Exhaust Aftertreatment Technologies for Curtailment of Diesel Particulate Matter and Gaseous Emissions

By Aleksandar Bugarski, Ph.D.

Exhaust Aftertreatment Technologies for Curtailment of Diesel Particulate Matter and Gaseous Emissions

- Diesel particulate matter (DPM), total carbon (TC), and elemental carbon (EC):
  - Diesel particulate filter (DPF) systems;
  - Filtration systems (FS) with disposable filter elements (DPEs);
  - Flow through filter (FTF) systems.

- CO and hydrocarbons:
  - Diesel oxidation catalytic converters (DOC).

- NO and NO₂:
  - Selective catalytic reduction (SCR) systems;
  - Lean NOₓ catalyst.

- Exhaust aftertreatment systems integrated with engine systems.
Implementation of retrofit aftertreatment technologies is perceived as important tool in reducing exposures in underground mines.

• **Current Trends (DOC OEM and DPFs retrofit)**
  
  – Diesel oxidation catalytic converters (DOCs) for CO and HC;
  
  – Flow trough filter (FTF) systems;
  
  – Diesel particulate filter (DPF) systems;
  
  – Filtration systems (FS) with disposable filter elements (DFE).

• **Future Trends (OEM and retrofit)**
  
  – DOC;
  
  – DPF or FTF systems;
  
  – Selective catalyst reduction (SCR).
  
  – Integrated engine/exhaust aftertretament systems
Diesel Particulate Filter (DPF) Systems

• **Design:**
  – Filtration media;
  – Catalyst;
  – Regeneration.

• **Performance:**
  – Effects on particulate emissions;
  – Effects on gaseous emissions.

• **Implementation:**
  – Selection;
  – Installation;
  – Maintenance.
Diesel Particulate Filters (DPFs)  
Filtration Media

- wall flow monoliths (honeycomb)
  - Cordierite (2MgO-2Al₂O₃-5SiO₂);
  - Silicon carbide (SiC).

- sintered metal elements
DPFs are primarily designed to reduce PM emissions.

DPM cake improves filtration efficiency.
Diesel Particulate Filters (DPFs) Catalyst

- Non-catalyzed DPF systems

- Catalyzed DPF systems
  - washcoated (Al$_2$O$_3$, SiO$_2$, CeO$_2$, TiO$_2$, ZrO$_2$, V$_2$O$_5$, La$_2$O$_3$ and zeolites) or impregnated with catalyst:
    - noble metals (platinum, palladium, rhodium)
    - base metals (vanadium, iron, cerium…)
  - fuel borne catalyst (FBC):
    - platinum, platinum-cerium, cerium, cerium-iron, iron, iron-strontium…
DPF Systems
Regeneration

- DPF regeneration – burning off carbon collected in a filter media:
  - oxidation by \( \text{O}_2 \);
  - oxidation by \( \text{NO}_2 \).

- Approximate minimum exhaust temperatures required to initiate regeneration process (\( \text{O}_2 \)):
  - Non-catalyzed DPF – over 600 °C;
  - Base metal catalyst – over 390 °C;
  - Nobel metal catalyst – over 325 °C;
  - Continuously regenerated trap (CRT) type systems – over 250 °C.

- 25-30% or more of a vehicle/engine duty cycle should generate exhaust temperatures that exceed the regeneration temperatures shown above.
DPF Systems
Regeneration

• Regeneration temperatures are function of:
  – Catalyst presence, formulation, and loading;
  – Contact between catalyst and DPM;
  – Type of the DPM;
  – \(\text{NO}_x/\text{PM}\) ratio in the exhaust.

• DPF regeneration systems are classified as:
  – Passive;
  – Active.
DPF Systems
Passive Regeneration

• The exhaust gas temperatures are favorable for regeneration of the DPF type and the process takes place during a duty cycle.

• The regeneration is typically supported by imbedded catalyst, use of fuel-borne catalyst, or fuel injection.

