Diesel Particle Filter Testing for In-Use Vehicle Retrofit

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Xiamen Environment Protection Vehicle Emission Control Technology Center
Agenda

- Background
- Test Procedure and Results
- Summary
Particles can penetrate deep into the human lungs due to their respirable size.

A short-lived climate forcer with a high global warming potential.

Complex mixture of solid and liquid materials

1. elemental carbon (EC, solid), i.e. soot,
2. soluble organic fraction (SOF, solid or liquid substances finely distributed in gases) from fuel and engine lubricant oil,
3. sulfates (hydrated sulfuric acid, metal sulfates, and liquid, depending on the sulfur content of the fuel),
Background

- DPF has been proved as a high efficacy technology to control diesel particle emission.
- Recently, the verified wall-flow DPFs are available and have been widely retrofitted on on-road and off-road in-used diesel engines.
Background

- China-Swiss cooperation programme CCLP (the Clean Air & Climate Change Legislation and Policy Framework)
- BCEMS (Black Carbon of Mobile Sources)
- The Vehicle Emissions Control Centre of Chinese MEP (MEP-VECC) wishes to explore the possibilities for lowering particulate emissions by retro-fitting DPFs onto commercial vehicles.
It is planned that a pilot trial will be run with a number of Xiamen and Nanjing city buses retro-fitted with DPFs. The first phase of the project involves the selection of a suitable DPF for the trial.

The selection will be made based primarily on the results from engine tests to be undertaken on the test bench utilizing a typical Xiamen city bus engine.

The testing is to be accomplished by making use of the experience, assistance and test methods from the Swiss organization “Verification of Emission Reduction Technologies” (VERT).

Xiamen Environment Protection Vehicle Emission Control Technology Center (VETC) undertakes the engine tests with different DPFs manufactured by three different manufacturers.
Key elements

- Typical in-used engine & engine out PM emission levels
  - typical Xiamen city bus engine
- Representative fuel
  - China Stage3 commercial diesel
- Suitable lubricant
  - Low SAPS lubricant
## Engine

**Chinese Stage 3 emission legislation**  
4 cylinders in line  
**Rate power** 132kW  
**Turbo charger + Common rail + Direct injection**  
No EGR and A/T

<table>
<thead>
<tr>
<th>Manufacturer / type</th>
<th>Yuchai Machine / YC4G180-30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission legislation level</td>
<td>GB17691-2005 phase3 (=EU3)</td>
</tr>
<tr>
<td>Cylinder number and configuration</td>
<td>4 cylinders in-line</td>
</tr>
<tr>
<td>Bore x stroke / overall displacement</td>
<td>112 x 132 [mm] / 5.202 [L]</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>17 [-]</td>
</tr>
<tr>
<td>Cooling medium (air, water, etc.)</td>
<td>Water</td>
</tr>
<tr>
<td>Combustion process</td>
<td>direct injection</td>
</tr>
<tr>
<td>Supercharging / Charge air cooling</td>
<td>TC / IC engine water / 1.2 [bar]</td>
</tr>
<tr>
<td>Charge pressure max.</td>
<td></td>
</tr>
<tr>
<td>Exhaust aftertreatment measures to reduce emissions</td>
<td>None</td>
</tr>
<tr>
<td>EGR</td>
<td>None</td>
</tr>
<tr>
<td>Rated power / Rated speed</td>
<td>132 [kW] @ 2300 [min⁻¹]</td>
</tr>
<tr>
<td>Max.Torque @ RPM</td>
<td>660 [Nm] @ 1300~1500 [min⁻¹]</td>
</tr>
<tr>
<td>Max mass flow ; max volume flow @ nominal RPM</td>
<td>1008kg/h@2300 [min⁻¹]</td>
</tr>
<tr>
<td>Max exhaust temperature downstream TC @ nominal RPM</td>
<td>n.a.</td>
</tr>
<tr>
<td>Low idle speed / high idle speed</td>
<td>650<del>700 [min⁻¹]; 2570</del>2640 [min⁻¹]</td>
</tr>
</tbody>
</table>
Test stages utilised for this project are stage 5, 7, 3, 1, 5, as defined in ISO 8178, according to VERT certification procedure.

