Investigation of underbody Metal SCR Systems with active thermal management: Experience update

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ABSTRACT

The Selective Catalytic Reduction (SCR) is the main after-treatment solution for high efficient Diesel engines under development to cope with future lower fuel consumption and NOx emissions requirements (EU6+ legislation). Exhaust gas temperatures are decreasing too, leading to new after-treatment system developments in a close coupled position. Nevertheless before all vehicle architectures allow it, SCR systems are and will still be installed in underbody position.

The current paper deals with an underbody Metal SCR after-treatment systems, which is capable of active thermal management, and an ultra-compact SCR dosing system. These technologies are described and emission results obtained on several application examples (from Passenger Cars to Light Duty Commercial Vehicles) are presented and discussed in conjunction with an effective active thermal management of the SCR function. It is shown that the NO\textsubscript{2}/NOx ratio as well as the temperature level at SCR system inlet, among all the parameters governing the SCR efficiency play an important role for the feasibility and the acceptance of an underbody SCR solution.

Keywords: Electrically Heated Catalyst, Electrically heated SCR System.

INTRODUCTION

CO\textsubscript{2} / fuel consumption reduction regulations for next decades (2020 and after) for internal combustion engines are introduced worldwide to cope with limited fuel resources and the preservation of the environment for limiting the global warming [1]. Development routes for higher efficient gasoline engine [2] are under progress and will be introduced progressively in the market. The Diesel engine, well appreciated in Europa and India [3], is already known for its high energy efficiency and is further improved in CO\textsubscript{2} emissions as far as the combustion noise allows it. However this CO\textsubscript{2} emission improvement is accompanied by a strong increase of engine NOx emissions.

The Selective Catalytic Reduction (SCR) with its high level of performance is the main after-treatment solution for high efficient Diesel engines under development to cope with future lower fuel consumption and NOx emissions requirements (EU6+ legislation). Exhaust gas temperatures are decreasing too, leading to new after-treatment system developments in a close coupled position as a compact system.

Nevertheless before all vehicle architectures allow it, SCR systems are and will still be installed in underbody position. This has as a consequence that the catalyst function could require an active thermal management.

The paper deals therefore with underbody SCR systems with the integrated heating function. The Electrically Heated Catalyst (EHC), which provides the active heating function into the catalyst converter is integrated into the metal SCR systems as the first brick. These metal SCR systems are add-on systems and are installed downstream a Diesel oxidation catalyst and a Diesel particulate filter. These technologies are described and emission results obtained on two application examples (from Passenger Cars to Light Duty Commercial Vehicles) are presented and discussed in conjunction with an effective active thermal management of the SCR function.

SCR TECHNOLOGY

PRINCIPLE - The “Selective Catalytic Reduction” of nitrogen oxides under lean operating conditions, i.e. in the presence of excess oxygen, by means of ammonia (NH\textsubscript{3}) has been used in the chemical industry or the after-treatment of power station emissions for decades. In the automotive industry the SCR system, initially developed for, and used in, commercial
vehicles in order to reduce fuel consumption is also introduced in Diesel passenger cars. In this case a urea-water solution (AdBlue™) is used to generate ammonia onboard. In passenger car applications increased temperature stability is especially important in SCR catalysts installed behind a particulate filter since relatively high temperatures are generated during filter regeneration. For these applications coatings based on zeolite technology were developed. With technical options which allow to achieve NOx conversion rate above 95% [4], SCR technology is also the best way to operate Diesel engines under fuel-efficient operating conditions and thus reducing CO₂ emissions.

PARAMETERS INFLUENCING THE SCR PERFORMANCES

The exhaust gas temperature is an important factor that decide whether it is possible to inject the AdBlue™ without it forming deposits so that the SCR reaction can proceed. It is generally considered that a minimal temperature of 160°C is required for the AdBlue™ injection. Then the temperature influences the degree of NOx reduction performance of the SCR converter [5]. Therefore the position of the SCR converter at underbody location induces low exhaust gas temperatures and may require some heating to catch up the SCR light off temperatures and allow the injection of AdBlue™.

The amount of NO₂ entering the SCR catalyst is another important factor: Zeolite catalysts are highly sensitive to the NO₂/NO ratio in the exhaust gas especially at low temperatures. In absence of NO₂ only the standard SCR reaction with NO takes place with temperature above 200°C. With the presence of NO₂ (with an optimal NO₂/NO ratio of 1/1) the so called fast SCR reaction involving one molecule of NO and one molecule of NO₂ with two molecules of NH₃ can be realized at temperature as low as 150°C. The influence of NO₂ on the performances of Cu and Fe Zeolite SCR formulations is presented in [5] for example. The presence of NO₂ relies on the capacity of the upstream Diesel Oxidation function to produce it.

