}{\lambda^5\left(e^{\left(\frac{C_2}{\lambda T}\right)}-1\right)}$$

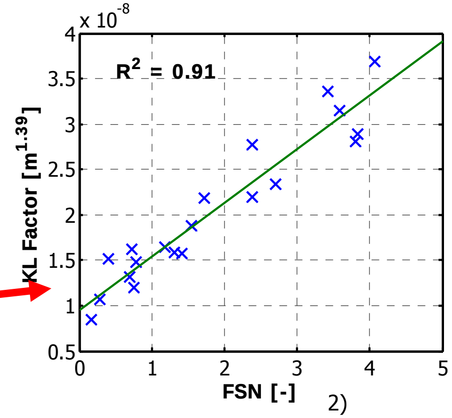
$T_{BB,1}$, $T_{BB,2}$, $T_{BB,3}$

$$\left[1-\left(\frac{e^{\frac{C_2}{\lambda_1 T_{Soot}}}-1}{e^{\frac{C_2}{\lambda_1 T_{BB,1}}}-1}\right)\right]^{\lambda_1^{\alpha}} = \left[1-\left(\frac{e^{\frac{C_2}{\lambda_2 T_{Soot}}}-1}{e^{\frac{C_2}{\lambda_2 T_{BB,2}}}-1}\right)\right]^{\lambda_2^{\alpha}}$$

T_{Soot}

$$kL = -\lambda^{\alpha}\ln\left[1-\left(\frac{e^{\frac{C_2}{\lambda T_{Soot}}}-1}{e^{\frac{C_2}{\lambda T_{BB}}}-1}\right)\right]$$





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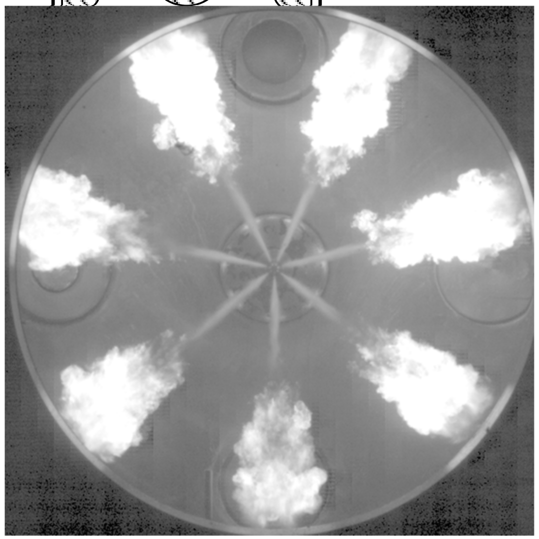


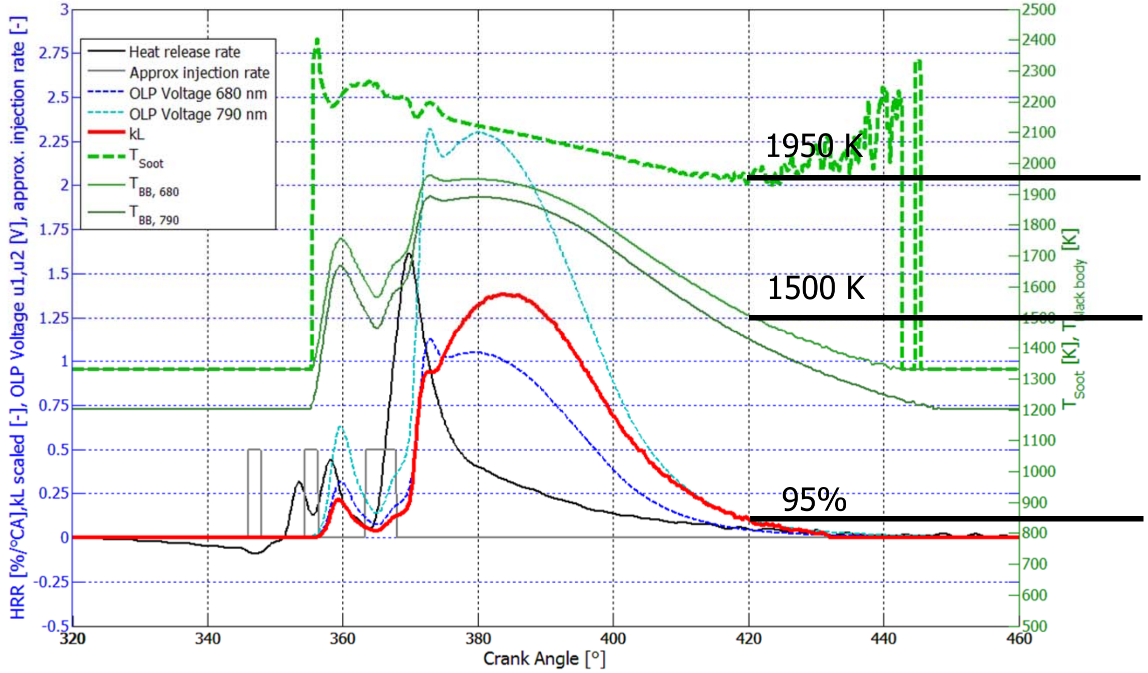
1)