The space velocities (SV) were checked at these points to ensure that the DPF is a correct match for the engine.
## Fuel and lubricant

<table>
<thead>
<tr>
<th>Base fuel (without additive)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>GB 252-2011 market fuel</td>
<td></td>
</tr>
<tr>
<td><strong>Manufacturer</strong></td>
<td>SINOPEC</td>
<td></td>
</tr>
<tr>
<td><strong>Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Density @20°C</strong></td>
<td>0.8537 kg/litre</td>
<td></td>
</tr>
<tr>
<td><strong>Cetane number</strong></td>
<td>42.4</td>
<td></td>
</tr>
<tr>
<td><strong>Sulphur content</strong></td>
<td>164 mg/kg</td>
<td></td>
</tr>
<tr>
<td><strong>Cloud point</strong></td>
<td>- °C</td>
<td></td>
</tr>
<tr>
<td><strong>Pour point</strong></td>
<td>&lt;-4 °C</td>
<td></td>
</tr>
<tr>
<td><strong>Flash point</strong></td>
<td>&gt;65.0 °C</td>
<td></td>
</tr>
<tr>
<td><strong>Viscosity@20°C</strong></td>
<td>5.721 mm²/s</td>
<td></td>
</tr>
<tr>
<td><strong>Aromatic hydrocarbons</strong></td>
<td>- % vol</td>
<td></td>
</tr>
<tr>
<td><strong>50 vol %</strong></td>
<td>282 °C</td>
<td></td>
</tr>
<tr>
<td><strong>90 vol %</strong></td>
<td>338 °C</td>
<td></td>
</tr>
<tr>
<td><strong>95 vol %</strong></td>
<td>353.5 °C</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacturer / specification</th>
<th>Shell RIMULA R6LM 10W-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic Viscosity @40°C mm²/s</td>
<td>82</td>
</tr>
<tr>
<td>Kinematic Viscosity @100°C mm²/s</td>
<td>13</td>
</tr>
<tr>
<td>Sulphate ash (ASTM D874) [% mass]</td>
<td>0.9</td>
</tr>
<tr>
<td>ACEA or API category</td>
<td>API CI-4</td>
</tr>
<tr>
<td>Sulfur content [%]</td>
<td>0.12</td>
</tr>
<tr>
<td>Phosphorus content [%]</td>
<td>0.05</td>
</tr>
</tbody>
</table>

- China Stage3 commercial diesel with the 164ppm Sulphur content was used.
- A certain amount of FBC were mixed into the diesel as required by the DPF manufacture.
- Low SAPS lubricant was used.
## DPFs

<table>
<thead>
<tr>
<th>OEM</th>
<th>Sample ID</th>
<th>Substrate materials</th>
<th>Regeneration mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEM1</td>
<td>DPF-1</td>
<td>Ceramic</td>
<td>PGM-Coated</td>
</tr>
<tr>
<td>OEM1</td>
<td>DPF-2</td>
<td>Ceramic</td>
<td>Uncoated</td>
</tr>
<tr>
<td>OEM2</td>
<td>DPF-3</td>
<td>Ceramic</td>
<td>DOC+DPF</td>
</tr>
<tr>
<td>OEM3</td>
<td>DPF-4</td>
<td>Metal</td>
<td>Uncoated</td>
</tr>
</tbody>
</table>

**VERT certified DPFs**
Test Items

• Test cell setup
• Base line - Engine out emission test
• Filtration test before/after regeneration
• Regeneration test
• WHTC tests
Test cell setup

- Dynamometer AVL 440kW
- Test Engine
- DPF
- CVS tunnel
- NanoMet
- AVL PSS i60 PM Sampling
- MD19 Minidiluter
- CPC
- AVL i60
Baseline

- Measurement of the raw exhaust emission of the test engine without exhaust gas aftertreatment. These measurements are used as baseline for the qualification of the tested DPF’s.

