Measurement of the Instantaneous In-Cylinder Soot Temperature and Concentration in a Multi-Cylinder Engine

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OVERVIEW

GOALS: Correlation between in-cylinder and engine-out soot emissions
Characterize cylinder and cycle specific soot emissions in a multi-cylinder engine

- Overview of instrumentation and measurements
- Selection and evaluation of a suitable correlation between FSN and Pyrometry
- Use of the correlation to investigate cycle to cycle soot emission variations
- Investigation of soot formation and oxidation processes
INTRODUCTION

GOALS: Correlation between in-cylinder and engine-out soot emissions
Characterize cylinder and cycle specific soot emissions in a multi-cylinder engine

<table>
<thead>
<tr>
<th>FSN</th>
<th>Pyrometry</th>
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<tbody>
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<td>- Measurement of the steady-state, engine-out soot emissions (in exhaust system)</td>
<td>- In-cylinder measurement of soot formation and oxidation processes</td>
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<tr>
<td>- Extracted exhaust is drawn through filter paper - paper blackening is measured</td>
<td>- Light radiated from soot is used to determine:</td>
</tr>
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</table>
| - A measure of all particulate components |   | Soot temperature
|                            |   | KL-Factor (~ soot concentration)
|                            |   | Considers only hot (glowing) soot |

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<th>INTRODUCTION</th>
<th>SOOT INSTRUMENTATION</th>
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11th ETH Conference on Combustion Generated Nanoparticles 15.08.2007 Kirchen et al.
**MEASUREMENTS**

- **VW TDI, 4 cyl. (Kistler)**
- **Soot instrumentation**
  - In-cylinder 3 color pyrometry (KL-factor)
  - Exhaust mounted AVL 415S (FSN)
- **Additional parameters**
  - Cylinder pressure (cylinders 1, 2, 4)
  - Intake air pressure (1 Sensor)
  - Air mass flow rate (venturi)
  - Exhaust CO$_2$ concentration for $\lambda$
- 20 steady state operating points from the entire map
- Wide soot emission range: $\text{FSN} = 0.4 \ldots 4.1$
- Reference point
- Cylinders 1, 2, 4 with 3 color pyrometry und cylinder pressure

Reference point repeated 4x
3 COLOR PYROMETRY

- System developed by:
  - Kistler AG
  - LAV (ETH Zürich)
  - Sensoptic

- Uses 3 wavelengths for redundancy

- Window heated to 600°C to prevent contamination

- Small size permits use in production engines (glowplug adapter, for eg.)

\[ d_{\text{Sensor}} = 3\text{mm} \]
3 COLOR PYROMETRY

\[
1 - \left(\frac{C_2}{e^{\lambda_1 T} - 1}\right) \lambda_1^{1.39} = 1 - \left(\frac{C_2}{e^{\lambda_2 T} - 1}\right) \lambda_2^{1.39}
\]

\[
T_{\lambda_1, \lambda_2} = T_{\lambda_1, \lambda_3} = T_{\lambda_2, \lambda_3}
\]

\[
KL_{\lambda_1} = KL_{\lambda_2} = KL_{\lambda_3}
\]

\[
KL = -\lambda^{1.39} \ln \left[ 1 - \left(\frac{C_2}{e^{\lambda T} - 1}\right) \right]
\]
Characteristics of the KL-factor that can potentially be correlated to FSN

- Maximum KL-factor value
- 1st plateau
- 2nd plateau (KL_{end})

\[
\sum_{i=1,2,4} KL_{Cyl.i}
\]

**CORRELATION OF KL VALUES WITH FSN OVER ALL POINTS**

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<td><strong>0.91</strong></td>
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KL-FSN CORRELATION

- Maximum KL-Factor value - no correlation with FSN
- Investigation of the correlation between 1st and 2nd plateau and FSN
- Correlations using cylinder specific and summed KL factor values
- Best correlation with the summed KL factors from all cylinders

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$\sum_{i=1,2,4} KL_{Cyl.i}$

$R^2 = 0.91$
FSN and KL COMPARISON

- Time averaged, engine-out soot emissions
- Qualitative soot emission tendencies are reproduced by both methods
KL\_END VALUES

- **Cylinder 2:**
  - $KL_{\text{end}}$ is an order of magnitude higher than other cylinders
  - Non-perpendicular sensor installation
  - Additional sensor access (lower compression ratio)

- **Combustion and KL-factors in cylinders 1 and 4 are similar**

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**Cylinder Specific Considerations**

![Graphs and data](graph.png)

- Zyl. 1
- Zyl. 2
- Zyl. 4

$n=2000 \text{[min}^{-1}]$; IMEP=4.0 [bar]
CYCLE TO CYCLE VARIATIONS

- KL history compared for 144 consecutive operating cycles during steady state operation ($n_e = 2500 \,[\text{min}^{-1}]$, IMEP = 16 [bar])
- Soot formation process $\sim$ const.
- Soot oxidation higher variability

![Graph showing cycle to cycle variations in KL factor and soot temperature](image)
KL_{\text{max}} and KL_{\text{end}}

- KL_{\text{max}} \rightarrow \text{maximum soot concentration}
- KL_{\text{end}} \rightarrow \text{soot quantity after oxidation}

More soot formed at higher loads (NOT the same as engine out)

Oxidized soot fraction strongly influenced by operating point...
KL\textsuperscript{max} AND KL\textsubscript{end}

- IMEP = 12 [bar], \sim const KL\textsubscript{max}

- n_e=2000 [min\textsuperscript{-1}], KL\textsubscript{max} increasing

Oxidation influenced by:
- Turbulence (n_e, p\textsubscript{inj})
- Oxygen concentration (EGR, \lambda)
- Temperature
- Time available for oxidation
CONCLUSIONS / SUMMARY

- Engine out and in-cylinder soot emissions from a production, multi-cylinder engine were measured using FSN and 3 color pyrometry.
- The KL_{end} value provides a measure of the cylinder and cycle specific cylinder out soot emissions.
- FSN correlates well to the sum of the average cylinder specific KL_{end} values.
- Cylinder out soot emissions are defined by:
  - Soot formed (~injected fuel quantity)
  - Soot oxidized:
    - Turbulence
    - Oxygen availability
    - Temperature
- Fluctuations in KL_{end} values during steady state operation are predominantly due to fluctuations in the oxidation process.
THANK YOU FOR YOUR ATTENTION!