Potential of PM Reduction through Post Injection Application

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Extended Summary

The emission trade-off between PM (particulate matter) and NO_x is an issue of major concern in automotive diesel applications. Measures need to be taken both on the engine and on the aftertreatment sides in order to minimize the engine emissions while maintaining the highest possible efficiency. Past research has shown that post injections can potentially reduce exhaust PM concentration without any significant influence on the NO_x emissions. However, an accurate and general rule of how to parameterize a post injection such that it provides a maximum reduction of PM emissions does not exist. Moreover, the underlying mechanisms are not understood thoroughly. The experimental investigation presented here provides insight into the fundamental mechanisms of soot formation and reduction due to post injections under different turbulence and reaction kinetic conditions. The current work is based on measurements presentment in [1], where soot elementary carbon is measured in the exhaust (using a Photo Acoustic Soot Sensor), in parallel with measurements of the in-cylinder soot formation and oxidation processes using an Optical Light Probe (OLP). The experiments confirm observations from earlier work which shows that soot reduction due to a post injection is mainly based on two reasons: increased turbulence from the post injection during soot oxidation and lower soot formation due to lower amount of fuel in the main combustion at similar load conditions. A third effect of heat addition during the soot oxidation, which was often mentioned in the literature, could not be confirmed. The interdependence between the post injection timing and the soot formation progress is assumed to be an interaction between the spray of the post injection and the soot of the main injection. This interaction is assumed to be beneficial for the soot oxidation process and shows the highest exhaust soot reduction if the post injection occurs around the in-cylinder soot peak (Figure 1). This in-cylinder soot peak is strongly dependent on EGR-rate or swirl level.

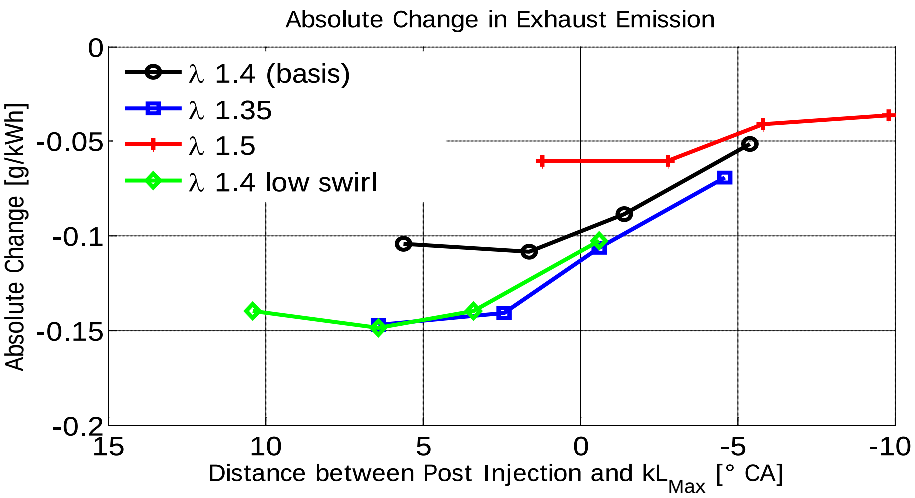

Figure 1: Absolute reduction of exhaust soot emission vs. the position of kL-maximum of the corresponding operating point w/o post injection minus start of injection of the post injection (positive if post injection is before the kL-maximum) [1].

The experimental data recorded at the engine showed that the exhaust emissions are strongly dependent on the position (timing) of the post injection relative to the progress of the soot evolution. However, the assumption of an interaction between the soot clouds of the main- and post injection is only based on a higher probability of interaction due to higher in-cylinder soot concentration since the OLP does not provide any information about the in-cylinder soot distribution. In this work, additional experimental data, recorded on a constant volume chamber with high optical access, has been compared with the measured in-cylinder data. 2D-2-Colour-Pyrometry has been applied. The spatially resolved soot- distribution confirms an influence of the soot from the post injection on the soot formed in the main injection for cases with short dwell, compared to no influence for cases with long dwell between main and post injection. Furthermore, the enhanced soot oxidation in the short dwell case is visible in Figure 2.

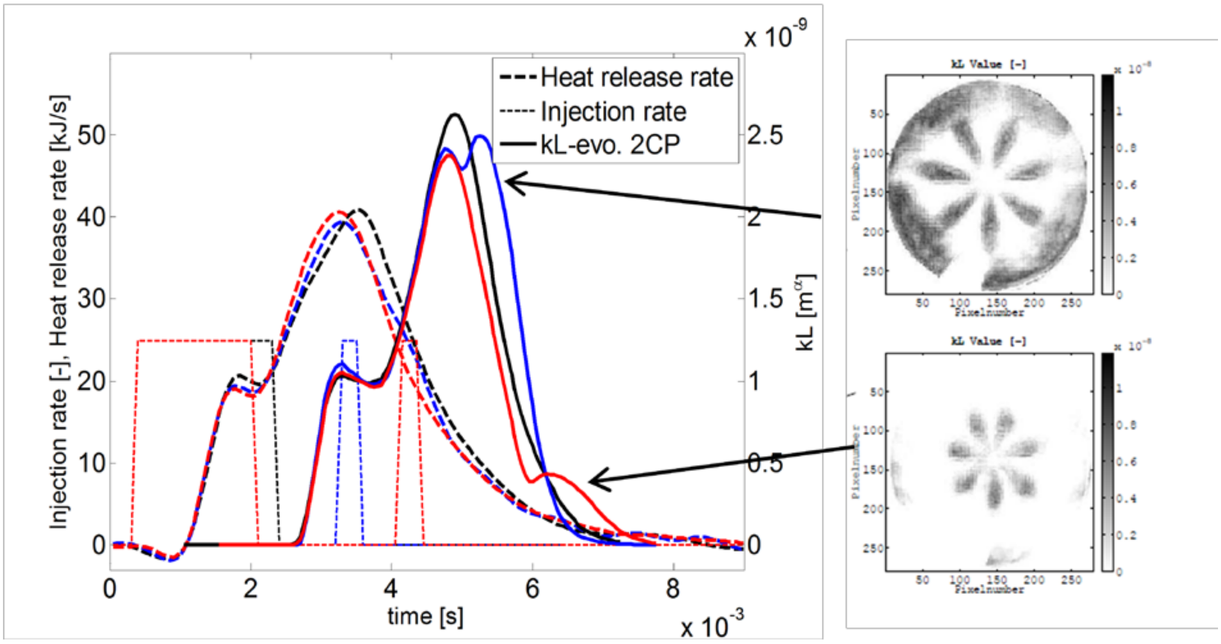

Figure 2: Left: Heat release rate, injection signal and kL evolutions of a cases without post injection (black), with early post injection (blue) and late post injection (red). Right: Corresponding post injection pictures of 2D-2-Colour-Pyrometry of early post injection case (top) and late post injection case (bottom).