The quantity of stored ammonia (NH₃) over the SCR catalyst will determine the level of efficiency of the Zeolite SCR converter at low temperatures. Zeolite SCR formulations have the capability to store NH₃ at low temperatures (below 300°C) and this characteristic is used to improve the NOx conversion rate at low temperatures by increasing the quantity of NH₃ stored on the Zeolite based SCR catalyst. A nice example of the influence of the quantity of stored NH₃ on NOx conversion rate in dynamic tests is shown in [5]. Therefore in real driving conditions the quantity of stored NH₃ on the catalyst at time t will depend on the short history of the catalyst before the time t.

The SCR converter volume, i.e. the Gas hourly Space Velocity (GHSV) will help to get high efficiency at low temperatures. Today a SCR Catalyst volume / engine sweep volume ratio around two is a standard.

The amount of SCR washcoat: a high amount of washcoat improves the NOx conversion rate at low temperatures [6]. At high temperatures this advantage disappears, as the SCR reactions take place at the surface of the washcoat layer only.

The ammonia preparation, i.e its uniform distribution is beside the development of the SCR catalyst the second most important process of the SCR converter. It is expected that all systems for the NH₃ preparation in development lead to an ideal uniform NH₃ distribution (with Uniformity Index ~ 0.95) in front of the SCR catalyst without producing Urea deposit. Today mixer together with mixing pipe systems are used. The difficulty is to make them more compact.

SCR CATALYST AND METAL SUBSTRATES

As exhaust gas temperatures of modern diesel passenger cars are cooler, SCR catalysts will require high efficiency at low temperatures, irrespective of their position in the exhaust line, up- or down-stream the particle filter, and might require an integrated heating function. Therefore the requirements on a SCR catalysts could be summarized as follow:

- Good low and high temperature effectiveness
- Mixing attributes
- Short pressure drop
- Active heating function

To achieve these requirements the catalytic substrate and the catalytic coating have to be fully optimized. Concentrating on the substrate development, it was found that an optimum SCR-converter is likely to consist of two assembly levels [6].

The requirement of the first level is the residual evaporation, hydrolysis and the mixing of the reducer, mainly in the low temperature range and LS/PE-Design™ substrate technology (Fig. 1) has been proposed for this first level, accordingly [6]. The LS/PE-Design™ substrate technology takes advantages from the LS-Design™ structured corrugated foils [7], allowing a reduction of the thermal mass of the substrate matrix and the improvement of the mass transport at high temperatures, and of the PE-Design™ flat foils [7], allowing a gas mixing from one channel to the neighbor channels.

The requirement of the second level in this temperature range is the NOx reduction. Standard foil metal substrates with their high specific geometric surface area and their relatively low pressure drop would be good candidates for the second level. In a car low temperatures only appear together with low
exhaust mass flow, and hence the space velocity is similarly low. At higher exhaust mass flow and consequently higher space velocity temperature rises and also the first level of the SCR catalyst can be used to reduce the NOx.

Figure 1: LS/PE-Design™ substrate structure with flow details

The required temperature management of the underbody SCR system is ensured by the Electrically Heated Catalyst (EHC) (Fig. 2) as first brick of the system. The principle and the construction of the EHC or EMICAT® developed almost twenty years ago and in serial application the early ninety has been reported earlier [8,9,10].

Figure 2 - Design of the electrically heated catalyst (EHC).

Thus, the actual heater was designed as an integral part of the catalyst in the form of a honeycomb disc at the catalyst inlet. This directly heated disc also has a catalytic coating, which allows it to start converting pollutants immediately. The disc is mechanically supported by the second part, the support catalyst. This catalyst and other downstream (after) components are heated by the exhaust gas, which is heated by the disc.

The disc works on the principle of a heating coil. Power is supplied at one end by an electrical connection, which conducts electricity to the foil packet via a half shell. The resistance of the foil packet itself determines the electric power of the heated catalyst. Like the normal winding process of the metal matrix, the disc receives its specific form by being wound into a S shape. Contact with the vehicle ground is provided by a second half shell, which is usually connected to another section of the catalyst jacket or via a separate contact.

An air gap prevents short circuits inside the heated disc and ensures that power flows through every part of it. The heated disc is mechanically supported by insulated pins that are brazed to the heated disc and the support catalyst. This construction ensures that the catalyst is able to permanently withstand the high thermal and mechanical loads in the exhaust system [11].

The effectiveness of such an electrically heating, which brings the heat directly at the catalyst place in comparison to conventional engine exhaust gas heating measures has been reported [10, 12].

Then the support catalyst of the EHC construction is integrating the LS/PE-Design™ substrate technology in order to combine the functions of the first assembly level with the heating function.

RESULTS

Results presented in this section are preliminary results gained on two development programs carried out at Emitec, where the objectives were to demonstrate the capabilities of these electrically heated SCR systems.