• Establishing exhaust temperature profile crucial for success of selection process.

• Engine idling should be minimized.
DPF Systems
Active Regeneration

• Accumulated DPM is removed using external source of energy:
  
  – On-board of vehicle
    • Electrical heater:
      – power and compressed air supply is on-board the vehicle;
      – power and compressed air supply is off-board the vehicle.
    • Fuel burner;
    • Fuel injection + DOC or catalyzed DPF.

  – Off-board of vehicle
    • electrical heaters.
Uncatalyzed DPFs reduce PM emissions.
Uncatalyzed DPF has minor effects on gaseous emissions.

Regeneration temperature:
- > ~ 600 °C
Catalyzed DPF

Regeneration temperatures:
- Nobel metal catalysts: >~ 325 °C
- Base metals catalyst: >~ 390 °C

- Pt catalyzed DPFs reduce PM, CO, HC emissions.
- Base metal catalyzed DPFs reduce primarily PM.
- Secondary NO₂ emissions are issue with Pt catalyzed DPFs.
- Base metal catalyzed DPFs do not tend to produce secondary NO₂ emissions.
DPF Regenerated with Help of Fuel Borne Catalyst (FBC)

Regeneration temperature:
- Pt/Ce
- >= 325 °C

- More intimate contact between catalyst and DPM.
- Secondary NO₂ emissions are not issue with FBC.
- FBC doped fuel should not be used in the vehicles that are not equipped with DPFs.
- Larger amount of ash deposition in DPF.
**Continuously Regenerated Trap (CRT):**

**DOC followed by DPF**

- Oxidation by NO₂.
- CRT system reduces PM, CO, HC emissions.
- Secondary NO₂ emissions are major issue with CRT systems.

**Regeneration temperature:**

- $> \sim 250 \, ^\circ C$
Catalyzed Continuously Regenerated Trap (CCRT): DOC Followed by Catalyzed DPF

- CCRT has lower regeneration temperature threshold.
- Secondary NO$_2$ emissions are major issue with CCRT systems.

Regeneration temperature:
- $\geq 200 \, ^{\circ}C$
Electrically Regenerated DPF (on-board)

- Uncatalyzed DPF system reduces PM emissions.
- Secondary NO\textsubscript{2} emissions are not an issue with uncatalyzed DPFs systems.
- Source of power and compressed air:
  - On-board the vehicle;
  - Off-board the vehicle.
Electrically Regenerated DPF (off-board)

- Require removal of the filter from the system:
  - suitable for smaller units;
  - integrity of the system (the gaskets need to be replaced);
  - downtime for swapping filter elements.
DPF Regenerated with Help of Diesel Fuel Burner

- Uncatalyzed DPF system reduces PM emissions.
- DOC is used to control CO and HC emissions during the regeneration.
- Secondary NO₂ emissions might be an issue with the systems that use DOC.
- Complexity and fuel penalty are major issues.
DPF System with Diesel Fuel Burner
DPF Regenerated with Help of Late Fuel Injection and Catalytic Combustion

- Common-rail fuel injection system is used to inject fuel in the late stage of compression and into expansion stroke.
- Catalytic combustion is used to increase exhaust temperature to app. 450 ºC.
DPF Systems
Passive vs. Active Regeneration

- **Passive DPF systems**
  - low operational requirements;
  - low maintenance requirements;
  - relatively inexpensive, depending on catalyst formulation;
  - regeneration depend on exhaust heat!!!
  - potential for increase in NO₂, sulfates emissions.