1) Schneider 2003, 2) Kirchen 2008

Method

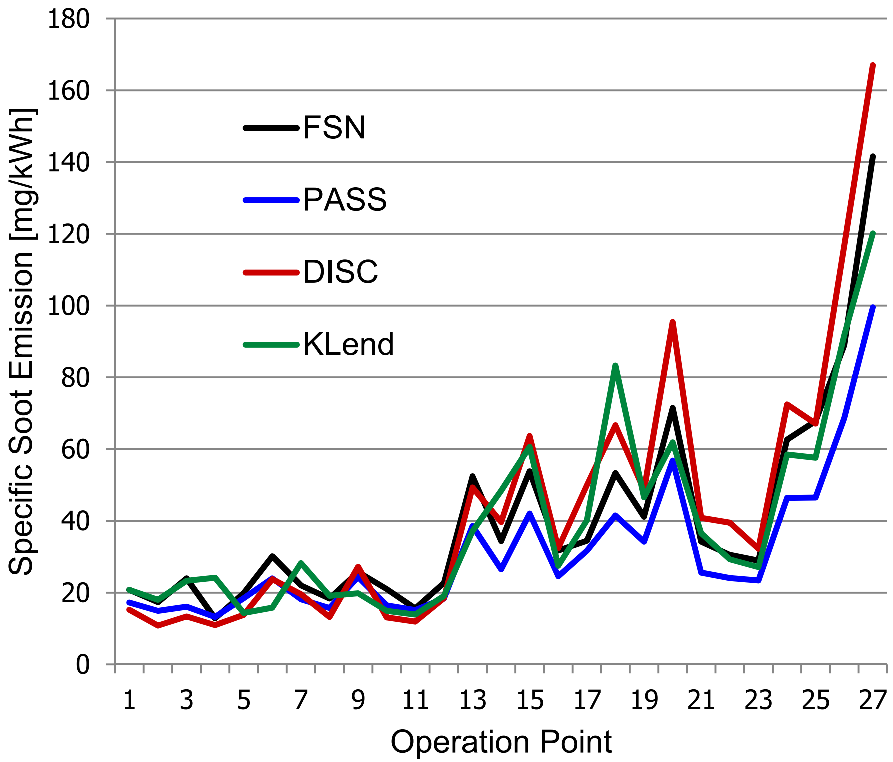
- **kL_{end} – Soot-Correlations**

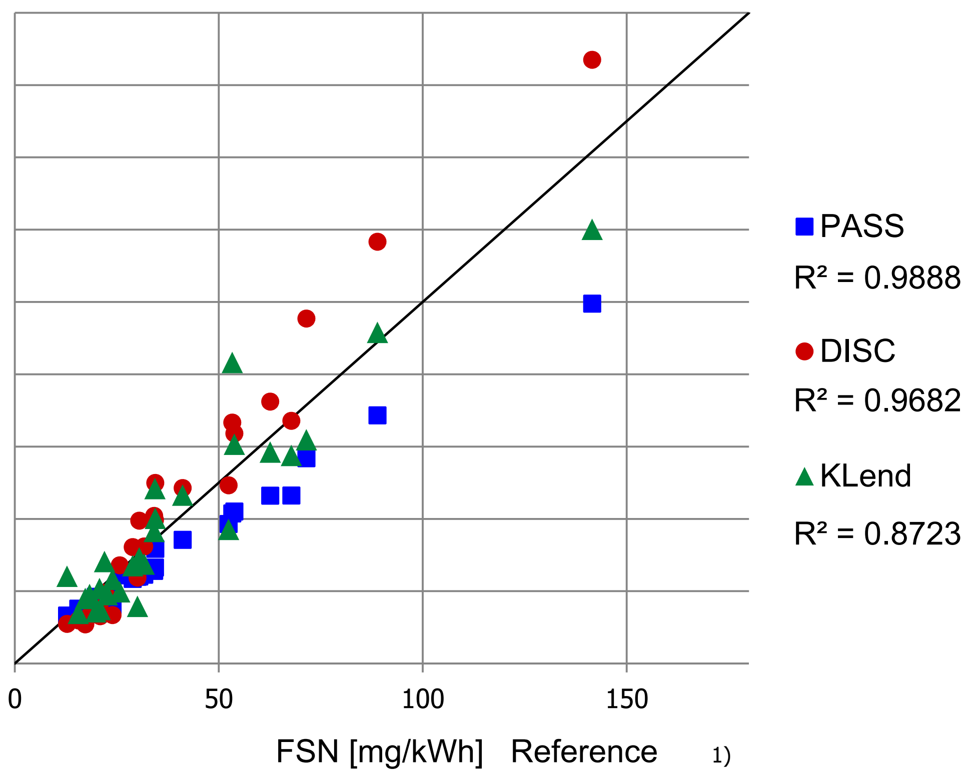
  - % of Integral kL evolution
  - Intensity (~black body temperature) threshold
  - Soot temperature threshold



