Catalyzed Exhaust Filters: Future directions

CLEERS
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• Introduction to catalysed filters
  • Drivers for catalyzed filter technology

• Next generation catalyzed filters
  • SCR filter (SCRF®) system
  • 3-way filter (TWF®) system

• Summary
Johnson Matthey’s history with filters

- Patented the Continuously Regenerating Trap (CRT®) system
  - Commercialized in 1995 for HD retrofit market
  - Use of a DOC to generate increased NO\textsubscript{2} at filter inlet, and use of that NO\textsubscript{2} to combust filtered particulate at normal exhaust temperatures.
- The principle of the CRT® technology underpins the function of the majority of filter systems in the market.

\[ \text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2 \]
\[ \text{[HC]} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} \]
\[ \text{NO} + \frac{1}{2}\text{O}_2 \rightarrow \text{NO}_2 \]
# Evolution of diesel exhaust filter systems

<table>
<thead>
<tr>
<th>Year</th>
<th>Filter system</th>
<th>Catalyzed filter?</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 2000</td>
<td>DOC upstream</td>
<td>N</td>
<td>Retrofit systems</td>
</tr>
<tr>
<td>2000</td>
<td>DOC upstream + fuel-borne catalyst (fbc)</td>
<td>N</td>
<td>First OEM commercialization (PSA)</td>
</tr>
<tr>
<td>2003 – 07</td>
<td>DOC upstream (+ fbc)</td>
<td>Y (DOC)</td>
<td>Substantial use of catalyzed filter substrates</td>
</tr>
<tr>
<td></td>
<td>Filter only</td>
<td>Y (NAC)</td>
<td>First catalyzed filter with NOx removal function (Toyota)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Y (DOC)</td>
<td>Systems without additional catalysts employed (e.g. VW)</td>
</tr>
<tr>
<td>2007 - 10</td>
<td>DOC (+NAC) upstream (+SCR downstream)</td>
<td>Y (DOC)</td>
<td>Mass production by HD OEMs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Limited integration of specialized NOx control catalysts</td>
</tr>
<tr>
<td>2010 - 13</td>
<td>DOC upstream + SCR downstream</td>
<td>Y (DOC)</td>
<td>Majority of on-road filter systems combined with NOx control catalysts</td>
</tr>
<tr>
<td></td>
<td>DOC + SCR (or NAC) upstream</td>
<td></td>
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</table>
Benefits of an oxidation catalyst on a filter

- Faster passive regeneration
- Less frequent active regeneration
  - CO$_2$ savings as less thermal management required
- Clean-up of active regeneration emissions
  - Enhanced emissions performance
Drivers for next generation catalyzed filters

- CO₂ emissions and light-off
  - An increasing focus on cold-start emissions and a filter upstream of SCR is a large heat sink
  - A filter downstream of SCR means more active regens
  - Multiple components increases backpressure
- Emission performance
  - Enhanced passive soot regeneration
  - Multifunction filter may minimize compromises made in arranging separate components
- Smaller packaging
  - A large total catalyst volume impacts vehicle design and weight
- PN legislation means engines designed without filters today may need them in the future
Possible future diesel exhaust system evolution

Lower total volume, same performance

Low volume helps packaging and commonality across platforms

High performance allows fuel savings – higher EO NOx and/or less warm-up.

Similar total volume, increased performance

SCRF may find use in high-performance LNT systems
Performance of SCRF® systems require extensive optimization of catalyst/substrate characteristics with OEM.
SCRF® system advantages on a HD engine
Equivalent performance at lower volume, or improved performance at equivalent volume

![Bar Chart]

- **DOC+SCRF®+SCR** (small volume)
- **DOC+CSF+2xSCR** (baseline)
- **DOC+SCRF®+2xSCR** (high performance)
Performance window of different SCR/SCRF® system configurations

Baseline system architecture

- SCR
- SCRF®
- SCR + SCRF®
- SCRF® + SCR
- 2 x SCR - baseline
- SCRF®
SCRF® system has equivalent performance to SCR system on a transient cycle
Hot LA4 cycle

<table>
<thead>
<tr>
<th>NOx Conversion (%)</th>
<th>Total</th>
<th>Bag 2</th>
<th>Bag 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>baseline</td>
<td>SCR</td>
<td>SCR</td>
<td>SCR</td>
</tr>
</tbody>
</table>

Baseline system architecture
SCRF® system can warm up faster than an uf SCR system
Enables earlier urea dosing and increased NOx performance
Effect of filtered soot on SCRF® system NOx conversion is minimal