However, for diesel engine applications, the threshold post injection timing, where interaction between the two soot clouds occurs is difficult to find, since the peak soot position is very sensitive on several engine operating parameters like e.g. EGR rate. Furthermore, in a common production diesel engine, the soot trace is unknown. Though the post injection application is a very fast acting tool (cycle and cylinder resolved), but its parameterization is exceedingly difficult for a permanently beneficial engine operation with respect to soot emissions.

[1] Barro C. et al. ICEF2012- 92075 Technical Conference, ASME, 2012

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Outline

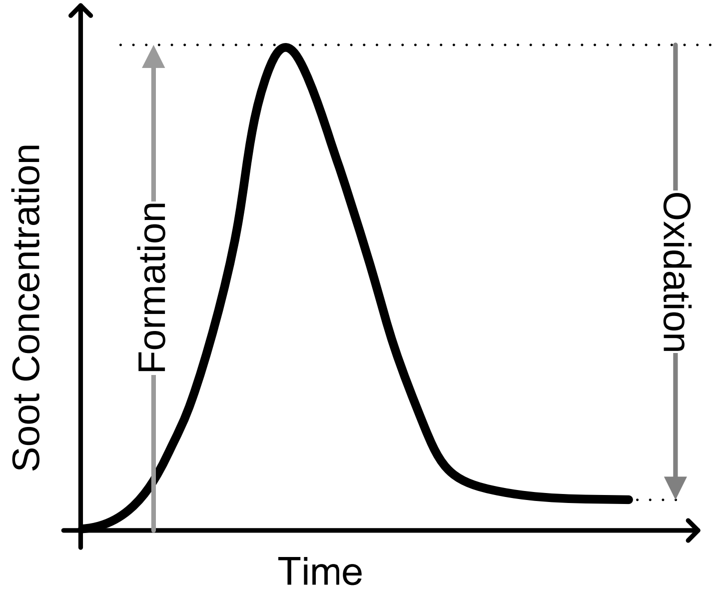
- **Introduction / Soot formation process**
- **Soot characterization**
- **Influence of post injection on in-cylinder soot evolution**

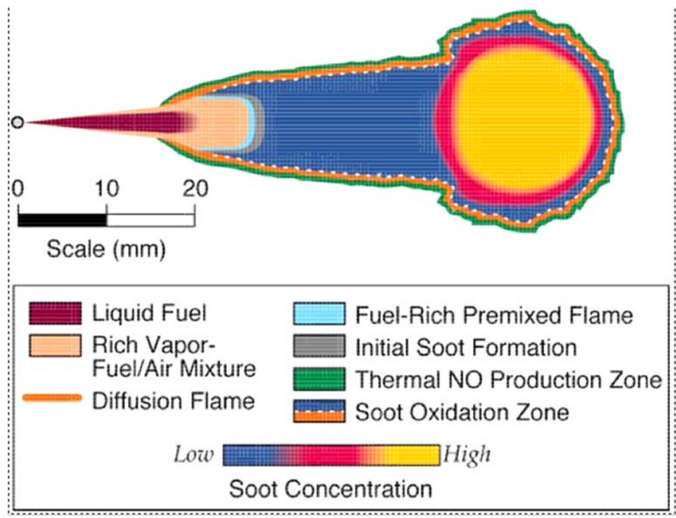
  Barro C. et al. ICEF2012- 92075 Technical Conference, ASME, 2012
- **Results**
  - 2D-2-Colour Pyrometry on a constant volume chamber
  - Influence of post injection timing
- **Conclusions**

Soot Formation in Diesel Engines

- **Soot is the result of:**
  - Formation
    - Fuel pyrolysis
    - Formation and growth of PAHs
    - Particle inception (nucleation)
    - Surface growth
    - Particle coagulation and agglomeration
  - Oxidation
    - Occurs concurrent to formation
    - Requires sufficiently high temperature and oxidant concentrations (O_2, O, OH, …)
- **Heterogeneous environment of diesel combustion**

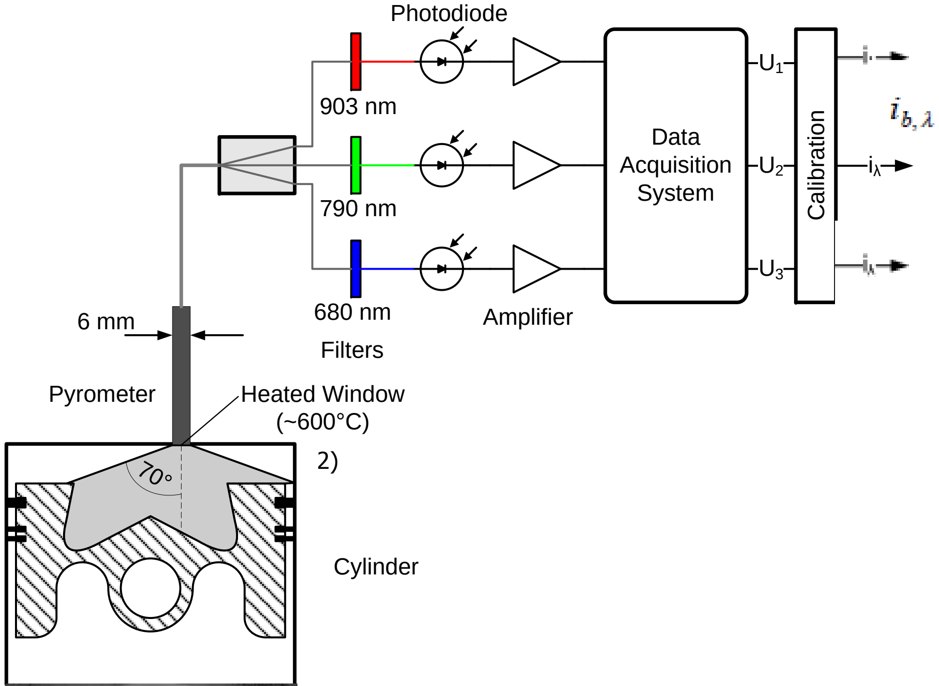
  ➔ Formation and oxidation vary over space as they are dependent on local O_2 concentration and temperature