- **Active DPF systems**
  - regeneration does not or is less dependent on exhaust heat;
  - no effects on secondary emissions;
  - require changes in way vehicles are operated;
  - higher maintenance requirements;
  - require change in operator’s attitude;
  - relatively expensive.
DPF Systems – Uncontrolled Regeneration

- Thermal meltdown as result of uncontrolled regeneration.
Effects of DPF Systems and DFEs on DPM Emissions

Verifications/Certifications

MSHA Verification

<table>
<thead>
<tr>
<th>Filtration System</th>
<th>Efficiency (TDPM)</th>
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<tbody>
<tr>
<td>Cordierite DPF</td>
<td>85%</td>
</tr>
<tr>
<td>Silicon carbide DPF</td>
<td>87%</td>
</tr>
<tr>
<td>Sintered metal DPF</td>
<td>81, 99%</td>
</tr>
<tr>
<td>DFE</td>
<td>80-83%</td>
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</table>
Effects of DPF Systems and DFEs on DPM Emissions
Verifications/Certifications

VERT Filter List
(www.dieselnet.com/tech/text/ch_filterliste.pdf)

<table>
<thead>
<tr>
<th>Filtration Rate</th>
<th>New</th>
<th>After 2000 hours</th>
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<tbody>
<tr>
<td>Solid Particle Count (20-300 nm)</td>
<td>&gt; 95%</td>
<td>&gt; 95%</td>
</tr>
<tr>
<td>EC mass conc.</td>
<td>&gt; 90%</td>
<td>&gt; 90%</td>
</tr>
</tbody>
</table>

CARB Verification
(http://www.arb.ca.gov/diesel/verdev/vt/vt.htm)

<table>
<thead>
<tr>
<th>Reduction</th>
<th>Classification</th>
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<tbody>
<tr>
<td>&lt; 25%</td>
<td>Not verified</td>
</tr>
<tr>
<td>&gt; 25%</td>
<td>Level 1</td>
</tr>
<tr>
<td>&gt; 50%</td>
<td>Level 2</td>
</tr>
<tr>
<td>&gt; 85%, or &lt; 0.01 g/bhp-hr</td>
<td>Level 3</td>
</tr>
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</table>
Field Evaluations

DEEP
(http://www.deep.org/research.html)

- Field evaluation of diesel particulate filter systems in an underground mine – INCO;
- Field evaluation of diesel filter systems in an underground mine - Noranda Technology Centre.

NIOSH (http://www.cdc.gov/niosh/mining/pubs/programareapubs8.htm

- Effectiveness of Selected Diesel Particulate Matter Control Technologies for Underground Mining Applications:
  - Isolated Zone Study, 2003;
Laboratory Evaluations in Underground Environment

NIOSH Lake Lynn Laboratory Evaluations

- Laboratory evaluation of exhaust aftertreatment systems in an underground mine.
Secondary emissions of NO$_2$ have been major road block for implementation of passive DPF systems in underground mines.

- Effects of the aftertreatment system on NO$_2$ emissions is function of:
  - catalyst formulation and loading;
  - exhaust temperatures;
  - NO$_x$ to PM ratio in the engine-out exhaust;
  - amount of soot in DPF system;
  - fuel sulfur content.

- Several studies showed that the systems with platinum based wash-coated catalysts promote NO to NO$_2$ conversion at the temperatures needed for DPF regeneration.

- Some DOC formulations tend to produce secondary NO$_2$ emissions.
The concern over NO$_2$ “slip” influenced selection of regeneration strategy for DPF systems for coal mining applications.

- MSHA advises against using platinum catalyzed passive DPF system in underground coal mines due to potential for increase in NO$_2$ emissions (PIB02-04).

- The popular choices of DPF systems in coal mining:
  - Passive systems regenerated with help of platinum/cerium fuel born catalyst;
  - Passive systems with wash-coated base metal catalyst;
  - Passive systems with wash-coated NO$_2$ suppressing catalyst;
  - Active systems with on-board electrical regeneration;
  - Active systems with off-board electrical regeneration.
Not all catalyzed DPF systems promote NO to NO$_2$ conversion.

- Base metal wash-coated catalysts do not exhibit tendency to increase NO$_2$ emissions.

- The systems using fuel borne catalysts, even those that are based on platinum, were not found to increase significantly NO$_2$ emissions.

- The reaction between NO$_2$ and DPM in uncatalyzed filters may result in slight reduction in overall NO$_2$ concentrations.

