Key Parameters Affecting DPF Performance Degradation and Impact on Lifetime Fuel Economy

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Ash Accumulation Reduces DPF Life and Engine Efficiency

DPF Ash Accumulation

- Incoming ash/soot particles
- Ash composition
- Exhaust conditions/Regeneration
- DPF design parameters
- DPF operating history important

FEP $\rightarrow f(\Delta P)$

Source: K. Aravelli

Image: Adapted from ORNL

Efficiency & DPF Life

DPF Design Parameters

Lube/ Fuel 

Engine-Out Emissions

DPF Ash Accumulation

DPF $\Delta P$ Catalyst

Efficiency & DPF Life

Engine-Out Ash Emissions

Lubricant Additives

Image: Adapted from ORNL
Ash Accumulation and Deposit Formation Differs from PM!

\[ \tau_{cr} \]

~ 100 nm

~ 1 \( \mu \)m
Experimental Apparatus – DPF Performance Testing

Cummins ISB 300
- Variable geometry turbocharger
- Cooled EGR
- Common rail fuel injection
- Fully electronically controlled
- Gaseous and PM emissions measurement systems

DPF Bench Reactors

Accelerated Ash Loading
Accurately Simulate Key Oil Consumption Mechanisms

• Each parameter independently variable
• Precise control of quantity and characteristics of ash generated

Accelerated Ash Loading System

System Specifications

• Exhaust heat exchangers – counter flow
• Centrifugal blower – backpressure control
• D5.66” x 6” DPF
Initial Ash Deposition and Layer Formation

Ash layer build-up evident by changing ΔP profiles.

Benefit from ash layer formation

Ash layer not fully established until 10 g/L or ~50,000 miles
Unlike PM depth filtration in DPF surface pores, very little soot penetrates into ash layer.
Ash Primary Particles Exist as Porous Shells

Multiple length scales for porosities in ash layer and primary particles.

\[ \Delta P_{\text{Wall/Ash/Soot}} = \left( \frac{\mu}{K_p} \right) \cdot v_w \cdot w \]

\[ K = f(\varepsilon, \overline{D_p}) \]

\[ \varepsilon = 1 - \frac{\rho_{\text{Packing}}}{\rho_{\text{Theoretical}}} \]

Potential to improve ash packing!
Additive Chemistry Impact on Ash Properties

Lubricant matrix all formulated to 1% sulfated ash, except base oil.

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Ca</th>
<th>Mg</th>
<th>Zn</th>
<th>P</th>
<th>S</th>
<th>B</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ppm</td>
<td>ppm</td>
<td>ppm</td>
<td>ppm</td>
<td>ppm</td>
<td>ppm</td>
<td>ppm</td>
</tr>
<tr>
<td>Base</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>8</td>
<td>60</td>
<td>1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Base + Ca</td>
<td>2,928</td>
<td>5</td>
<td>&lt;1</td>
<td>2</td>
<td>609</td>
<td>3</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Base + Mg*</td>
<td>&lt;1</td>
<td>2,070</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>460</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Base + ZDDP</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>2,612</td>
<td>2,530</td>
<td>6,901</td>
<td>1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Base, Ca+ZDDP*</td>
<td>2,480</td>
<td>&lt;1</td>
<td>1,280</td>
<td>1,180</td>
<td>2,750</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Base, Mg+ZDDP*</td>
<td>&lt;1</td>
<td>1,730</td>
<td>1,280</td>
<td>1,180</td>
<td>2,840</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Commercial CJ-4</td>
<td>1,388</td>
<td>355</td>
<td>1,226</td>
<td>985</td>
<td>3,200*</td>
<td>586</td>
<td>77</td>
</tr>
</tbody>
</table>

Composition of ash directly related to lubricant additive chemistry.

