Microstructural Evolution of EGR Cooler Deposits

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Outline

• Exhaust Gas Recirculation as a Method for Reducing NO\textsubscript{x} Emissions
• Review new DOE-funded project: Materials Issues Associated with EGR Systems
• Experimental Methodology for Depositing Particulate Matter (PM) on Model Cooler Tubes
• Microstructural Evolution of EGR Deposits
  – Deposits from Steady-State Laboratory Cooler Tubes
  – Deposits from Half-Useful-Life Industry-Provided Coolers
Background: High-Pressure Exhaust Gas Recirculation (HP-EGR)

- High-pressure EGR is the dominant NO$_x$-reduction technology.
- Exhaust gas laden with PM flows through the EGR cooler which causes deposits to form through thermophoresis and condensation.
- The deposit thermal conductivity is very low, which reduces the effectiveness of the EGR system.
- Increasing demands placed on the technology by more stringent NO$_x$ emissions, advanced combustion, increasing use of non-petroleum-based fuels, and engine/aftertreatment system optimization requirements are leading to expansions of the technology into operational conditions that are relatively unknown or known to be problematic.
Background: Fouling of (HP) EGR Coolers

• Information about deposit formation and removal is needed:
  – Thermo-physical and chemical properties of the deposit are needed for modeling.
  – Effectiveness of EGR systems often decline but then reach a plateau. Why?
  – The deposit changes with time due to temperature and HC/water condensation.
  – What is the adhesion mechanism and how can we stop it?
  – How does the deposit affect the EGR valve.

• Bio-based fuels produce different exhaust gas chemistry and PM.
New DOE-Funded Project: Materials Issues Associated with EGR Systems

- Feb-09 Milestone: An advisory team consisting of chief engineers responsible for EGR systems from nine Diesel Crosscut Team members was assembled:
  - Caterpillar, Cummins, Detroit Diesel, Ford, GM, John Deere, Navistar, PACCAR, Volvo/Mack.

- Feb-09 Go/No-Go Decision
  - Survey EGR Team Members as to what the greatest materials issues are relating to EGR systems. The survey results clearly indicated EGR cooler fouling as the primary concern

<table>
<thead>
<tr>
<th>Component</th>
<th>Problem</th>
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</thead>
<tbody>
<tr>
<td>(HP) EGR Cooler</td>
<td>Fouling</td>
</tr>
<tr>
<td>(HP) EGR Valve</td>
<td>#1</td>
</tr>
<tr>
<td>(HP) Flow Meter</td>
<td>#2</td>
</tr>
<tr>
<td>(LP) EGR Cooler</td>
<td>Corrosion</td>
</tr>
<tr>
<td>(LP) EGR Valve</td>
<td></td>
</tr>
<tr>
<td>(LP) Flow Meter</td>
<td></td>
</tr>
<tr>
<td>(LP) Charge-air Cooler</td>
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</tr>
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</table>
Project Objective: Provide information to industry EGR specialists about fouling deposit properties

Aim is to enable improved models and potential design improvements to reduce fouling and its impact on performance

– Characterize the thermo-physical properties of the deposit under different operating conditions on model EGR cooler tubes.

– Determine the long-term changes in deposit properties due to thermal cycling and water/HC condensation.

– Leverage existing project funded by the DOE Fuels program to allow more in-depth analyses on samples from biodiesel operation.

– Determine deposit adhesion mechanisms and methods to minimize them.
Approach FY2009

• Task 1: Experimental Setup
  – We are pursuing a traditional engine-on-dynamometer to generate fouling deposits on model tubes.
  – Bench flow reactor is being built for accelerated aging of deposits.

• Task 2: Obtain and Evaluate Representative (Half-Useful-Life) EGR Coolers from Industry Members
  – This will provide a reference point that will guide our future research
  – It will also provide an opportunity to refine effective characterization tools:
    • Microstructural Analysis: SEM, TEM, Electron Microprobe, Optical Microscopy
    • Chemical Analysis: XRF, FTIR, XPS, Raman, GC-MS
    • Thermal Analysis: Heat Capacity, Thermal Conductivity, TGA/DTA
    • Neutron Tomography
  – Seven companies have provided eleven coolers for analysis.
Approach to investigating NPBF effects on EGR cooler fouling is based on studying surrogate EGR cooler tubes

- Ford 6.4-L V-8 used as exhaust generator.
- Engine was operated at 2,150 RPM with a brake power output of 49 kW.
- Exhaust passed through surrogate EGR cooler tubes at constant flow rate and coolant temperature.
  - Tubes were ¼ inch square cross-section stainless tubes.
  - Thermal effectiveness of tubes is assessed during exposure.
Experimental Conditions

• Fuel:
  – Ultra-low sulfur certification diesel (ULSD) sourced from Chevron-Phillips Specialty Chemical Company
  – 5 and 20% volume blend of soy biodiesel in ULSD (B5 & B20)

• Feed gas conditions:
  – 1.5 Smoke Number
  – 50 PPM HC (as C₁)

• Tube Conditions
  – 40, 70 and 90 °C coolant
  – 375 °C inlet gas temperature
  – 30 SLPM per-tube gas flow
Significant thermal effectiveness loss due to deposit formation occurs within a few hours

- Steady-flow, time-of-exposure experiments showed very good repeatability.