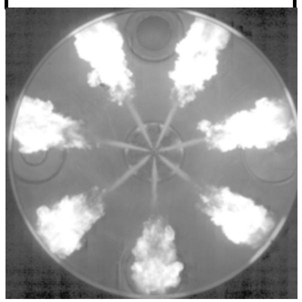




J. Dec. **SAE** 970873, 1997

Soot Characterization / Multi-Colour-Pyrometry





1)

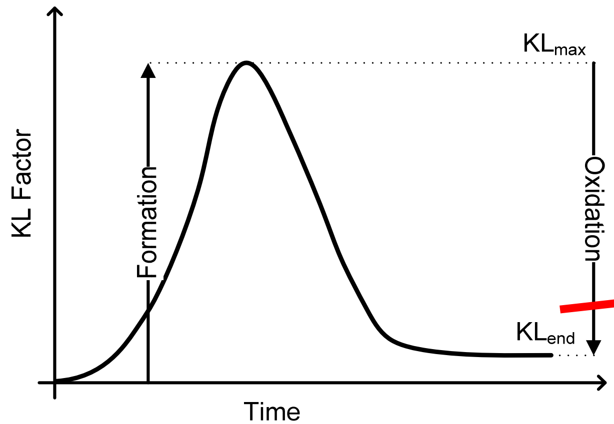
$$i_{b,\lambda}(T) = \frac{2C_1}{\lambda^5\left(e^{\left(\frac{C_2}{\lambda T}\right)}-1\right)}$$

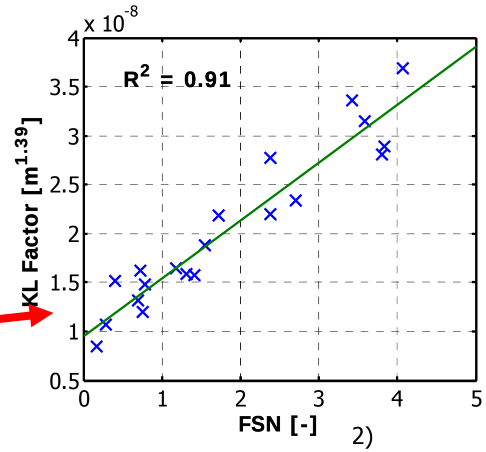
$T_{BB,1}$, $T_{BB,2}$, $T_{BB,3}$

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

T_{Soot}

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





2)

[1] Schneider 2003, [2] Kirchen 2008

Signal Overview of Multi-Colour-Pyrometry

Aquired Signals after Post Processing:

- 3 soot cloud temperature evolutions
- 3 kL evolutions
- Evolutions match for perfect calibration

