Evaluation methods for passive regeneration of particulate filters for the city bus
Regulations and the state of HDD engines

- **Euro III**: Combustion optimization. Higher, cooled EGR
- **Euro IV**: High pressure fuel injection >1600 bar (Common Rail)
- **Euro V**: High pressure fuel injection >1800 bar, fully flexible fuel injection (with pilot and post-injection capability). Modified combustion.
- **Actual**
  - **EURO III**: PM filters + Lean Nox Catalyst
  - **EURO IV**: PM filters
  - **EURO V**: SCR DeNOx


- **US 2007**: High pressure fuel injection >1600 bar (Common Rail)
The focus of this work

Engine investigation of different types fuel additives and optimization their dosing for:

• inhibiting the formation of PM and their accumulation in the DPF
• improvement performance of fuel additive for lowering the soot burning temperature to promote natural filter regeneration either continuously or at the regular intervals
• evaluation of interaction and synergy between fuel additive components in oxidizing soot deposited on the filter
• impact estimation of the additive type on the aiding filter regeneration process inside DPF developed for retrofitting of the city bus engine
Measurement set-up on the engine test bench

Functional diagram of sootfilter operation control system
Test fuel and particulate filter

**Fuel specifications**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Ekodiesel Plus 50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full fuel specification</td>
<td>EN 590</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>835</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>62</td>
</tr>
<tr>
<td>Cetan number</td>
<td>52,1</td>
</tr>
<tr>
<td>Sulfur content (weight %)</td>
<td>0,0048</td>
</tr>
<tr>
<td>Ash content (% m/m)</td>
<td>0,002</td>
</tr>
<tr>
<td>Water content (% m/m)</td>
<td>0,0015</td>
</tr>
</tbody>
</table>

**Cordierite filter monolith specifications**

<table>
<thead>
<tr>
<th>Type of filter</th>
<th>TBA (Uncoated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension of filter</td>
<td>11,25×14”</td>
</tr>
<tr>
<td>Volume</td>
<td>22,8 dm³</td>
</tr>
<tr>
<td>Cell density</td>
<td>100 cpsi</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>0,017”</td>
</tr>
<tr>
<td>Material</td>
<td>Cordierite</td>
</tr>
<tr>
<td>Total porosity</td>
<td>48%</td>
</tr>
<tr>
<td>Mean pore size</td>
<td>13 µm</td>
</tr>
</tbody>
</table>
Test fuel additives

<table>
<thead>
<tr>
<th>No</th>
<th>Additive components</th>
<th>Components concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>METAL</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>IRON</td>
<td>4 levels: 5ppm Fe; 12ppm Fe; 17ppm Fe; 20ppm Fe</td>
</tr>
<tr>
<td>2</td>
<td>CERIUM</td>
<td>2 levels: 5ppm Ce; 20ppm Ce</td>
</tr>
<tr>
<td>3</td>
<td>CALCIUM</td>
<td>2 levels: 6.5ppm Ca; 20ppm Ca</td>
</tr>
<tr>
<td>4</td>
<td>COPPER</td>
<td>2 levels: 3ppm Cu; 5ppm Cu</td>
</tr>
<tr>
<td>5</td>
<td>IRON/ CALCIUM</td>
<td>2 comb.: 10ppm Fe + 10ppm Ca; 5ppm Fe + 5ppm Ca</td>
</tr>
<tr>
<td>6</td>
<td>IRON/ CERIUM</td>
<td>3 comb.: 3ppm Fe + 7ppm Ce; 30ppm Fe + 10ppm Ce; 10ppm Fe + 30ppm Ce</td>
</tr>
<tr>
<td>7</td>
<td>IRON/ COPPER</td>
<td>2 comb.: 5ppm Fe + 1ppm Cu; 5ppm Fe + 5ppm Cu</td>
</tr>
<tr>
<td>8</td>
<td>IRON/ MANGANESE</td>
<td>3 comb.: 5ppm Fe + 2ppm Mn; 5ppm Fe + 5ppm Mn; 10ppm Fe + 5ppm Mn</td>
</tr>
<tr>
<td></td>
<td>METAL + COMBUSTION IMPROVER</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>IRON/ NITROCET</td>
<td>2 comb.: 5ppm + 200ppm Nitrocet; 5ppm Fe + 1000ppm Nitrocet</td>
</tr>
<tr>
<td></td>
<td>ASHLESS COMPONENTS</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>AMINA</td>
<td>20ppm Amine</td>
</tr>
<tr>
<td>11</td>
<td>AMINA C₈</td>
<td>31ppm Amine C₈</td>
</tr>
<tr>
<td>12</td>
<td>RFN-6</td>
<td>20ppm RFN-6</td>
</tr>
<tr>
<td></td>
<td>METAL + ASHLESS COMPONENTS</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>IRON/ AMINA C₈</td>
<td>5ppm Fe + 31ppm Amine C₈</td>
</tr>
<tr>
<td>14</td>
<td>IRON/ RFN-6</td>
<td>5ppm Fe + 20ppm RFN-6</td>
</tr>
</tbody>
</table>
Test method