Method

- kL_{end} Results from a single cylinder engine

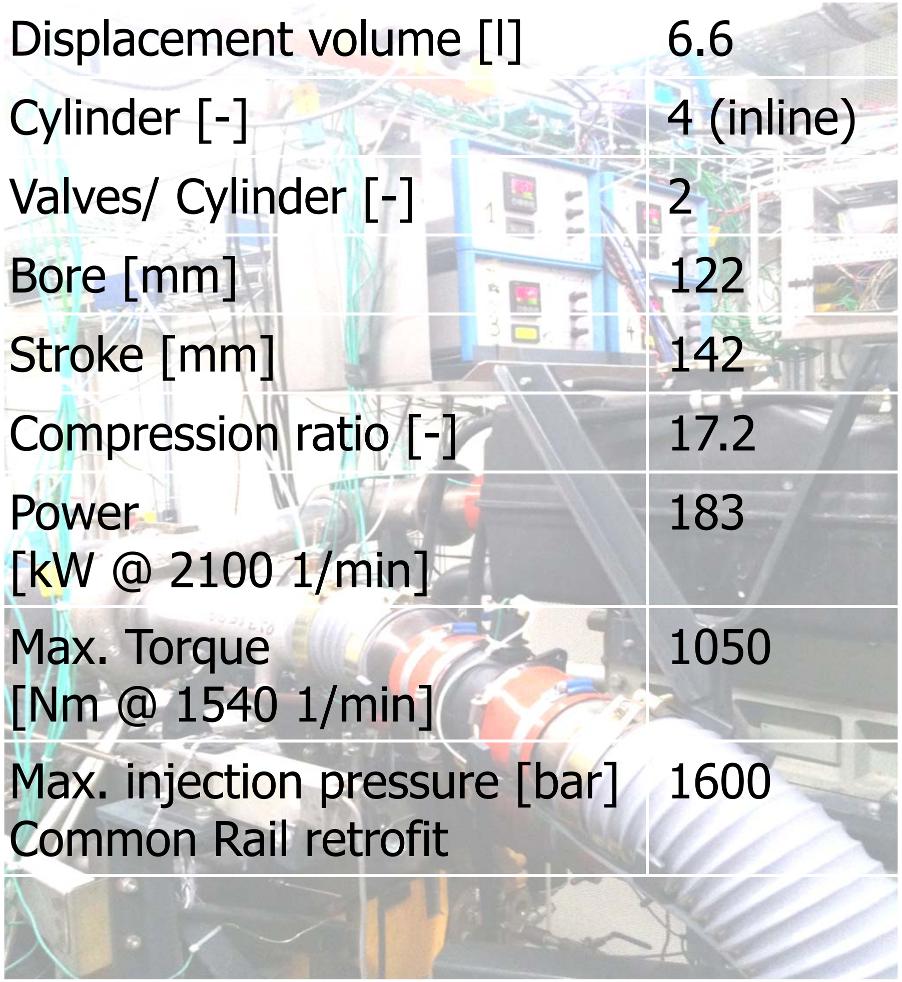




1) Barro 2010

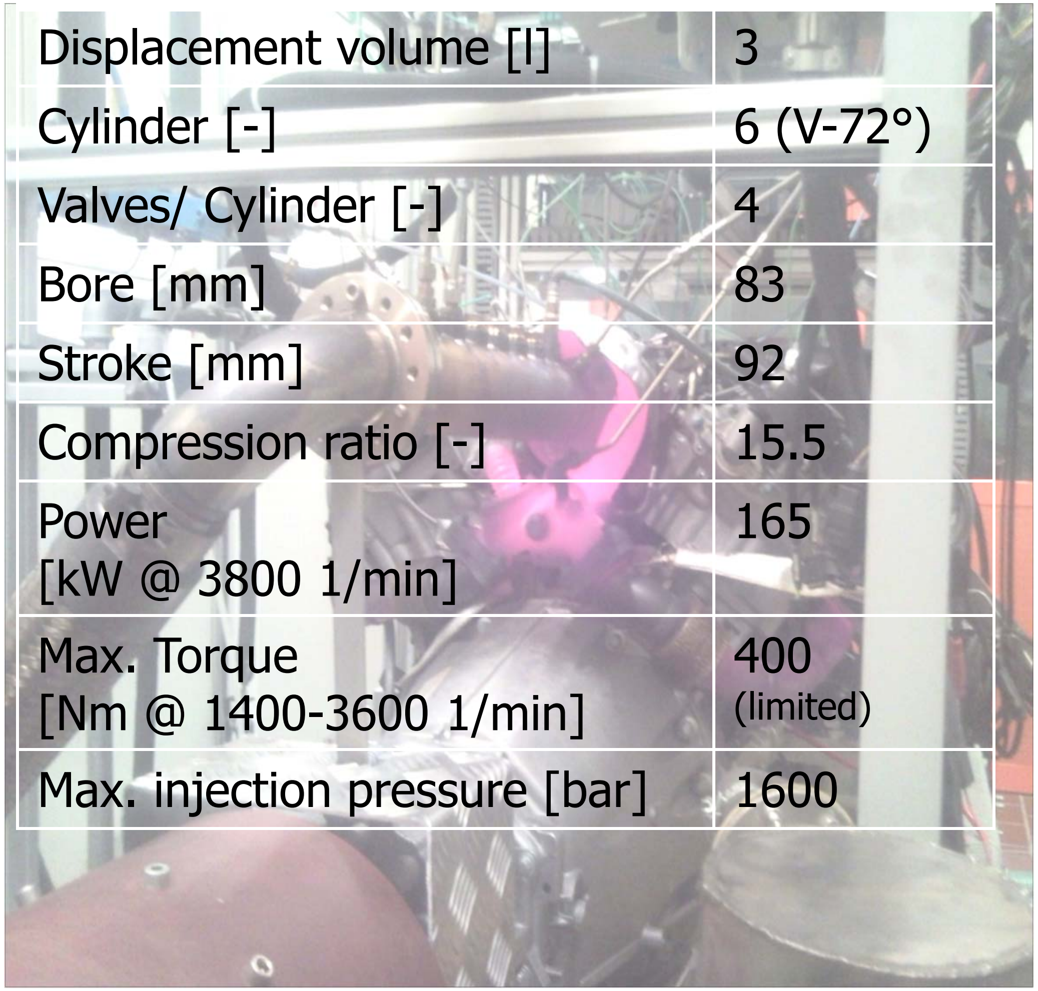
Test facility

Liebherr D924



Displacement volume [l]	6.6
Cylinder [-]	4 (inline)
Valves/ Cylinder [-]	2
Bore [mm]	122
Stroke [mm]	142
Compression ratio [-]	17.2
Power [kW @ 2100 1/min]	183
Max. Torque [Nm @ 1540 1/min]	1050