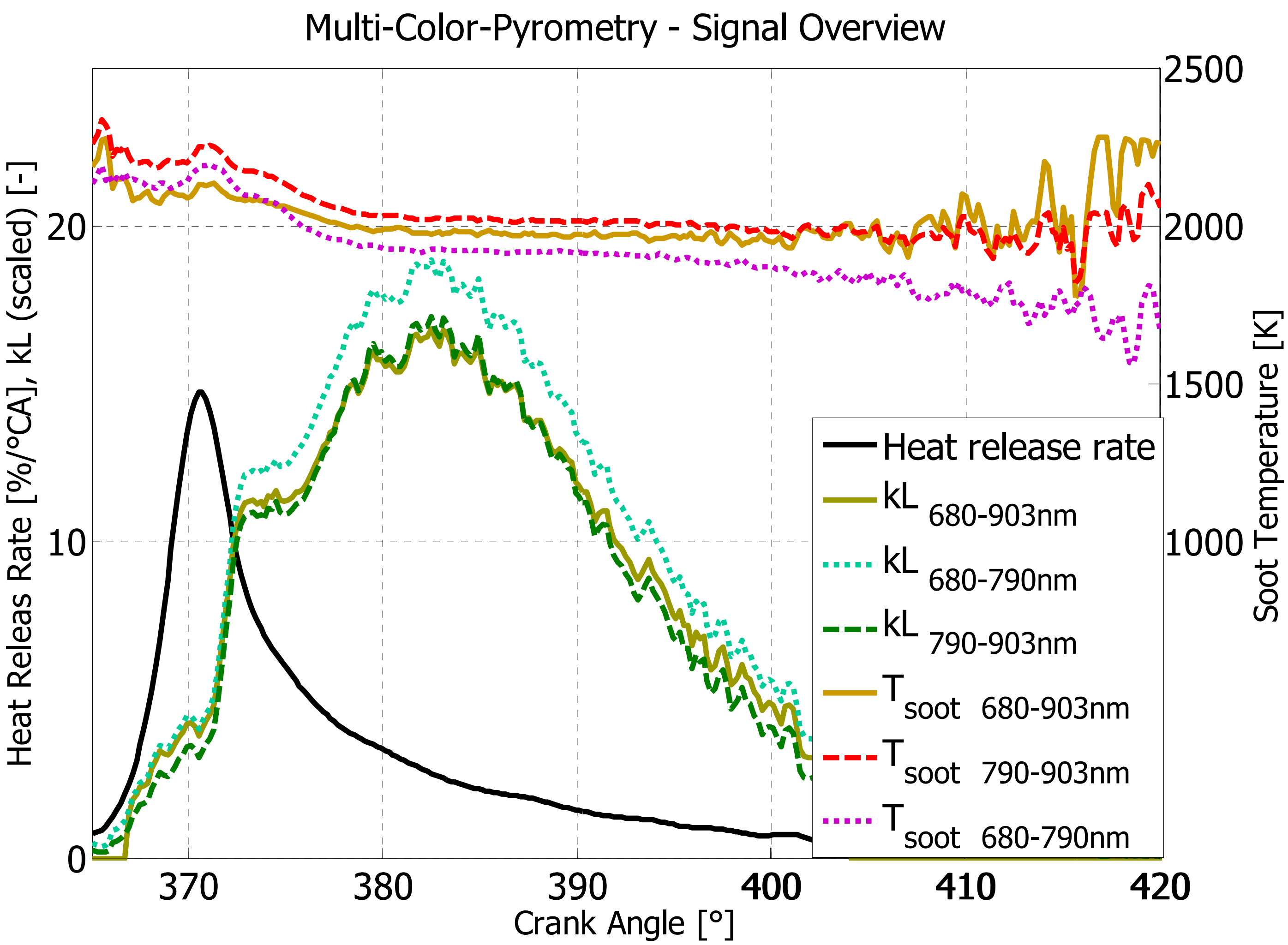


Fig: Exemplary operating point

Influence of EGR and IPS on In-Cylinder and Tailpipe Soot

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4 engine operating points with different EGR, swirl rate and **constant fuel mass**

• Basis: λ = 1.4, 28 % EGR swirl valve: IPS (Intake Port Shut-Off) closed

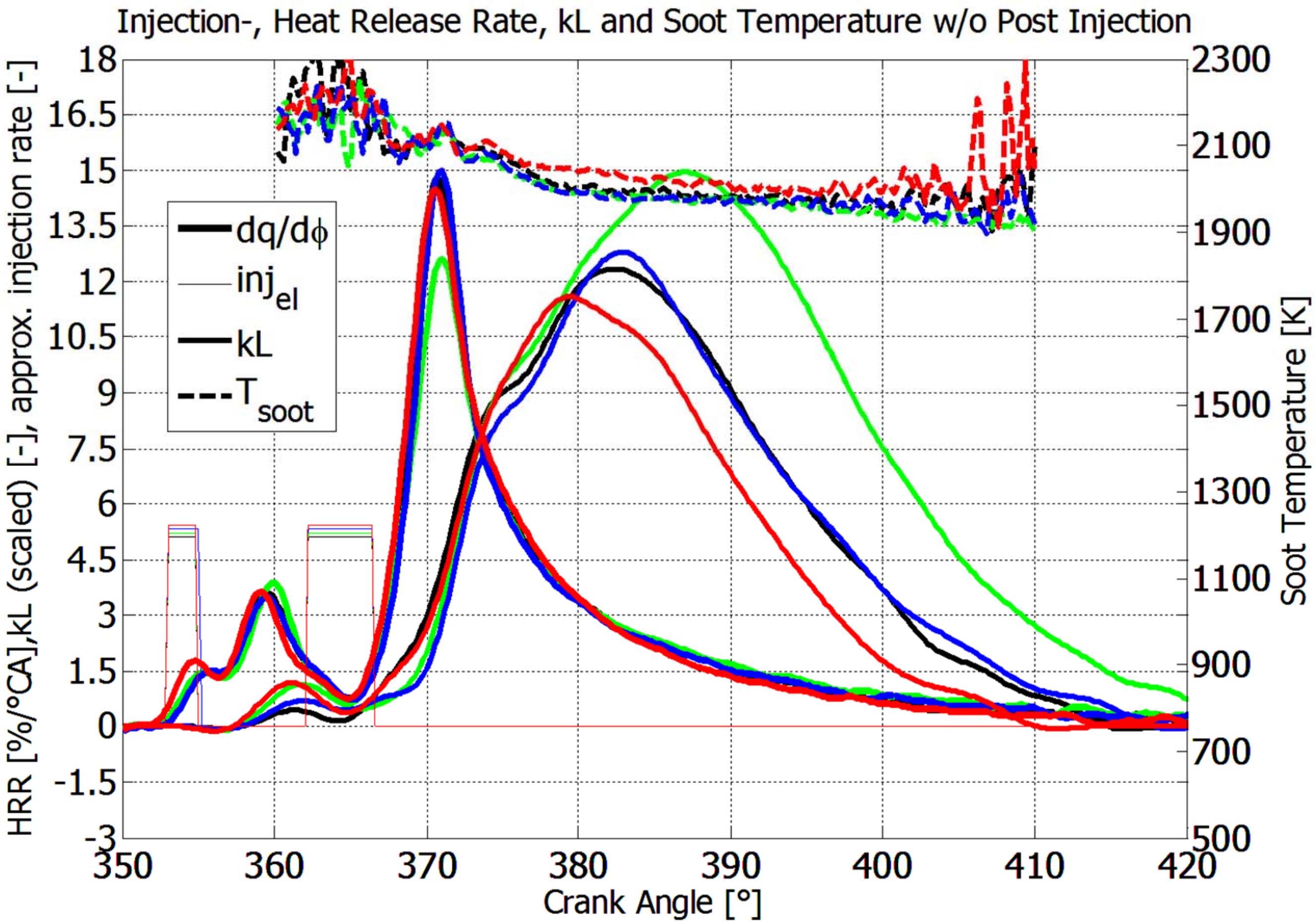
•Lowered EGR: λ = 1.5, 25 % EGR IPS closed

•Increased EGR: λ = 1.35, 30 % EGR closed IPS

•Lowered swirl λ = 1.4, 28 % EGR IPS open

-Minor influence on heat release rate

-Engine: Daimler OM 642, OLP via glow plug bore



Operating Point	Soot Emission [g/kwh]
λ = 1.4 (basis)	**0.23**
λ = 1.5	**0.13**
λ = 1.35	**0.35**
λ = 1.4, low swirl (IPS open)	**0.5**