- Consist of:
  - 4 points test (4PTS) / stationary test cycle 5-7-3-1-5
  - WHTC cold-hot tests

<table>
<thead>
<tr>
<th>Stationary 8-point cycle</th>
<th>Rated speed</th>
<th>Intermediate speed</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test stage</td>
<td>1  2  3  4</td>
<td>5  6  7  8</td>
<td></td>
</tr>
<tr>
<td>Relative torque M [%]</td>
<td>100 75 50 10</td>
<td>100 75 50 0</td>
<td></td>
</tr>
<tr>
<td>Duration of test stage [minutes]</td>
<td>15  15  15  10</td>
<td>10  10  10  15</td>
<td></td>
</tr>
</tbody>
</table>
Filtration test

- Measurement of the exhaust emissions of the test engine equipped with a DPF.
- Consist of:
  - 4 points test (4PTS) / stationary test cycle 5-7-3-1-5 before/after DPF regeneration
  - WHTC cold-hot tests

<table>
<thead>
<tr>
<th>Stationary 8-point cycle</th>
<th>Rated speed</th>
<th>Intermediate speed</th>
<th>Idle</th>
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<tr>
<td>Test stage</td>
<td>1 2 3 4</td>
<td>5 6 7 8</td>
<td></td>
</tr>
<tr>
<td>Relative torque M [%]</td>
<td>100 75 50 10</td>
<td>100 75 50 0</td>
<td></td>
</tr>
<tr>
<td>Duration of test stage [minutes]</td>
<td>15 15 15 10</td>
<td>10 10 10 15</td>
<td></td>
</tr>
</tbody>
</table>
DPF-1 PM results

PMG-Coated DPF

DPF-2 PM results

DPF-3 PM results

DPF-4 PM results
DPF-1 NOx results

DPF-2 NOx results

DPF-3 NOx results

DPF-4 NOx results
NO$_2$ in NOx

PMG-Coated DPF

Regenerated
New DPF
No DPF

DPF-1 NO$_2$ friction

DPF-2 NO$_2$ friction

DOC

Good control in NO$_2$

DPF-3 NO$_2$ friction

DPF-4 NO$_2$ friction
PM reduce efficiency of PGM-coated DPF

- PN after DPF were significantly reduced. However, PM were found increased.
- A filter baking test was carried out to preliminarily investigate the PM components.
Filter baking test

PM before bake

Particulate mass [mg]

<table>
<thead>
<tr>
<th>Engine speed with 100% load [rev/min]</th>
<th>No DPF</th>
<th>With DPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>1500</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>1800</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>2300</td>
<td>0.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

PM after 180°C bake

Particulate mass [mg]

<table>
<thead>
<tr>
<th>Engine speed with 100% load [rev/min]</th>
<th>No DPF</th>
<th>With DPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>1500</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>1800</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>2300</td>
<td>0.4</td>
<td>0.5</td>
</tr>
</tbody>
</table>

DPF-1 PM results

DPF-1 PM results after baking

- Some volatile material was removed on the bake, especially the “with DPF” filters
- Those volatile material by the coated DPF might the primary cause of increasing of PM
The PGM-coated DPF promote oxidize sulfur dioxide (SO$_2$) in diesel exhaust to sulfur trioxide (SO$_3$) with the subsequent formed hydrated sulfate particulates during PM sampling $<$52$^\circ$C.

This reaction is dependent on the level of the sulfur content of the fuel.

\[
SO_2 \xrightarrow{[0]} SO_3 \\
SO_3 + 8H_2O \rightarrow H_2SO_4 \cdot 7H_2O
\]

PN measure is based on the dry material after pretreated over 300$^\circ$C.
PM Sampling System

- PM is a mass filtered out of the gas below 52°C, so it may contain condensates of sulfates, sulfites hydrocarbon and water.

