Plugging of Exhaust Gas Recirculation Coolers

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Background: Exhaust Gas Recirculation Cooler Fouling

- High-pressure exhaust gas recirculation (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 HC condensation.
- During rich combustion, the high concentration of HCs in the exhaust gas may accelerate the rate of deposition causing plugging of the EGR cooler channels.
- More stringent regulations require the expansion of EGR into engine operating realms known to be problematic.
Exhaust Gas Recirculation Cooler Fouling Causes 1 to 2% Loss of Efficiency

**Stabilized Effectiveness Loss**

- Deposits reduce cooling effectiveness, but do not typically restrict gas flow.
- Low-density, low-K, powdery deposit.
- May be mitigated by changes in cooler geometry or engine operation.

**Loss of Flow (Plugging)**

- Deposits form plugs strong enough to occlude gas passages.
- Usually evidence of large hydrocarbon influence.
- Lacquer-like or tar-like consistency.
Recent Work on Stabilized Effectiveness Loss at ORNL

### Surface Treatments did not Reduce Fouling

<table>
<thead>
<tr>
<th>Tube type</th>
<th>Mass gain, mg/cm²</th>
<th>Effectiveness loss, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain 316 SS</td>
<td>0.598</td>
<td>16.7</td>
</tr>
<tr>
<td>Polished SS</td>
<td>0.598</td>
<td>17.9</td>
</tr>
<tr>
<td>Al₂O₃-BN</td>
<td>0.601</td>
<td>19.5</td>
</tr>
<tr>
<td>Ni-Teflon®</td>
<td>0.600</td>
<td>19.4</td>
</tr>
<tr>
<td>SiO₂-Si-O</td>
<td>0.303</td>
<td>16.9</td>
</tr>
</tbody>
</table>


### EGR Cooler Deposits were Removed Through Flow-Induced Shear

C.S. Sluder, J.M.E. Storey, and M.J. Lance, “Removal of EGR Cooler Deposits Through Flow-Induced Shear” to be presented at SAE 2013 World Congress & Exhibition.

### 5-factor, 3-level Design-of-Experiments with 9-liter John Deere Engine


### High-Temperature SEM Heating Stage Used to Visualize Devolatilization

C.S. Sluder, J.M.E. Storey, and M.J. Lance, “Removal of EGR Cooler Deposits Through Flow-Induced Shear” to be presented at SAE 2013 World Congress & Exhibition.

With Carl Justin Kamp (MIT)
2nd Round of Coolers Representing Specific Applications

- First round of industry-provided “half-useful-life” coolers came with little information.
- A second round was requested with more information about cooler origins.
- Coolers tended to show the plugging failure mode from applications requiring long idling times; school buses, delivery trucks, etc.

Thermogravimetric Measurements

- Coolers A & B were both lacquer-like and had the lowest ash content.
- Cooler C burned at a low temperature and showed exothermic spikes during oxidation.
- Cooler D was very wet and oily and contained the most ash.
Videos Taken While Heating in Air are Useful for Visualizing Deposit Behavior at High Temperatures

- Cooler D was soot mixed with oil.
Cooler A: Deposit Flowed and Boiled During Use

• Industry Representative:
  - “This particular test was an extremely severe EGR valve sticking test. The EGR valve and throttle were forced open, the engine ran at low idle, and timing was retarded by 7 degrees.”

• Bubbles in the deposit were observed using neutron tomography.
Cooler A: Lacquer Deposit Starts to Soften around Room Temperature

- Density = 1.2 g/cm³
  - More similar to a polymer than fuel or oil.
- Thermal Conductivity = 0.11 W/mK
Fourier Transform Infrared (FT-IR) Spectroscopy of Cooler A Showed the Presence of Oxygen-containing Hydroxyl and Carboxyl Groups

- X-ray Photoelectron Spectroscopy (XPS) showed 15 at% oxygen and 0.5 at% nitrogen.
• Peaks are variants of 2 to 4 ring PAHs and oxygenated PAHs with a narrow range of melting/boiling points.
• Cooler B contained 3 to 5 ring PAHs.
• Paraffinic fuel or oil peaks are not present.
• Deposit chemistry was representative of PM collected from low temperature combustion regimes – “proto-soot” compounds that have not lost all of the hydrogen necessary to form particulate carbon.
These Observations Compare well to Recent Experimental Work

  – Resinification of phenols through contact with formaldehyde.
  – High amounts of NO$_x$ will produce nitric acid which acts as a catalyst.
  – Dew point of HC is critical. EGR walls must be held at temperatures above dew points.
Cooler C Deposit Contained Oxygenated Species

IR Imaging from 500 to 700°C in Air

- An infrared camera revealed local heterogeneous oxidation likely caused by oxygenated PAHs feeding the combustion.
- Contained similar HC species to coolers A and B but at far lower concentrations and more dispersed by soot.
- Soot may be hindering the gas-liquid phase reaction that produces lacquer.
Summary

• Coolers exhibiting plugging failure were donated by industry representatives.

• Coolers A and B contained lacquer-like deposits which were composed of polycyclic aromatic hydrocarbons possibly polymerized by aldehyde and catalyzed by nitric acid.
  – This deposit can be prevented by maintaining the cooler above the dew point of the hydrocarbons.

• Cooler C contained the similar species as the lacquer but at lower amounts with more soot.

• Cooler D deposit was probably due to a failure in a lubricant seal.