TEST SETUP - Results were obtained on two different EURO 4 Diesel vehicles A and B (Table 1), which were installed with underbody electrically heated SCR systems as add on systems downstream the DOC and DPF functions (Table 2).

Table 1: Main characteristics of the EURO 4 vehicles A and B.

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types</td>
<td>Light Duty Commercial vehicle (class N2)</td>
<td>Passenger Car</td>
</tr>
<tr>
<td>Engine displacements</td>
<td>3.2 l</td>
<td>4.2 l</td>
</tr>
<tr>
<td>SCR cat volume / engine displacement ratios</td>
<td>~2</td>
<td>~2</td>
</tr>
</tbody>
</table>
Table 2: Descriptions of the electrically heated SCR systems used on vehicles A and B. Zeolite based SCR coating is the same for both systems.

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>Electrically heated SCR system</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td><img src="image" alt="SCR Diagram A" /> EHC Power 2 kW, 12 V</td>
</tr>
<tr>
<td>B</td>
<td><img src="image" alt="SCR Diagram B" /> EHC Power 1.6 kW, 12 V</td>
</tr>
</tbody>
</table>

TEMPERATURES AND NOx EMISSIONS IN CASE OF INACTIVE THERMAL MANAGEMENT (NO HEATING) – Temperatures and NOx emissions of both vehicles have been measured over NEDC. For emission measurement Adblue™ dosing strategies adapted to each vehicle were applied. It is to notice that measurements with vehicle A were carried out with a SCR catalyst loaded with NH₃ while the measurements on vehicle B were carried out with an empty SCR catalyst.

Up- and down-stream exhaust gas temperatures of the electrically heated SCR systems are presented in Fig. 3. Upstream temperatures of vehicle A are more favorable to a SCR process, with temperatures above 160°C after 500 seconds, than the temperatures of vehicle B which are reaching 160°C only after 950 seconds. Vehicle A is almost 50°C warmer than vehicle B.

NO₂/NOx ratios upstream the SCR converter are shown in Fig. 4. It indicates that vehicle A has a very low production of NO₂ over NEDC, the NO₂/NOx ratio being well under 10% for the first 1050 seconds of the NEDC. That means that the fast SCR reaction cannot happen once the temperature of 160°C in the SCR converter is reached. On contrary vehicle B produced much more NO₂, with NO₂/NOx ratio values above 10%, up to 40%, that is favorable to the SCR process.

As a result of the combinations temperatures - NO₂/NOx ratios, both vehicles convert NOx at a low rate when the temperature of 160°C is reached and at higher rate once the gas temperatures are above 200°C (Fig. 5 and Fig. 6). The average NOx conversion rates are given in Table 3.
TEMPERATURES AND NOx EMISSIONS IN CASE OF ACTIVE THERMAL MANAGEMENT - Technical paper [13] worked on the thermo-management of such a system and defined some heating strategies based on the temperature into the SCR converter and the exhaust mass flow: For example the conditions on the temperature was heating if $T$ higher than $T_{\text{Min}}$ (when $T$ is below $T_{\text{Min}}$, the heating isn’t efficient to reach the SCR working temperature window) and below $T_{\text{Max}}$ (when $T$ is higher than $T_{\text{Max}}$, the heating isn’t necessary). The condition on the mass flow was heating if mass flow below a given quantity. This allows to modulate the heating phase and choose when the heating should take place. For example at idle or during deceleration phase to prevent the system to cool down. With a fine tuning it has been demonstrated that a given NOx conversion rate could be achieved with a minimal supply of energy, representing the lowest fuel penalties.

Here different and simple heating strategies, adapted to both vehicles were carried out. Here are reported the results for an energy supply of 745 kJ for vehicle A and 1050 kJ for vehicle B.

**Vehicle A** - The electrical energy is delivered on the vehicle by the battery and the generator. Due to the high output of the EHC, the EHC is mainly powered by the generator. The operation of the generator increases the load of the engine and leads to slightly higher exhaust gas temperatures. Fig. 7 shows the derived influence of the heating on the exhaust gas temperatures at the electrically heated SCR system inlet. A temperature increase of about 10°C can be observed from 400 seconds to 1050 seconds, the heating period being started at 220 seconds as shown in Fig. 8.

Fig. 8 shows as example the temperature behavior into the electrically heated SCR system with a discontinuous heating (heating only when the inlet gas temperature is higher than 130°C and the mass flow is below 90 kg/h, mostly during deceleration and idle phases). An increase of about 100°C of the temperature at the inlet of the EHC support matrix, just after the heating slice of the EHC with an output of 2 kW is observed during the heating phases. This produces a heat wave, that is moving from the inlet to the outlet of the SCR converter and losing its intensity with the heat up of the converter.