Max. injection pressure [bar] Common Rail retrofit	1600

Daimler OM 642



Displacement volume [l]	3
Cylinder [-]	6 (V-72°)
Valves/ Cylinder [-]	4
Bore [mm]	83
Stroke [mm]	92
Compression ratio [-]	15.5
Power [kW @ 3800 1/min]	165
Max. Torque [Nm @ 1400-3600 1/min]	400 (limited)
Max. injection pressure [bar]	1600

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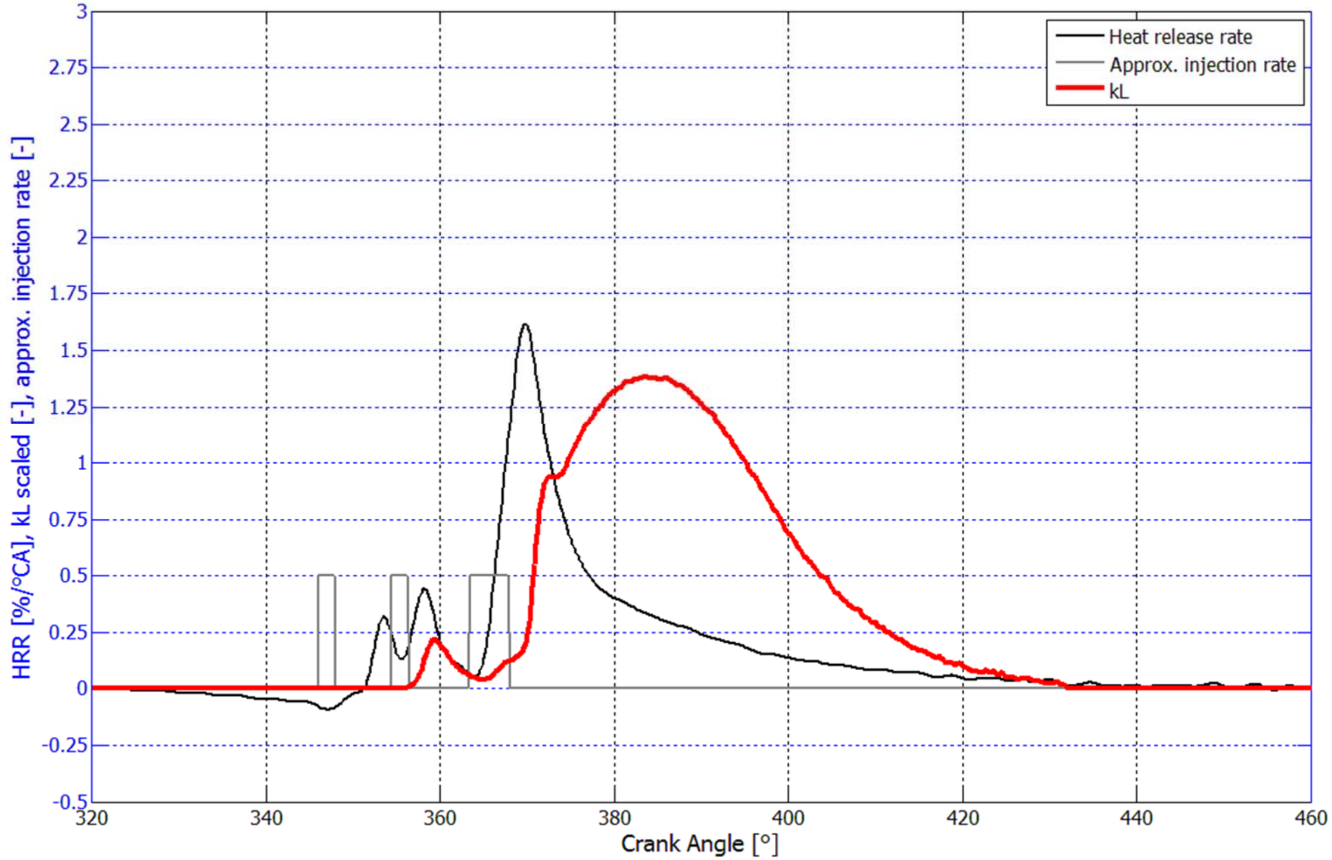
Measurement Results