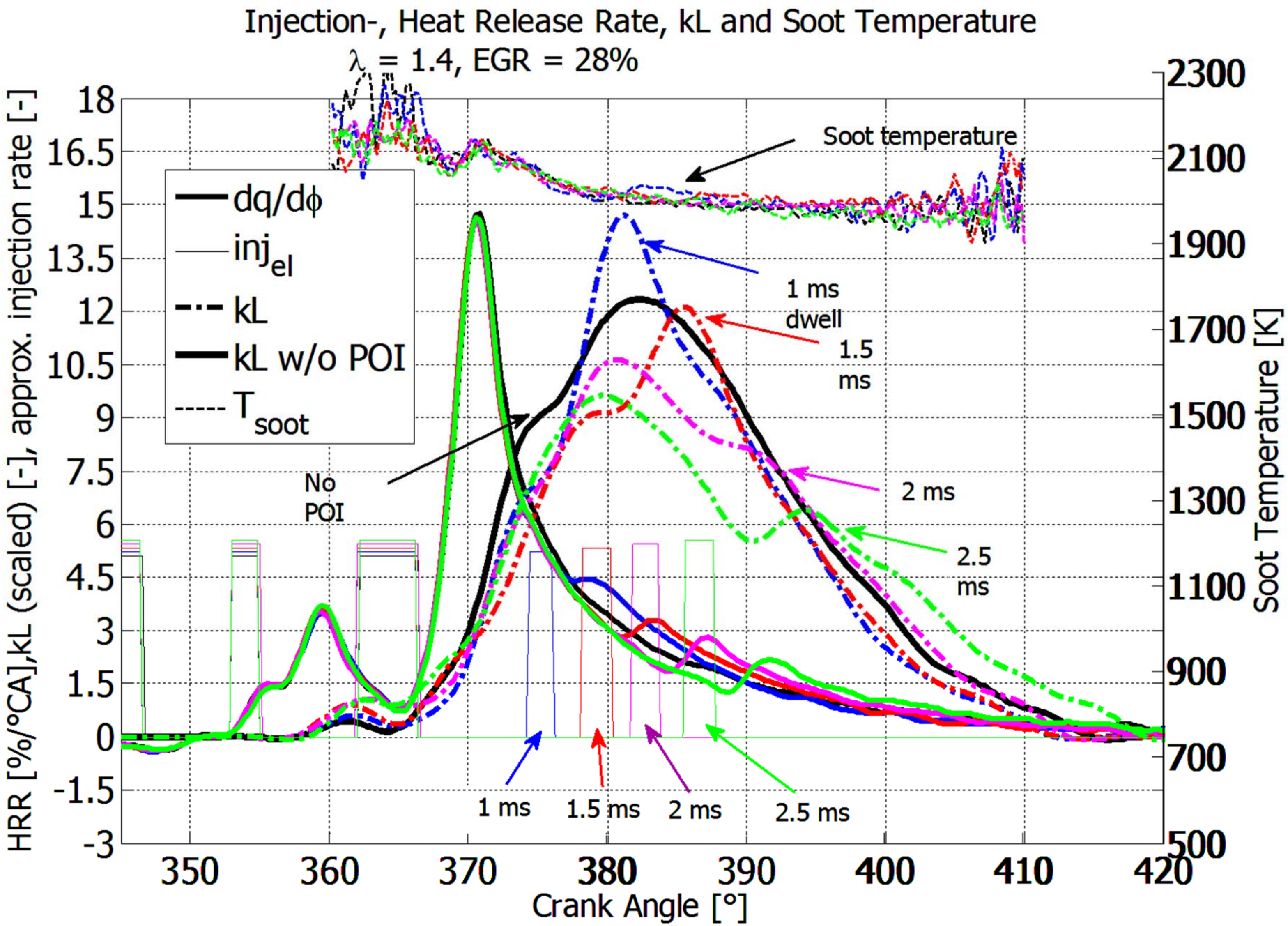
Influence of Post Injections on In-Cylinder Soot in Detail

Detailed Investigation of Post Injections:

- Post injections at 1, 1.5, 2 and 2.5 ms after end of main injection, 10% of main injection fuel mass

