Development of Advanced Diesel Particulate Filtration (DPF) Systems
(ANL/Corning/Caterpillar CRADA)

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PI: Kyeong Lee
(Postdoc: Joe Song)

Transportation Technology R&D Center
Argonne National Laboratory

DOE Project Managers:
Kenneth Howden & Gurpreet Singh
Office of Vehicle Technologies

This presentation does not contain any proprietary or confidential information
Motivation of Current DPF CRADA Project

  - Heavy-duty: 0.01 g/bhp-hr (90% reduction)
  - DPFs are known to be most promising for the efficient control of PM emissions.

- “Corning wants to further improve material properties, related to the pore structures, durability, filtration/regeneration efficiencies, and back pressure.”

- Caterpillar
  - Technical and intellectual capabilities of Argonne will provide the fundamental understanding necessary to derive efficiency of aftertreatment systems.
  - Working closely with the industry leader in PM filtration will accelerate the learning process and eventually a choice of diesel aftertreatment technology.
**Purpose of Work**

- Characterize filtration and regeneration processes in the course of visualization (both still and video images) by micro-imaging system.
  - Establish a bench-scaled flow reactor (which simulates filtration and regeneration processes of DPFs), and a µ-imaging system (which consists of a stereo-microscope, CCD camera, and image acquisition software).

- Provide efficient filtration/regeneration strategies for industry sponsors.
  - Reduce the DPF pressure drop
  - Evaluate material durability caused by regenerations and ash build-up
  - Reliable start of regeneration at low exhaust temperatures (elec. heater, fuel injection)
  - Thermal run-away control
  - Characterize properties of deposits (soot cake & ashes) in terms of morphology, nano-structures, and chemistry
  - Characterize properties of nano-particles (< 100 nm) and find control technologies

- Parametric studies
  - Engine operating conditions \(\rightarrow\) Effects of particle size, fractal geometry, chemistry
  - Exhaust gas compositions \(\text{NO}_x, \text{O}_2\)
  - Filter material and geometry (Cordierite vs. SiC, catalyst, pore size, porosity)
Previous Review Comments

- Other institutes, such as Univ. of Minnesota, Michigan Tech., and PNNL, have done similar work.
  
  - Detailed microscopic analysis on DPF filtration and regeneration processes have not been done yet. Instead, they mostly conducted DPF system performance tests on engines or vehicles.
  
  - Detailed morphological characteristics of PM emissions have not been considered in their research. For examples,
**Barriers**

- PM filtration mechanisms have not been revealed to the same scale as nano-sized diesel particulates.
  - Nano-particle control technologies.

- PM regeneration causes material failure during the period of high thermal-energy release, due to thermal run-away.
  - Optimal regeneration schemes.

- Use of DPF systems may result in an excess energy consumption.
  - Operational schemes of DPF system with minimized energy input.

- A high-resolution μ-imaging system is required to provide images for diesel particulates and filter-membrane structures.

- Experimental equipments and conditions must be scaled down for bench-tests.
**Approach**

- Schematic of Experimental Setup
Accomplishments

Contributions from industry sponsors have been significant

- Corning
  - Wall-flow type cordierite membranes (full/bench scales, various models) with detailed material properties
  - Accurate diamond-cutting, canning, and assembly-part supply

Φ2” X 6” bisected (bench scale)  Φ2” X 6” Canned DPF  Φ5.66” X 6” bisected (Full scale)
Contributions from Industry Sponsors (cont’d)

- Caterpillar
  - Catalytic coating of membranes
  - Development of a diesel-simulating combustor for PM generation.
  - A most advanced 2007 model C7 diesel engine has been delivered to Argonne (07 EPA Certified).

- 7.2L Inline 6-cylinder, DI, T/C, EGR
- CAT Common-rail Injection
- 350 hp max @ 2400 rpm; 860 lb-ft @ 1440 rpm
- The engine requires aftertreatment system to comply with 07 EPA emissions regulations.
A unique Flow/Thermal Reactor has been designed and fabricated successfully.