- Clean SCRF®
- 5g/l soot-loaded SCRF®
Urea can reduce passive soot removal over SCRF® system

NO₂/NOx ~ 40%, 400°C, 8g/l soot

NO₂ reacts preferentially via fast SCR reaction
Good passive regen is achievable with optimised SCRF® system

Filters loaded to 3g/l soot, bp monitored over repeated FTP cycles

- % bp drop after 15 FTP cycles
- % bp drop after 30 FTP cycles
- % dp drop after 50 FTP cycles
A downstream ASC can be used to provide additional performance benefits

Removal of the oxidation coating from filter can result in increased emissions during active regeneration

Use of an ASC downstream can oxidise active regeneration emissions
A downstream ASC can be used to provide additional performance benefits.

**Graph 1:**
- **NOx Conversion (%)**
- **Temperature (°C)**
  - Without ASC
  - With ASC

**Graph 2:**
- **NH3 Slip (ppm)**
- **Temperature (°C)**
  - NH3 Slip Without ASC
  - NH3 Slip With ASC

**Legend:**
- **Without ASC**
- **With ASC**

**Notes:**
- Improved High Speed NOx Conversion
- No NH3 slip
Possible to incorporate SCRF® system into LNT systems
Passive SCR

Optimise LNT to make NH3 when rich

Store NH3 on downstream SCRF for SCR use when lean
An LNT+SCRF® system with urea injection can give additional benefits

- Combination with active SCR or SCRF® systems
  - Urea injection downstream of LNT for high temperature / high flow conversion
SCRF® system summary

• Replacement of flow-thru SCR system with SCRF® system is demonstrated for both HD and LD applications
  • SCRF® systems can be compatible with LNT systems and bring additional performance benefits

• Competition for NO₂ between soot and SCR reactions can be managed with appropriate SCRF® system design

• Utilise SCRF® systems for packaging reduction or high performance systems
  • High performance can bring CO₂ benefits via increased engine-out NOx and less aggressive warm-up requirements
  • Optimisation of system design needs close collaboration between substrate suppliers, catalyst companies and OEM.
TWF™ product requirements

Product Requirements

- Particle number reduction
  - Meet Euro 6 limits
  - Tune filtration for OEM requirements
- Durability
  - >160k km for emissions
  - Ash loading over lifetime
  - Thermal & Physical
- Soot regeneration
  - Optimise passive regen
- Backpressure
  - Minimise impact on powertrain
- TWC activity
  - Promote regeneration
  - Substitute TWC volume
TWF™ product benefits compared to an uncoated gasoline exhaust filter

- Allows substitution for TWC volume
  - TWF™ coating is based on current TWC coating chemistry
  - Reduced packaging space and cost
  - Many Euro 6 systems will be twin brick for OBD requirements
- Enhanced soot regeneration
- Good particle filtration from fresh
  - Don’t need to build up soot layer for effective filtration
- Potential for OBD diagnosis of thermal events using $\lambda$ sensors
## Possible system architectures

<table>
<thead>
<tr>
<th>Architectures</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="TWC TWF™" /></td>
<td>Substitute TWF™ part for rear TWC, allows good TWC emissions control and PN filtration</td>
</tr>
<tr>
<td><img src="image2" alt="TWC TWF™" /></td>
<td>Close-coupled cascade TWC + TWF™ system, especially for smaller vehicles</td>
</tr>
<tr>
<td><img src="image3" alt="TWF™" /></td>
<td>TWF™-only system for minimised components</td>
</tr>
<tr>
<td><img src="image4" alt="TWC TWC TWF™" /></td>
<td>TWF™ part additional to existing TWC system, increases packaging, remote location hinders regeneration and activity</td>
</tr>
</tbody>
</table>
PGM impacts soot regeneration

- TWF™ part with and without PGM
- PGM promotes oxygen-based passive regeneration
- Stable filtration and backpressure
- Additional emission benefits over single TWC
Regeneration of a TWF™ system using fuel cuts

- DI vehicle
- 45 repeat NEDCs to accumulate soot layer
  - >99% PN filtration efficiency
- Only 320 mg of soot (0.26 g/l) accumulated in filter in ~500 km

- Regeneration conditions
  - Steady state cruise (140 kph) with filter inlet T of 650 °C
  - Introduction of fuel cuts by decelerating to 95 kph in 25 seconds