Time diagram of exhaust gas temperature measured during city bus service before engine muffler.
Performance map of SWT11/300/1 test engine with marked of four operating points of the engine bench test.
Results

Time relationship between filter pressure drop and front filter temperature for fuel without additive and with additive (Fe-5ppm). 1200 rpm/50kW
Time relationship between filter pressure drop and front filter temperature for fuel without additive and with additive (Fe-5ppm). 1500 rpm/70 kW
Time relationship between filter pressure drop and front filter temperature for fuel without additive and with additive (Fe-5ppm). 1500 rpm/100 kW.
Results

Time relationship between filter pressure drop and front filter temperature for fuel without additive and with additive (Fe-5ppm). 1800 rpm/95 kW
Results

Time relationship between filter pressure drop and front filter temperature for fuel with additive (Fe-5ppm) and with additive (Fe-5ppm+Cu-5ppm). 1200 rpm/50 kW
Time relationship between filter pressure drop and front filter temperature for fuel with additive (Fe-5ppm) and with additive (Fe-5ppm+Cu-5ppm). 1800 rpm/95 kW
Results

Time relationship between filter pressure drop and front filter temperature for fuel with additive (Fe-5ppm), with additive (Amine-31ppm), and with additive (Fe–5ppm + Amine–31ppm). 1200 rpm/50 kW
Results

Diagrams of promoted regeneration of DPF for fuel without additive and with additive Fe – 5ppm or with additive Fe – 5ppm + Amine – 31ppm
For investigations according to the VFT (VERT Filter Test) and VSET (VERT Secondary Emissions Test) have been selected Diesel Particle Filter and Fuel Additives as follows:

- DPF TBA, cordierite monolith, 100 cpsi pore size 13 µm, wall 0.017", porosity 48%, volume 22.8 dm³
  Manufacturer: Greentop GmbH

- Additive A (5ppm weight Fe in fuel)
- Additive B (5ppm weight Fe and 30ppm weight amine in fuel)
- Additive C (5ppm weight Fe and 5ppm weight Cu in fuel)
  Manufacturer: Institute of Petroleum Processing
Results

VFT1 Test Report
Results

VFT1 Test Report

comparison of regenerations with 3 DPF DIEXFIL/Greentop.
with additive Fe(G1), Fe+amine(G2) and Fe+Cu(G3) at 2000 min⁻¹/250/300/350/400/450/490Nm

- T5 G1
- T5 G2
- T5 G3
- ΔP5 G1
- ΔP5 G2
- ΔP5 G3
Mean emission factors: TEQ-sum of PCDD/F for Additive B (left) and Additive C (right)

RO 57 Reference Fuel  no additive w/o DPF
EO 61 no Cl added  Additive B: Fe w/o DPF
HEF 63 10ppm Cl added  Additive B: Fe DPF G2
KO 65 no Cl added  Additive C (Fe+Cu) w/o DPF
HKF 67 10ppm Cl added  Additive C (Fe+Cu) DPF G3