- Module design
- Durable design; a total weight of 50 lb
- Air-tight visualization quartz window: 3-1/2” x 1-3/4

Auto-CAD design completed with safety review.
The State-of-the-art stereo-microscopic imaging system provides unprecedented high-resolution still and video images

- Leica stereo-microscope (x640)
- Q-Imaging Retiga-EXI digital color CCD camera:
  - Ultra-high sensitivity and speed
    1920x1040 (1.5M pixels)
  - Video image: 110 fps max; 10 fps @ full resolution
- Two light sources
Microscopic Imaging System (cont’d)

- Pneumatic optical table – vibration free
- X-Y remote/motorized linear translation system
- 3 pressure transducers (abs. & differential)
- 2 flow meters
- 16 thermocouples adaptable
Computer-controlled Data Monitoring/Controlling/Recording Systems

- State-of-the-Art image recording system
  - Total 1.5 terabyte data storage capacity in two hard drives
  - High-speed video streaming software (Streampix)
- Ultra high-resolution 30” monitor (2560X1600)
- Remote control by Labview programming
  - Pressure
  - Temperature
  - Bypass flow
A customized Labview program remote-controls bypassing emissions flows for the lab-scaled membrane

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>$M_{total}$ (g/min)</th>
<th>$T_{exh}$ (°C)</th>
<th>$Q_{exh}$ (scfm)</th>
<th>$Q_{bypass}$ (scfm)</th>
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<tr>
<td>2400</td>
<td>20088</td>
<td>500</td>
<td>591</td>
<td>9.2</td>
</tr>
<tr>
<td>1440</td>
<td>12053</td>
<td>500</td>
<td>355</td>
<td>5.5</td>
</tr>
<tr>
<td>700</td>
<td>3054</td>
<td>100</td>
<td>90</td>
<td>1.4</td>
</tr>
</tbody>
</table>

- Membrane volume ratio = 64:1 (commercial : lab-scale)
- 7.2L CAT C7 engine

**Bypass Control Scheme**

1. Set $Q_{init}$
2. Open bypass valve
3. Measure $Q_{bypass}$
4. If $\Delta Q < 0.001$ then Yes, else No
5. If Yes then Start Filtration
6. If No then repeat steps 2-4
The DPF testing system needs to be integrated with the CAT’s most advanced C7 diesel engine installed on a dynamometer.
Experimental Results

Microscopic observation of DPF membrane structures has been successful.

- Mean pore size: 20 – 30 µm
- Total volume of pores can be measured in collaboration with our Chemistry Div.
The $\mu$-imaging system associated with automated translation system provides an extra capability for material defect inspection.
Technology Transfer

■ Corning
  – Provide design criteria for developing advanced DPF membrane materials, which are durable for thermal reactions and highly efficient in filtration and regeneration.

■ Caterpillar
  – Provide design criteria for developing a low-energy consumption, high-efficiency DPF system, which is optimized for CAT’s C7 engine.
FY08 Research Plans and Collaborations

- FY08 research plan
  - μ-images of membrane pores during filtration and regeneration
  - Filtration/regeneration efficiencies; ignition energy consumption
  - Morphology of soot deposits
  - Parameters to be varied
    - Engine speed and load
    - Gaseous emissions composition
    - Inlet gas temperature
  - CAT’s C7 engine installation on a upgraded dynamometer

- Collaborating research partners
  - Univ. of Wisconsin – Madison (Prof. Foster)
  - Honda Motor in Japan

- Complimentary Part Supply
  - Iljin Electric Co. (DPF heating systems for regeneration)
Summary

- Experimental setup for DPF filtration and regeneration tests has been completed.
  - Flow reactor with PM sampling system, μ-imaging system, data acquisition system with custom-made Labview programs, remote/auto control systems.

- Visualization of membrane substrates has successfully been achieved at a high resolution.
  - Both still- and video-images.

- In addition, an automated material inspection system has been developed.