<table>
<thead>
<tr>
<th>Major Ash Components</th>
<th>Density $g/cm^3$</th>
<th>Melting Point °C</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaSO$_4$</td>
<td>2.96</td>
<td>1,460</td>
<td>Sinters/Decomposes $\sim$1,250 °C</td>
</tr>
<tr>
<td>CaZn$_2$(PO$_4$)$_2$</td>
<td>3.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zn$_2$(P$_2$O$_7$)</td>
<td>3.75</td>
<td></td>
<td>Sintering begins $\sim$800 °C</td>
</tr>
<tr>
<td>Zn$_3$(PO$_4$)$_2$</td>
<td>4.00</td>
<td>900</td>
<td>Sintering begins $\sim$800 °C</td>
</tr>
<tr>
<td>Zn$_2$Mg(PO$_4$)$_2$</td>
<td>3.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>3.58</td>
<td>2,832</td>
<td></td>
</tr>
<tr>
<td>MgSO$_4$</td>
<td>2.66</td>
<td>1,124</td>
<td>Decompostion 900-1,100 °C</td>
</tr>
</tbody>
</table>
Ash Chemistry Impacts Ash Properties and DPF $\Delta P$

Flow Bench @ 25 C, Space Velocity: 20,000 hr$^{-1}$

Cordierite 200/12

Differences in DPF $\Delta P$ due to ash properties ($\rho$, $\varepsilon$, $D_p$)

Ash Distribution Profiles
### Sensitivity of DPF Design Parameters to Ash

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Porosity</th>
<th>Mean Pore Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Trial</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>2nd Trial</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>3rd Trial</td>
<td>Moderate</td>
<td>Low</td>
</tr>
</tbody>
</table>

#### Additional DPF Parameters
- Filter/substrate materials
- DPF coatings and catalysts
- Filter geometry and cell configuration

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**Multi-Cartridge Filter Holder**

**12 DPF Segments**

**Ash Loading**
Sensitivity of DPF Porosity to Ash Accumulation Varies

- Sensitivity of $\Delta P$ to ash accumulation increases with decreasing DPF porosity at low filter ash levels.
- At high ash loads, ash dominates $\Delta P$, which is insensitive to initial DPF porosity of filter, over range tested.
Exhaust Conditions Also Continually Changing

DPF Temperature Distribution

(300-420K Miles, HD Diesel)

- Potential for short excursions above 700°C over DPF operating history
- Exhaust flow rates also vary considerably, even over highway drive cycle
Elevated Temperatures Exert Large Effect on Ash Packing

High Flow Exposure to 200,000 hr\(^{-1}\)

- Ca (28 g/L, Per)
- Zn (28 g/L, Per)
- CJ-4 (13 g/L, Per)
- CJ-4 (33 g/L, Con)
- CJ-4 (42 g/L, Per)

Change in ΔP

-2.2% -2.4%
1.7%
2.4%
-5.3%

High Temperature Exposure

- Control (No Ash)
- 28 g/L Ca Ash
- 28 g/L ZDDP Ash
- 13 g/L CJ-4 Ash
- 42 g/L CJ-4 Ash

Ash Volume Reduction Fast

DPF core heated to 880 °C in 5 min, then quenched.

Lab Ca
Field
Lab CJ4
Field

650 C
800 C
1,000 C
Chemical and Physical Changes in Ash at High Temps.

Equilibrium Crystal Structures formed at High Temperatures

![Image of crystal structures](image)

\[ \min \left( \int \gamma_S dA_S \right) \]

![Image of elemental maps](image)

Ash Composition Changes Irreversibly

![Graph showing ash composition changes](image)
Understand Influence of Regeneration on Ash Properties

- Active/Passive strategies may impact ash agglomeration and mobility
- Role of soot interactions with ash during regeneration important

Regeneration Parameters

- Thickness of PM Layer
- Role of NO₂ from DOC vs. CDPF
- Temperature and flow conditions
- Catalysts interactions
Video: PM Oxidation with Ash (DPF Cross Section)
Summary and Conclusions

I. Ash Build-Up: Ash loading of ~ 10 g/L or around 50,000 miles required to form fully-established ash layer.

II. Ash Morphology: Two porosity scales identified in ash layer and ash primary particles, which are themselves hollow.

III. Lube Chemistry: Ash properties and DPF pressure drop strong function of additive composition.

IV. Exhaust Conditions: Transient changes in temperature induce much larger variations in ash packing than high flow rates.

V. DPF Parameters: DPF pressure drop relatively insensitive to original substrate porosity following ash layer build-up.

VI. Regeneration Effects: Preliminary optical studies highlight importance of regeneration parameters but requires further study.

Detailed understanding of all system parameters important to reduce impact of ash on DPF degradation and fuel efficiency.
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