- Visible improvement of soot oxidation rate only for 1 and 1.5 ms POI-timing

- Soot temperature changes are negligible



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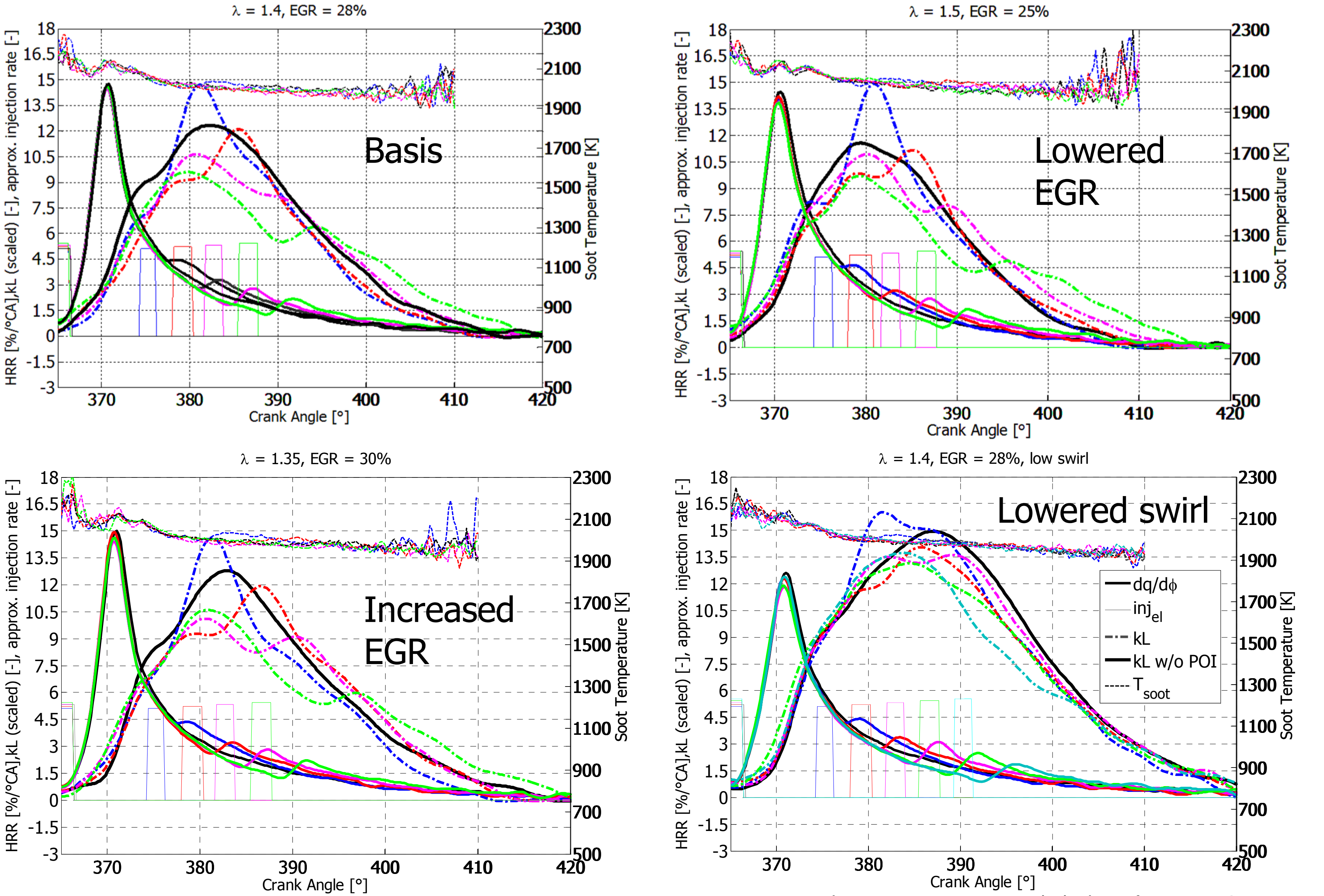
Variation of Post Injection Timing under Different Operating Strategies

- 4 operating points with according post injections

- Changes in soot oxidation rate depend on in-cylinder soot formation and oxidation progress



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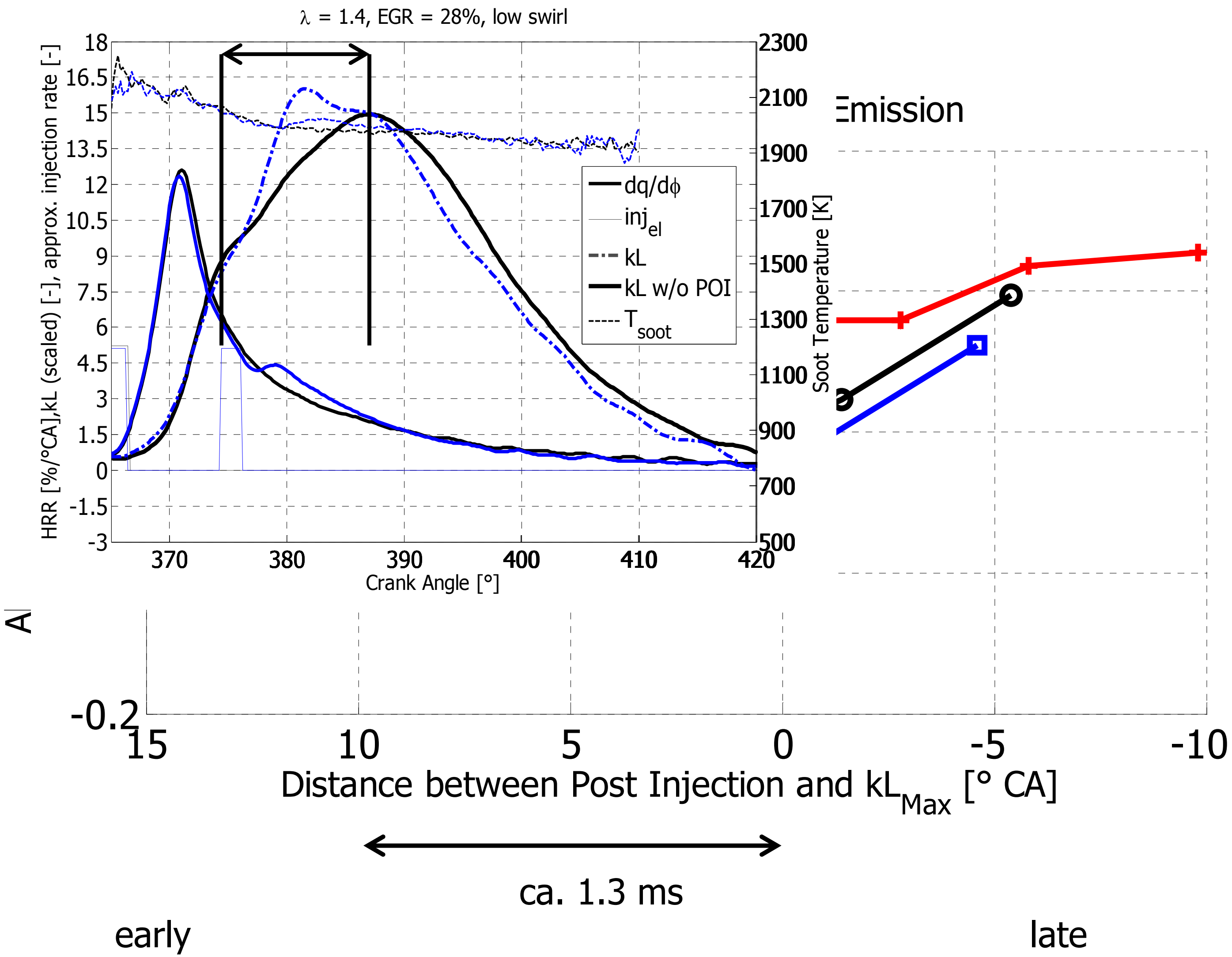
Influence of Post Injection on Exhaust Soot