- Mass accumulation in the tubes showed similar profiles for ULSD, B5, and B20 fuels.

Thermal Conductivity at 25°C

- The average thermal conductivity of the deposit was 0.041 W/mK.
- Since the thermal conductivity of air is 0.025 W/mK, the deposit is only slightly above air and is much lower than stainless steel which is ~15 W/mK.
- The porosity of the deposit was ~98% which is the main determinant of the thermal conductivity.

<table>
<thead>
<tr>
<th>Property</th>
<th>SS 304</th>
<th>ULSD</th>
<th>B5</th>
<th>B20</th>
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</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>0.5150</td>
<td>0.4140</td>
<td>0.3725</td>
<td>0.3600</td>
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<tr>
<td>Density (g/cm³)</td>
<td>7.9300</td>
<td>0.0316</td>
<td>0.0363</td>
<td>0.0379</td>
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<tr>
<td>Cp (J/gK)</td>
<td>0.4700</td>
<td>0.8668</td>
<td>0.8170</td>
<td>0.8706</td>
</tr>
<tr>
<td>Apparent Diffusivity 1,2 (cm²/s)</td>
<td>0.0280</td>
<td>0.0190</td>
<td>0.0172</td>
<td></td>
</tr>
<tr>
<td>Diffusivity (cm²/s)</td>
<td>0.0395</td>
<td>0.0209</td>
<td>0.0115</td>
<td>0.0097</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK)</td>
<td>14.7220</td>
<td>0.057</td>
<td>0.034</td>
<td>0.032</td>
</tr>
</tbody>
</table>
• The deposit cross-sections exhibit two layers:
  – A denser bottom layer
  – A dendritic top layer
• Many dendrites seem to bend in direction of gas flow.
• No dendrites bent against the gas flow.
Heavy hydrocarbon species condense on the cold metal forming a dense layer

- This layer is very thin compared to the porous soot on top of it and thus won’t affect the effectiveness of the cooler tube.
- Due to the thermal gradient, the HC can’t condense far into the deposit and will remain near the metal.
Hypothesis for Deposit Formation under Steady-State Conditions

• PM aggregates initially deposit randomly on the surface. Hydrocarbon condenses.

• Subsequent aggregates are caught by the initial aggregates forming dendrites that grow perpendicular to the surface.

• Once a critical mass/height is reached, the gas flow will topple the dendrite, fracturing it at its base.

• The toppled dendrites will lay flat on one another forming the denser bottom layer.

• New PM aggregates from the gas will then randomly deposit in the new ‘open’ area formed following dendrite toppling.

• This process will repeat itself as the deposit thickens.
Comparison of Early-Stage and Late-Stage Microstructures

- The late-stage deposit microstructure is far coarser than the early-stage deposit.
Thermo-gravimetric Analysis in Argon (Devolatilization)

• The late-stage deposit had 10 times more hydrocarbon and 20 times the density than the early-stage deposit.

• The thermal conductivity of the late-stage deposit is likely to be far higher than the early-stage deposit as well.
Mud-cracking is observed in many coolers

- Mud-cracking and subsequent spallation of the deposit may be a significant regeneration mechanism.

- Spontaneous regeneration of the EGR cooler has been reported.
Clogging of Cooler

- Some coolers exhibited significant clogging.
- Here, hydrocarbon-rich strata can be observed in the deposit (left).
- This suggests the importance of HC transients in deposit formation.
- There may be simple changes to the operating conditions that can mitigate problems like this.
Effect of Geometry

- Heat exchanger geometry has an enormous effect on the deposit properties: thickness, porosity, hydrocarbon content.
- Spallation often occurs adjacent to turbulators.
Summary

- A team of industry advisors has been assembled that will help guide future research directions of this pre-competitive research.

- An engine and a sampler tube system for laying down controlled PM deposits is being designed and purchased. A portable gas manifold for controlled post-deposition aging is being built.

- A conceptual model of deposit formation under steady-state conditions has been proposed based on microstructural imaging.

- Comparison between the early-stage and late-stage cooler deposits suggest the importance of aging and transient operation.
Acknowledgements

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Questions?