Investigation of In-Cylinder Soot Formation and Oxidation during Transient Engine Operation

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13th ETH Conference on Combustion Generated Nanoparticles
June 22 - 24, 2009 - ETH Zurich
INTRODUCTION

- Cycle specific characterization is necessary to understand processes
- Existing soot instrumentation is neither cylinder nor cycle specific
- 11th ETH Conference - correlation of exhaust stream and in-cylinder measurements
- 12th ETH Conference - Exhaust stream measurement of transient soot emissions
- Today: Combination of these two works to consider transient, in-cylinder processes

- Soot emissions measured using an AVL Micro Soot Sensor during ETC cycle
- Significant challenge to total emissions are „transients“

Source: Schindler et al, 2004-01-0968
OUTLINE

- Testbench and instrumentation
- Overview of in-cylinder pyrometry
- Overview of exhaust stream measurements
- Detailed analysis of in-cylinder measurements and observed phenomena
● **Passenger car, common rail engine:**
  - DaimlerChrysler OM611
  - VTG, EGR, $p_{\text{inj,max}} \sim 1350$ bar

● **Exhaust stream soot emissions:**
  - Dekati Fine Particle Sampler
  - AVL Micro Soot Sensor

● **Transient characterization of instrumentation ($\Delta t$, $\tau$)**

● **Pyrometers mounted in cylinders 1,3 and 4 provide:**
  - Soot concentration
  - Soot temperature
SOOT MEASUREMENT

- Multi-color pyrometry considers light intensity to determine in-cylinder:
  - Soot cloud temperature
  - Soot concentration (KL factor)

- Considers only hot ("glowing") soot
- Limited to soot within field of view

\[
\begin{align*}
1 - \left( \frac{C_2}{e^{\lambda_1 T} - 1} \right) & = 1 - \left( \frac{C_2}{e^{\lambda_2 T} - 1} \right) \\
T_{\lambda_1,\lambda_2} & = T_{\lambda_1,\lambda_3} = T_{\lambda_2,\lambda_3}
\end{align*}
\]

\[
KL = -\lambda^{1.39} \ln \left[ 1 - \left( \frac{C_2}{e^{\lambda T} - 1} \right) \right]
\]

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

Hottel and Broughton. *Ind. Eng. Chem.*, 1932. 4(2)
3 COLOR PYROMETRY

- System initially developed by LAV\(^1\); later in conjunction with Kistler AG and Sensoptic\(^2\)
- Uses 3 wavelengths for redundancy (T, KL cross-verification)
- Wide field of view (140°) considers “most” of the cylinder
- Window heated to \(~600°C\) to prevent contamination and provide long-term signal stability
- Very small size permits use in production engines (glowplug adapter, for eg.)

\(^1\) R. Schubiger et al. MTZ, 2002. 5(63):342-353
3 COLOR PYROMETRY

**USEFUL PARAMETERS**

- $KL_{end}$ - correlates with exhaust stream measurements ($R^2 \sim 0.8...0.9$)
- Cycle resolved engine out soot emissions

- $KL_{max}$ - measure of soot formation
- $\gamma_{ox}$ - measure of soot oxidation
- Relative characterization of formation and oxidation processes

TRANSIENT MEASUREMENTS

CONSIDERED TRANSIENTS

- **Acceleration** (speed increase)
  - No notable change over steady-state

- **Tip-in** (load increase)
  - 1250 and 2000 rpm
  - \( \Delta t = 0.5 \ldots 5 \) s

\[
\text{QSS} = f(n, p_{me})
\]

Transient and steady-state emissions compared using a Quasi Steady State (QSS) approximation\(^1\)

\(^1\)Hagena et al. SAE 2006-01-1151, 2006
- Transient soot emissions generally higher than steady-state (QSS)
- Faster transients result in much higher emissions

- Transient soot emissions lower than at 1250 rpm
- Only the fastest transient results in increased soot emissions

IN-CYLINDER PYROMETRY

TIP-IN TRANSIENT (1250 rpm)

- Comparison of normalized KL parameters during transient
- Increase in fuel quantity -> increase in KL_{max}
- Corresponding increase in oxidation (\gamma_{ox}) lags behind
  - Poor oxidation leads to increased engine-out emissions (KL_{end})
- What causes the poor oxidation?

1250 rpm
\Delta t = 0.5 s
- $KL_{\text{max}}$ not strongly influenced by transient operation
- Oxidation considerably slower during transient operation and stops earlier
- No significant differences between steady state and transient soot temperatures

$\Rightarrow$ Oxidation inhibited due to lack of $O_2$

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**OXYGEN AVAILABILITY**

**TIP-IN TRANSIENT (1250 RPM)**

- **Short term oxygen deficit caused by:**
  - Slow EGR valve closing
  - Slow increase in charge pressure
  - Rapid increase in fuel quantity

![Graph showing relative oxygen-fuel ratio over time for different time intervals.](image)

- **1250 rpm**
POST-TRANSIENT PHENOMENA

- **After transient:**
  - Transient soot emissions are lower than steady state
  - Only gradually increase and reapproach steady state value (~60s)

- **Phenomena correlates with a gradual increase in intake charge temperature**

- **Mechanism for reduction of engine-out emissions is unclear...**

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Graph:

- **2000 rpm**
- **Δt = 0.5 s**

**Axes:**
- **Time, t [s]**
- **Soot Emissions [g·kWh⁻¹]**

**Lines:**
- Measurement (trans. ave.)
- Measurement (trans. indiv.)
- QSS Approximation
**T DURING TI P-I N TRANSIENTS**

- Lower temperature after transient, when compared to QSS
- Intake charge temperature provides estimate of soot formation temperature

**Akihama et al. SAE 2001-01-0655, 2001**

**- Reduction of formation temperature results in lower soot emissions**
IN-CYLINDER PYROMETRY

TIP-IN TRANSIENT (2000 rpm)

- Same trends seen during transient as at 1250 rpm
- Influence of transient less extreme due to higher charge pressure
- Slower phenomena observed after transient (correlates with intake charge temperature)
- Causality focus of current research...

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2000 rpm
Δt = 0.5 s

Normalized KL Parameters [-]

~ Time [s]

m_f [kg/cycle]

15 13th ETH Conference on Combustion Generated Nanoparticles – Kirchen et al. 22.06.2009
CONCLUSIONS

- Multicolor pyrometry is a powerful tool for the measurements of cylinder and cycle specific, in-cylinder soot concentration and temperature
- During tip-in transients:
  - Soot formation is approximately the same as during steady-state \( (K_{\text{Lmax}}) \)
  - Soot oxidation is weaker due to an oxygen deficit \( (Y_{\text{ox}}) \)
- Only 5-10 cycles responsible for high engine out soot emissions
- Slow increase in intake charge temperature after transient results in:
  - Gradual increase in engine-out soot emissions to final steady-state values
  - Gradual increase in \( K_{\text{Lmax}} \) to steady state value
- Precise influence of charge temperature is not yet completely understood …
THANK YOU FOR YOUR ATTENTION!!

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