Effect on exhaust emissions depending on dwell between POI-timing and kL_{max}:

-Potential of soot reduction decreases soon as the POI occurs after the soot peak



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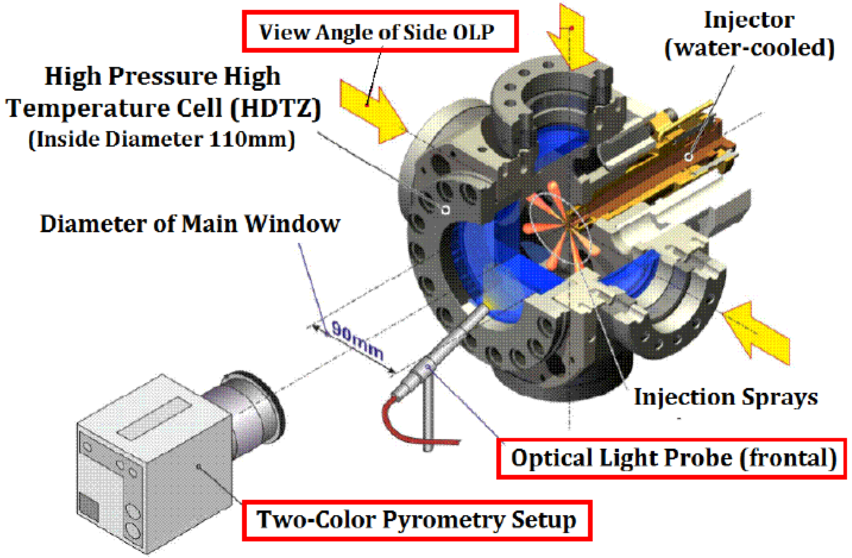
Influence of Post Injection on Spatial Resolved Soot Evolution I

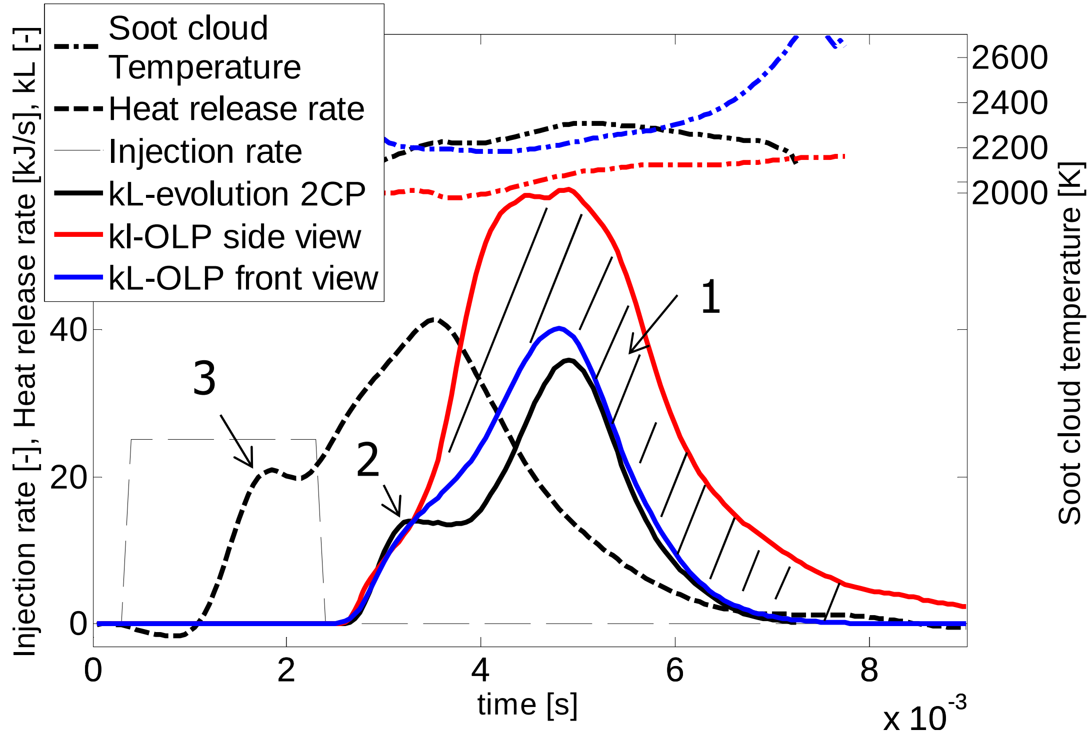
HDTZ (High Pressure, High Temperature, Constant Volume Device)