- Soot formation during pilot injection Daimler OM 642

1250 rpm, 5 bar BMEP

- 2 pilot injections
- 1 main injection
- kL-Signal from 2nd pilot injection (Soot formation occurs)

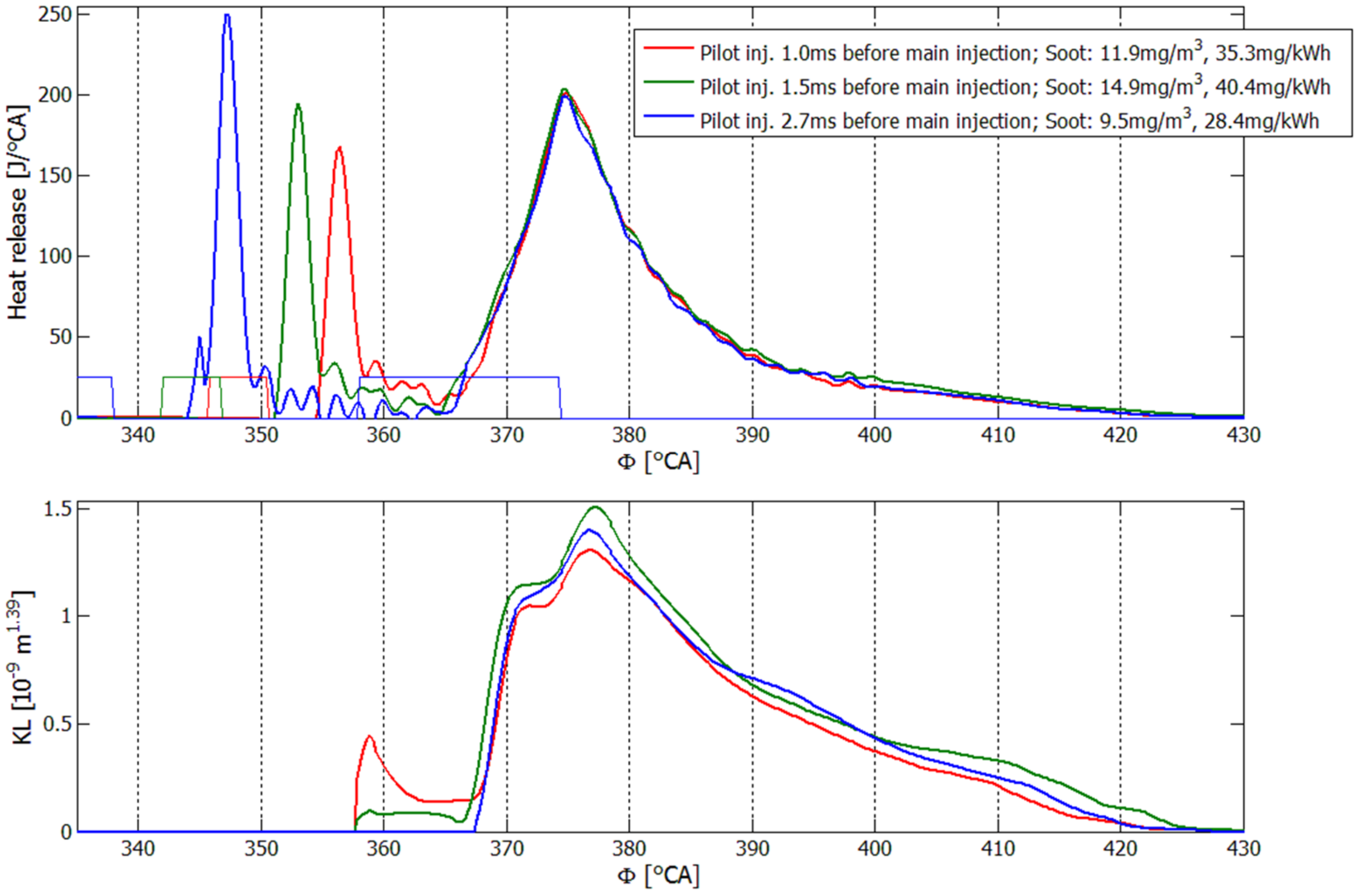


Measurement Results

- Soot formation during pilot injection Liebherr D924

1250 rpm, 80 mm³ Total Fuel

- 3 Load points with different PiI timings:
- No Soot with early pilot injection
- Soot formation form "nearer" pilot injection start at the same time