- Hydrated sulfuric acid was formed and increases the mass downstream.

PSS i60 for PM sampling
PN Counting System

Exhaust Gas

PND1 (First PN dilution device)
T: 150°C-400°C  DF: 10-200

ET (Evaporation Tube)
T: 300°C-400°C

PND2 (Second PN dilution device)
T: <35°C  DF: 10-30

All water, sulfate, sulfite evaporated

Dry material

MD19 Mini-diluter for CPC

NanoMet for PN counting
Regeneration test

- Repeat soot loading for more than 10 hours until the pressure drop of DPF increased to 10 mbar.

- After the pre-loading of the DPF, a steps-test is performed to demonstrate the regeneration behaviour of the system.
  Consist of:
  - 10-steps regeneration-test (each 10 min.) from 10% to 100% load at rated speed

- Compare of different regeneration mode
The balance point was reached after 2000 seconds at a load of 500 Nm and a delta P of 50 mbar. The inlet exhaust temperature was 343°C at the balance point.

DPF-1 Passive regeneration

The balance point was reached after 4000 seconds at a load of 377 Nm and a delta P of 95.5 mbar. The inlet exhaust temperature was 374.4°C at the balance point.

DPF-2 Passive regeneration

Compare to uncoated DPF, coated DPF is easier to trigger the passive regeneration.
The balance point was reached after 3000 seconds with a load of 270 Nm at 2300 rpm and a delta P of 40 mbar. The inlet exhaust temperature was 330°C at the balance point.

The balance point was reached after 2700 seconds at a load of 270 Nm and a delta P of 70 mbar. The inlet exhaust temperature was 330°C at the balance point.

- The DPFs can be well regenerated at certain condition.
Active regeneration strategy

- Combined regeneration filter system, comprising a passive component (fuel borne catalyst) and an active regeneration component (external fuel injection).
Active regeneration

Active regeneration in the way inject fuel with FBC into aftertreatment could be triggered when the DPF inlet temperature was above 300°C

FBC significantly reduce the active regeneration temperature
WHTC tests

- Performing World Harmonized Transient Cycle (WHTC) testing to simulate the exhaust emission of the on-road scenarios

- Tests were conducted according to Chinese HJ689-2014 Limits and measurement methods for exhaust pollutants from diesel engines of urban vehicles (WHTC)

- Exhaust emission before and after DPF regeneration were measured
- DPFs have high efficiency in reducing PM and PN.
- The DPF retro-fitted engines meet the PM requirement of Chinese Stage 4&5 legislation of urban vehicles.
The efficiency of Particulate Mass reduction following regeneration were slightly higher than the brand new due to the formation of soot cake.
Summary

- All sample DPFs have high efficiency in reducing PN.
- The DPFs can be well regenerated at certain condition.
- The efficiency of Particulate Mass reduction following regeneration were slightly higher.
- The hydrated sulfates oxidized by the coated DPF might cause of increasing of PM.
- Compare to the coated DPFs, the soot loading rate was higher in un-coated ones.
- The use of FBC (fuel bone catalyst) made a clear effect on reducing the soot ignition temperature. It helps the DPF regeneration at lower temperature.
Summary

• PGM-coated filters may currently not suitable in the Chinese retrofit market because this technology produces large amounts of sulfates and NO₂

• FBC-filters have good filtration rate on both PM and PN but do not produce any sulfates nor any NO₂
Where’re we

- Pilot testing in Xiamen and Nanjing of 2x10 vehicles
- Using data log to monitor the DPF operation
- Measure PN with NanoMet3
- Results show high PN filtration efficiency of DPF

Example of On-board PN Test Result
What’s next

- Endurance tests at pilot team
- Emission tests on the heavy duty chassis dynamometer or engine dynamometer
Acknowledgements

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• VERT Association
• Participating VERT members
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