2D-Pyrometry (2CP), front view
640 and 740 nm

0D-Pyrometry (OLP), front and side view
680, 790 and 903 nm

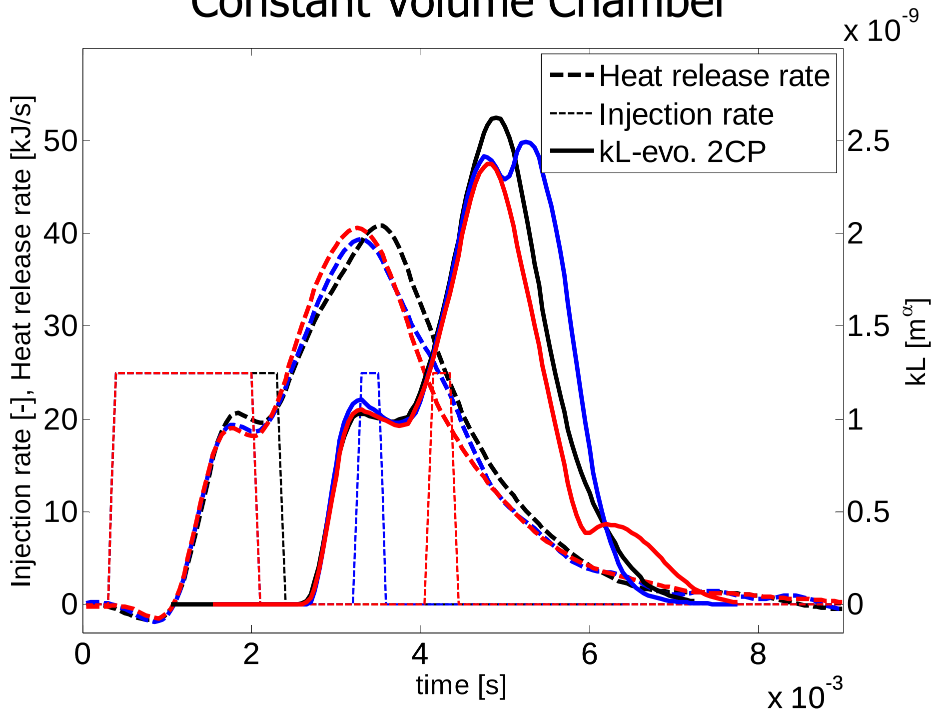
Comparison between 0D and 2D Systems



1. Difference in view-angle
2. Soot is „hidden" in non-visible area
3. Peak of premixed combustion

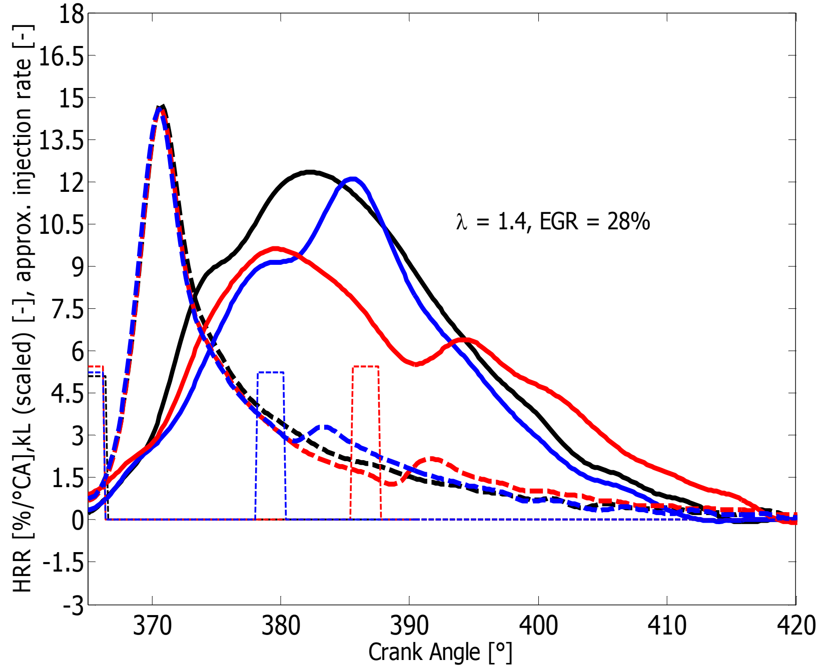
Influence of Post Injection on Spatial Resolved Soot Evolution II

Constant Volume Chamber



MI [ms]	POI [ms]	POI timing [ms after end of MI]
2	-	-
1.7	0.3	1.2
1.7	0.3	2

Engine



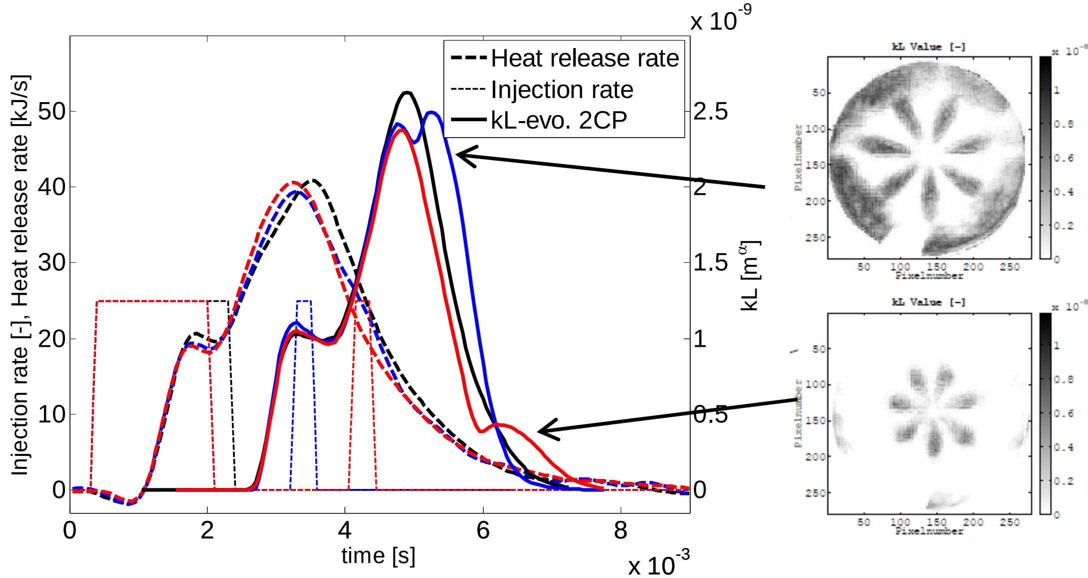
MI +PI [mm³]	POI [mm³]	POI timing [ms after end of MI]
22	-	-
20	2	1.5
20	2	2.5

Influence of Post Injection on Spatial Resolved Soot Evolution III

Early Post Injection | **Late Post Injection**

Temperature

kL-Values



Summary and Conclusions

- Soot evolution reacts sensitively to changes in turbulence and oxygen availability (in contrary to the heat release rate)
- Soot reduction due to post injection is depends on soot formation and oxidation progress at the post injection timing
- Post injections increase soot oxidation rate if interaction between the individual soot clouds occurs
- Too late post injection inhibits oxidation due to soot formation of post injection itself

Thank you for your attention