- Fuel cuts over hot filter gave clear regeneration
  - Soot reacts with oxygen
# Regeneration of a TWF™ system using fuel cuts

<table>
<thead>
<tr>
<th>TWF™ system condition</th>
<th>Backpressure on 140 kph cruise (mbar)</th>
<th>PN emissions on 140 kph cruise (#/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>119</td>
<td>3.44E+04</td>
</tr>
<tr>
<td>After 45 NEDC cycles</td>
<td>157</td>
<td>1.56E+04</td>
</tr>
<tr>
<td>After 1 fuel cut</td>
<td>137</td>
<td>2.67E+04</td>
</tr>
<tr>
<td>After 2 fuel cuts</td>
<td>124</td>
<td>3.39E+04</td>
</tr>
<tr>
<td>After 3 fuel cuts</td>
<td>120</td>
<td>3.41E+04</td>
</tr>
</tbody>
</table>
Effect of poisoning and ash accumulation

- Is a filter-only system robust to poisoning and thermal ageing?
- What is the effect of an upstream TWC?
  - Studies of twin-brick TWC systems show that the first catalyst is an effective trap for fuel and oil poisons

- Engine aging study using fuel doped with oil additives
  - 80 hours Lean Spike ageing, 950 °C inlet
  - Total poison deposition on catalyst system typical of that observed from full useful life vehicle durability trials

- Comparison between CC TWC + TWF™ cascade system and a CC TWF™-only system
  - TWC, 20/0:18:2, NGK 118.4x101.6 mm, 600/4 substrate
  - TWF, 85/0:16:1, NGK C650 118.4x101.6 mm, 300/12 filter
Ash accumulation

- Mass of TWF™ -only system increased by 13g from ash deposition
  - Ash-rich deposit visible on inlet face and washcoat surface
  - No plugging of inlet face or build up of loose ash within channels
  - Filter retained good filtration efficiency and TWC activity, meeting Euro 6 limits

- Upstream TWC reduced ash deposition in filter by 80%
  - No visible ash deposits on inlet
  - Backpressure lower by 20%
Emissions comparison of ash-aged filters
2.0l turbo DI EU5 vehicle, Testing as TWF™ -only in CC position

An upstream TWC acts as a poison and ash trap during ageing

Filtration of poisoned TWF™ remains high
Emission performance of different CC systems
Equivalent volume and PGM, oven aged

Cascade system (TWC+ TWF™) shows equivalent light-off to TWC
Demonstration that a TWF™-only system can meet EU6

- Coated NGK 4.66 x 5.5” (1.54L) C650 cordierite filter samples
  - PGM 40/0:12:1
  - Emissions optimised washcoat vs. backpressure optimised washcoat

- Oven ageing at 1100 °C, equivalent thermal load to JM Lean Spike engine ageing cycle

- Evaluation on a 2.0 litre DI EU5 vehicle
Backpressure at high speed

- Emissions optimised washcoat
- Backpressure optimised washcoat

Differential Pressure (mbar) vs. Time (s)

Speed (kph)

Graph showing the comparison between Emissions optimised washcoat and Backpressure optimised washcoat over time with differential pressure and speed metrics.
Emissions of both TWF™ versions meet EU6
Conclusions

- Coated gasoline filters demonstrated on a range of commercially available direct injection gasoline vehicles
  - TWF™-only and TWC + TWF™ systems
  - Good particulate filtration and three way activity
  - Durability trials after various full useful life ageing conditions
    - Oven ageing, engine ageing, poisoning
  - Met Euro 6 limits with aged TWF™ -only system on series DI cars
    - Emissions capable without changing engine hardware & calibration
  - Washcoat optimisation concepts to enhance emissions performance and reduce backpressure exist
Future work

- Significant filter optimisation and system integration work required
  - Close collaboration between OEM, substrate manufacturer and catalyst company is essential for success
- Key challenges include:
  - Real world durability trials
  - OBD of particulate filters
  - Evaluation of advanced development substrates
    - Thinner wall, high porosity materials
  - Low backpressure solutions for high performance engines
  - Soot regeneration protocols
Overall summary

- Effective design of a catalysed filter and the surrounding system directly impacts key strategic drivers
  - Criteria emissions performance and PN
  - CO$_2$ emissions
  - Packaging space

- Next generation catalyzed filters need intensive optimization of performance factors and system design

- SCR and TWC catalysts coated on filters bring novel but surmountable challenges
  - Performance / durability are demonstrated
  - Full systems are being proven out today