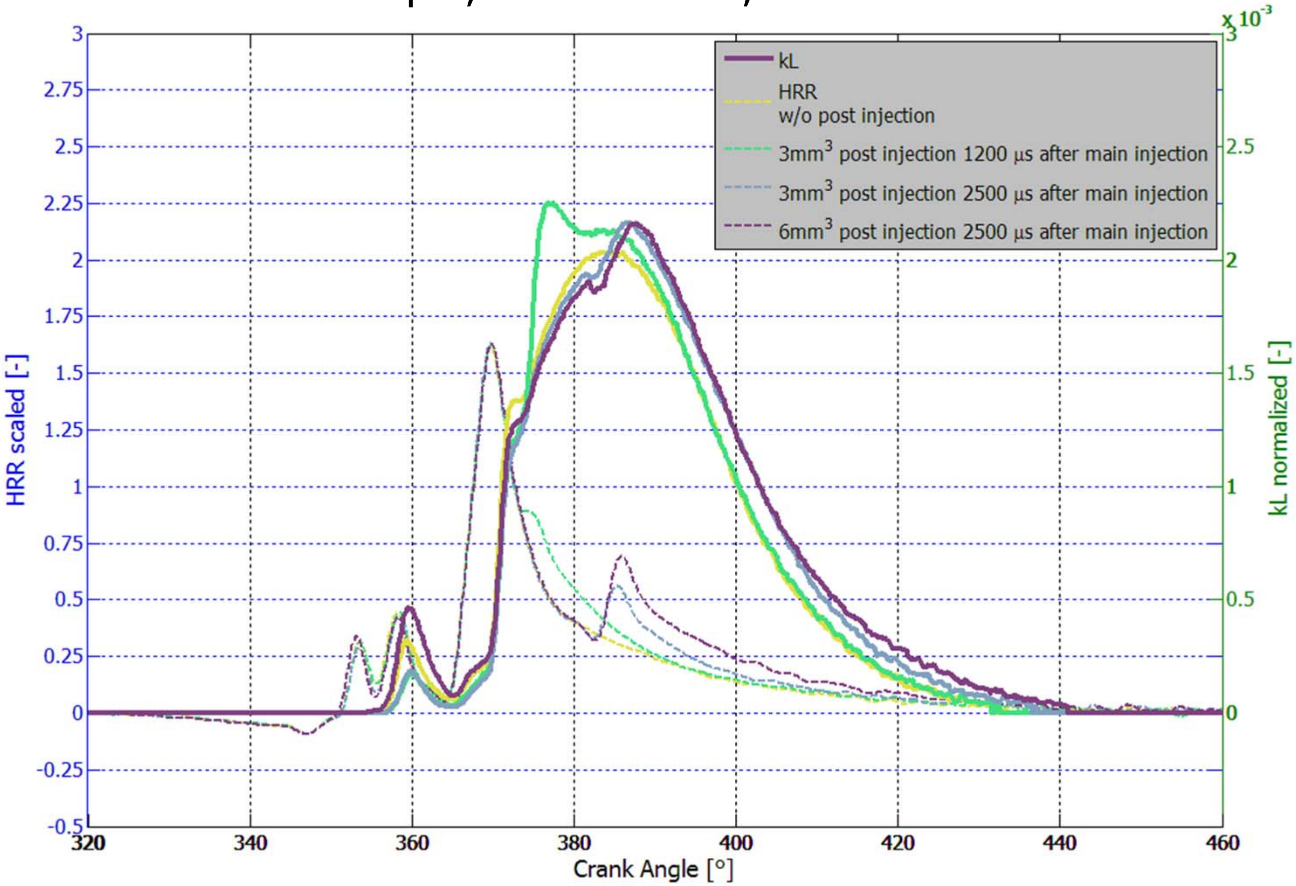
Measurement Results

- Soot formation during post injection Daimler OM 642

- 4 Load points: Soot:

- w/o PoI: 0.4 g/kWh
  42 mg/m^3
- early PoI: 0.37g/kWh
  44 mg/m^3
- late PoI 3mm^3: 0.48g/kWh
  58 mg/m^3
- late PoI 6mm^3: 0.65 g/kWh
  124 mg/m^3