- New formulations with NO$_2$ suppressant are marketed for underground mining industry.
Effects of aftertreatment technologies on fraction of NO$_2$ in NO$_X$ were found to be dependent on engine operating conditions (exhaust temperature).

In the majority of cases, DPFs and DFEs decreased NO$_2$ fraction in NO$_X$.

The DOC decreased NO$_2$ fraction in NO$_X$ for the light-load conditions, but increased NO$_2$ fraction in NO$_X$ for the heavy-load conditions.
Diesel Oxidation Catalyst (DOC)

- **Substrate (flow-through)**
  - ceramic monolith honeycomb (Cordierite, 2MgO-2Al₂O₃-5SiO₂);
  - Metal honeycomb (Fe-Cr-Al).
- **Washcoat** (Al₂O₃, SiO₂, CeO₂, TiO₂, ZrO₂, V₂O₅, La₂O₃ and zeolites) containing catalyst:
  - Platinum (Pt);
  - Palladium (Pd).
Diesel Oxidation Catalyst (DOC)

- DOCs are primarily designed to reduce CO and HC emissions.
- DOCs can reduce organic fractions of PM.
- Unwanted reaction might be one producing NO$_2$. 
Selective Catalytic Reduction (SCR) Systems

- SCR systems are primarily designed to reduce NO\textsubscript{X} emissions to inert molecular nitrogen.
- Diesel exhaust fluid (32.5% high-purity urea) is used as reducing agent.
Integrated Systems for DPM and NO$_2$ Control

- DOC + Cat DPF + NO$_2$ decomposition catalyst.
- NO$_X$ neutral.
- Control of NO$_2$ slip from CRT system.
Integrated Systems for DPM and NO\textsubscript{x} Control

- DOC + Cat DPF + SCR.
- Control of both DPM and NO\textsubscript{x} emissions.
Flow-Through-Filters (FTF)

- Theoretically, over 50% removal (CARB Level 2).
- Absence of regeneration and DPM buildup affects FTF performance.
- Storage and release (blow-off) phenomenon.
- Secondary NO$_2$ emissions.
Selection of Exhaust Aftertreatment Systems for Underground Mining Applications

- Selection of system type.
- Effects of systems on:
  - concentrations of DPM (EC);
  - concentrations of regulated and unregulated gases.
- Regeneration/disposal.
- Installation, implementation, and maintenance issues.
- Cost benefit analysis.
System Approach toward Selection and Optimization of Engine/Aftertreatment/Fuel system

• Exhaust aftertreatment should not be afterthought:
  – Selection of the engine for the application;
  – Selection of the aftertreatment;
  – Optimization.

• Identify hierarchy of solutions
  – Exhaust aftertreatment is not method for cleaning “dirty” engines and overcoming poor maintenance practices.
  – Exhaust aftertreatment systems are not equally effective in controlling all emissions of all pollutants, adequate ventilation will be required.
Aftertreatment System Installation and Survival
DPF Systems Operational Issues
Ash Accumulation

• Ash originates from fuel, lubricating oil, engine wear or fuel additives:
  – up to 1% of DPM.

• Ash can not be regenerated like carbon. Accumulation of the ash in the filter results in continuous increase in base backpressure.

• Periodic cleaning of the filter is required, usually every 1000-2000 hours.

• API CJ4 lubricating oil.
DPF Systems
Backpressure Monitoring

• Sizing of the system is critical:
  – Engine backpressure – engine limitations:
    • Caterpillar 3306 PCNA - 34 in H₂O;
    • DDEC Series 60 – 42 in H₂O.

• Reliable backpressure monitoring and logging capabilities are essential for performance of the filtration system.

• Pressure gage and alarm should be included as part of the filtration system.
Other Parameters that Can Potentially Affect Effectiveness and Performance of DPF System

• Exhaust system integrity:
  – Internal leaks;
  – External leaks.

• Avoid operating the system outside of design parameters.
Thank you for your attention!

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