HO 60 10ppm Cl added  no additive w/o DPF
EF 62 no Cl added  Additive B: Fe DPF G2
HEO 64 10ppm Cl added  no additive w/o DPF
KF 66 no Cl added  Additive C (Fe+Cu) DPF G3
XKF 68 100ppm Cl added  Ad. C (Fe+Cu) DPF G3
**Results**

**VERT - VSET**

**Test Protocol**

Emission factors for the sum of carcinogenic PAH (IARC) in µg/kWh, all configurations with the Fe – Additives B (left) and the Cu – Additive C (right)

- RO 57 Reference Fuel no additive w/o DPF
- EO 61 no Cl added Additive B: Fe w/o DPF
- HEF 63 10ppm Cl added Additive B: Fe DPF G2
- KO 65 no Cl added Additive C (Fe+Cu) w/o DPF
- HKF 67 10ppm Cl added Additive C (Fe+Cu) DPF G3
- HO 60 10ppm Cl added no additive w/o DPF
- EF 62 no Cl added Additive B: Fe DPF G2
- HEO 64 10ppm Cl added no additive w/o DPF
- KF 66 no Cl added Additive C (Fe+Cu) DPF G3
- XKF 68 100ppm Cl added Ad. C (Fe+Cu) DPF G3
CEC F-23-A-01
Procedure for Diesel Engine Injector Nozzle Coking Test

Fuel additives contain as follows:

- Fe
- Fe + amine
- Fe + Cu

have no disadvantageous influence on the nozzle cooking propensity.
Results

CEC F-06-A-96
Measurement of Diesel Fuel Lubricity (HFRR fuel lubricity tester)

All fuel additives presented in this work have undergone HFRR tests and shows not any significant effect on fuel lubricity.
Conclusions

- The iron additive at a total dose rate of 5 ppm metal allow for effective filter regeneration at the relatively low temperature about 350 – 370 °C

- In conditions of carried out experiments, have been showed that the regeneration performance of iron additive could be further improved by the addition of a small quantity of copper to iron (5 ppm Fe + 5 ppm Cu)

- The regeneration performance of iron additive can be also further improved by addition of a small quantity of ashless additive – amine, this especially in the low load/low speed engine conditions
The combination of iron and amine gave performance advantages over use of iron for DPF regeneration process. Synergy was demonstrated during bed engine tests, showing that the combination of 1:6 ratio of iron to amine gave better performance than the same total treat rate of either iron or amine alone.

The Greentop DPF used in this project reduce well the PM.

Filtration efficiency does not seem to be influenced by the additives at least not in a negative sense.

PAH are very effectively – up to 85% - reduced.

HC are reduced as well by about 40%, but CO was not affected.
Conclusions

- There is no influence on NOx – NO\textsubscript{2}/NO – ratio also did not change much.

- The regeneration speed for all 3 additives (A – Fe; B – Fe+amine; C – Fe+Cu) investigated in the VERT Phase 1 Test is the same (approx. 10 mbar/h) and the efficient regeneration with all used additives is possible.

- The investigated Greentop DPF with the additive supported regeneration fulfills the criteria of the VERT filter test Phase 1 and can be recommended to the users.
Conclusions

- VERT Secondary Emission Test VSET has proved that PCDD/F (polychlorinated dibenzodioxins/furans)-emissions did not increase in case of the additive (5 ppm Fe + 30 ppm amine), but did remarkably increase by more than 3 orders of magnitude with additive (5 ppm Fe + 5 ppm Cu) in combination with slightly increase chlorine additive in the used reference fuel.

- Cu containing additive (5 ppm Fe + 5 ppm Cu) should not be put on the market in any combination with or without filters but additive consist of (5 ppm Fe + 30 ppm amine) shows very promising data and no sign of any formation of secondary toxic substaces.

- FBCs have no disadvantageous influence on the fuel lubricity and the injector nozzle cooking propensity.
ACKNOWLEDGMENTS

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THANK YOU!