1250 rpm, 5-6 bar BMEP, 20% EGR



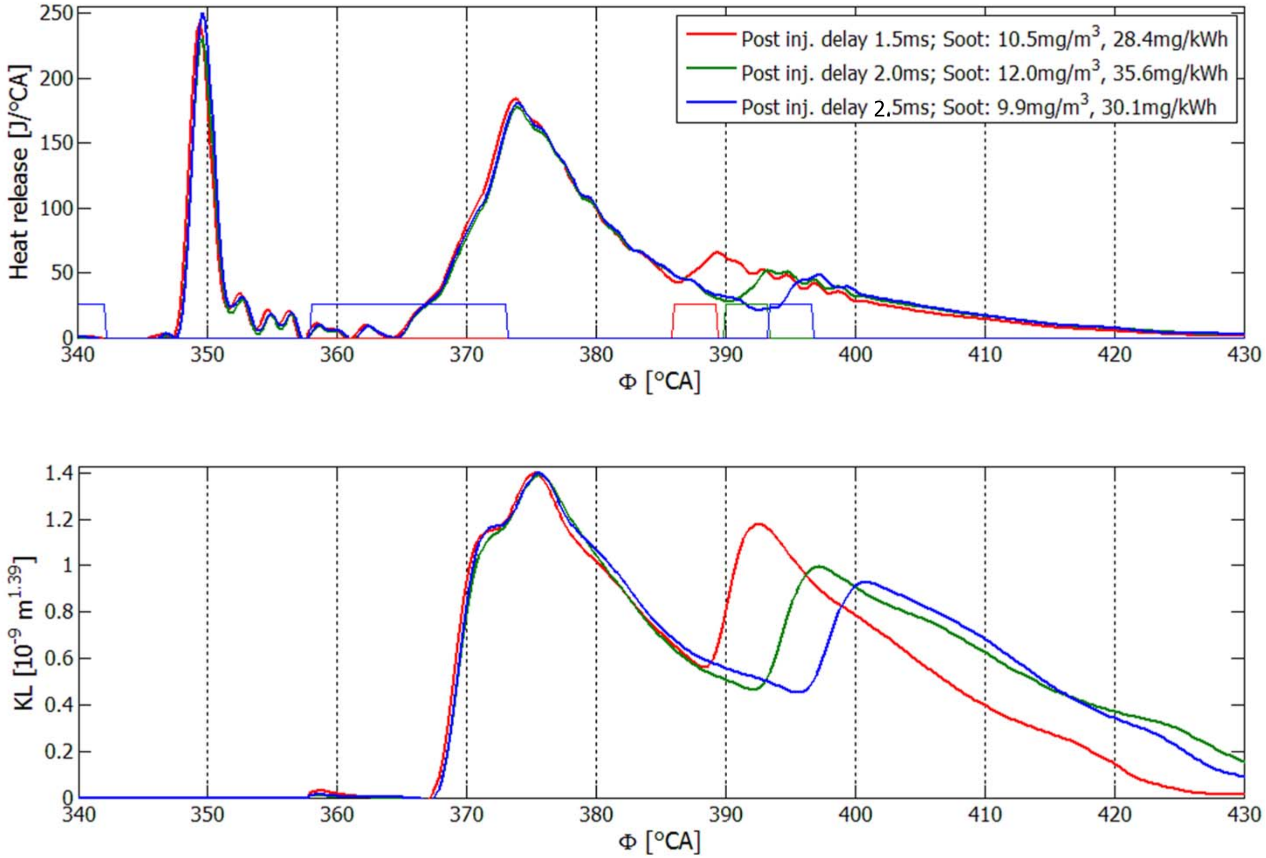
Measurement Results

- Soot formation during post injection Liebherr D924

1250 rpm, 80 mm³ Total Fuel, No EGR

- 3 Load points with different PI timings

- Soot formation during post injection



Measurement Results

- Change in soot formation and oxidation during change in EGR-Rate

- 4 Load points:

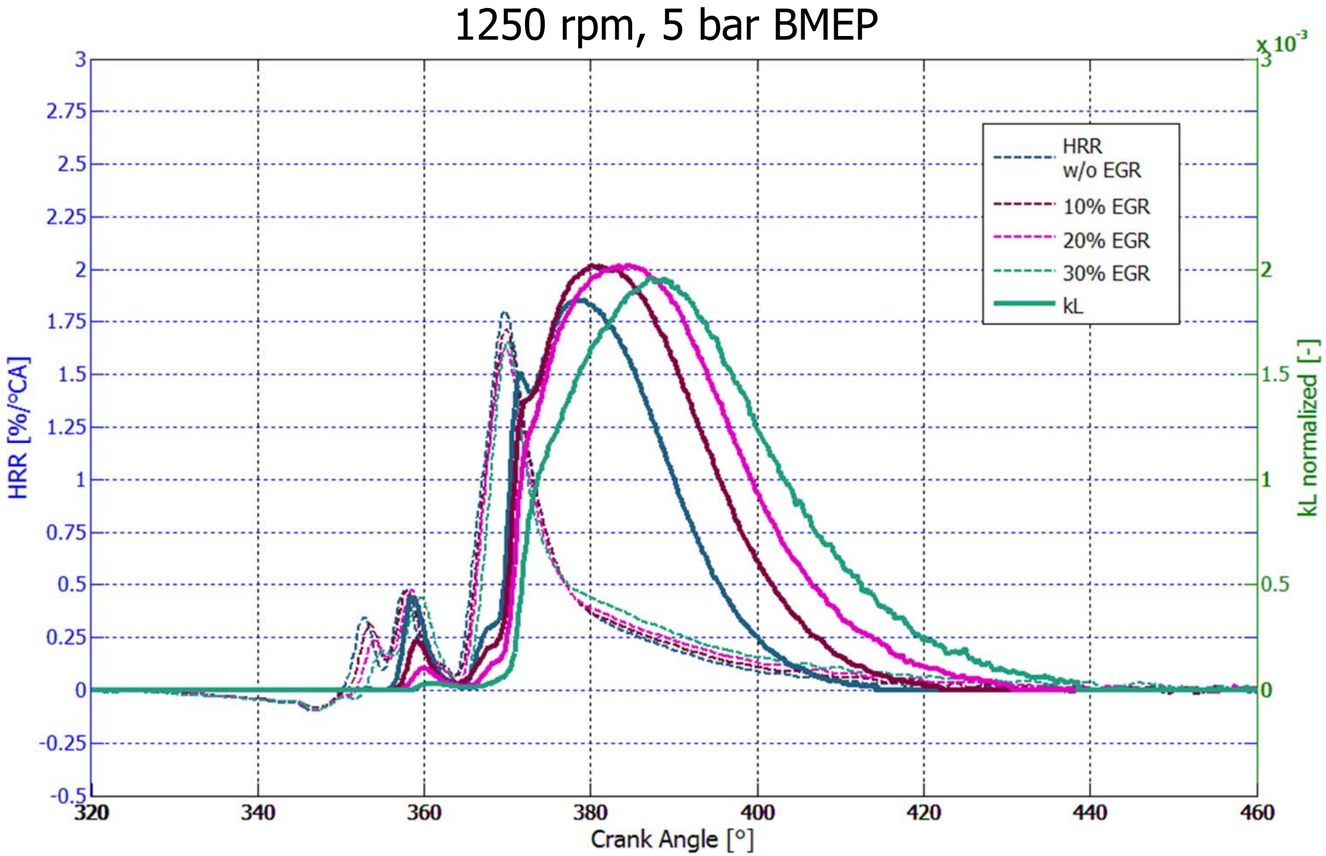
w/o EGR: 3.8 mg/m^3

10% EGR 9.1 mg/m^3

20% EGR 40.7 mg/m^3

30% EGR 215 mg/m^3

- Change of kL_{Max} - position

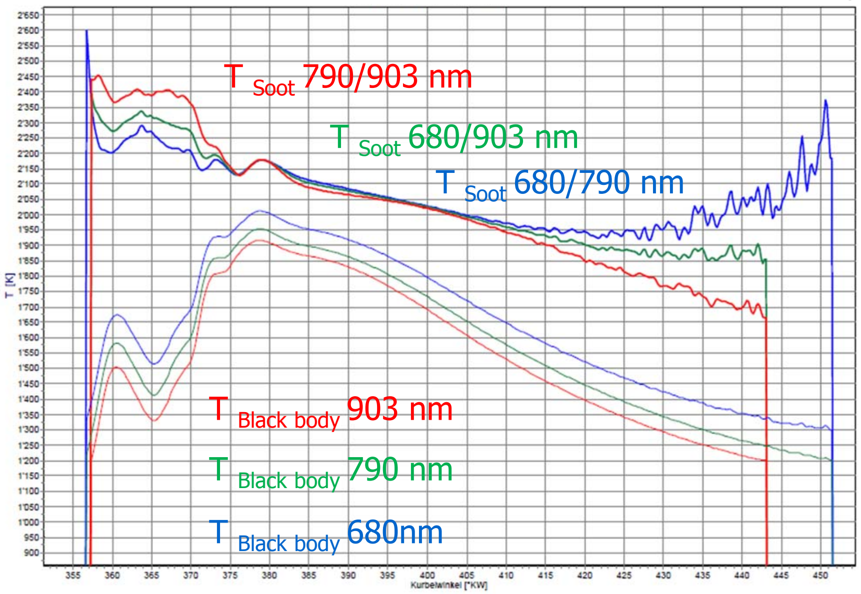


Conclusions

- **Benefits**
  - Recognition and evaluation of soot formation and oxidation during
    - either pilot injection
    - or post injection
  - Recognition of changes in soot formation rates as well as soot oxidation rates for different EGR rates

Conclusions / Outlook

OM 642 1250 rpm, 5 bar BMEP, T_{Soot} and $T_{Black\ body}$



- **Difficulties**
  - Calibration
  - Accurate thermal conditioning of the sensor
  - kL_{end} evalutation

Thank you for your attention

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