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**Table 3: NOx conversion rates over NEDC without active heating**

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>NEDC NOx conversion rate (%)</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>42</td>
</tr>
<tr>
<td>B</td>
<td>19</td>
</tr>
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</table>

The influence of the heating on the electrically heated SCR system outlet exhaust gas temperatures is shown in Fig. 9. Outlet gas temperatures are increased and kept above 200°C after 500°C, which represents an increase of 50°C.
Figure 9: Influence on heating on the electrically heated SCR system outlet temperatures in case of vehicle A.

Figure 10: Influence of heating on NO₂/NOx ratio upstream the electrically heated SCR system in case of vehicle A.

Table 4: NOx conversion rates over NEDC with / without heating for vehicle A

<table>
<thead>
<tr>
<th>Heating</th>
<th>NEDC NOx conversion rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
<td>42</td>
</tr>
<tr>
<td>yes</td>
<td>60</td>
</tr>
</tbody>
</table>

Vehicle B – Similar analysis can be carried out with vehicle B.

The heating strategy used on this vehicle was different than with vehicle A and heating periods were controlled by a condition over the temperatures in the second brick of the SCR converter (heating if T_{SCR-2nd Brick} < T minimal). Fig. 12 shows the up- and down-stream gas temperatures and the gas temperatures between the EHC brick and the second brick of the converter. Similarly to the previous example, the simple heating strategy lead to a heat wave propagating from inlet to outlet. The temperature curve downstream the EHC support matrix suggests that its temperatures is higher than 150°C after 150 seconds.

Fig. 13 and Fig. 14 show the derived influence of the heating on the exhaust gas temperatures at E-SCR system inlet and outlet. The engine load increase during heating leads to an increase of the inlet temperature of about 20°C. The outlet temperatures around 100°C without heating vary between 150°C and 230°C with heating.
Fig. 12: Influence of Heating on the electrically heated SCR system exhaust gas temperatures for vehicle B.

Fig. 13: Influence of Heating on the electrically heated SCR system inlet exhaust gas temperatures for vehicle B.

Fig. 14: Influence of Heating on the electrically heated SCR system outlet exhaust gas temperatures for vehicle B.

Fig. 15: Influence of Heating on NO$_2$/NOx ratios upstream the electrically heated SCR system for vehicle B over NEDC.

As a result of the heating a NOx conversion after 150 seconds is observed (Fig. 16). This underlines the importance of the fast SCR reaction. It is seen that the engine out NOx have been increased but tail pipe emissions have been reduced and reach the level of the Euro 6 emission limit. Table 5 shows a conversion rate gain of 41.8% with heating.

Fig. 16: Influence on heating on NOx conversion rate in case of vehicle B.

Table 5: NOx conversion rates over NEDC with / without heating for vehicle B.

<table>
<thead>
<tr>
<th></th>
<th>NEDC NOx conversion rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no heating</td>
<td>19</td>
</tr>
<tr>
<td>yes heating</td>
<td>60.8</td>
</tr>
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DISCUSSION OF THE THERMAL MANAGEMENT

Fuel penalties / electrically heating cost – As written before the heating in underbody position with the help of the electrically heated catalyst is more effective than an heating by engine measures [10]. But the cost of the electrically heating, fed by the generator, applying itself an additional load on the
engine, must be an acceptable increase of the fuel consumption. Table 6 shows the fuel penalty results for both vehicles and the applied simple heating strategies. As the vehicles are different, equipped with serial generators with different characteristics, not optimized for the heating through EHC, the electrically heating more or less has influence on the fuel penalties. It can be said that the heating is more effective on vehicle B as it generates lower fuel penalties.

**Table 6: Fuel penalties for both vehicles A and B according to the supplied energies by EHC.**

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>Supplied energy by EHC (kJ)</th>
<th>Fuel penalty for EHC usage(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>745</td>
<td>5.3</td>
</tr>
<tr>
<td>B</td>
<td>1050</td>
<td>4.7</td>
</tr>
</tbody>
</table>

With redesigned and more efficient oxidation function delivering NO\textsubscript{2}, the need of heating for vehicle A would be drastically reduced as SCR inlet temperatures are not too cold for SCR operation.

In case of vehicle B, a refined temperature management with control temperature, located one inch downstream the heating disc, and heating if T\textsubscript{inlet-SCR} higher than 80°C and heating on if T\textsubscript{control} below 190°C and heating off if T\textsubscript{control} higher than 200°C, has been simulated (Fig.17) This strategy would lead to a reduced fuel penalties of about 4%.

![Figure 17: Simulated Temperatures at control point located one inch downstream the heating disk for vehicle B. Heating if T\textsubscript{inlet-SCR} higher than 80°C and heating on if T\textsubscript{control} below 190°C and heating off if T\textsubscript{control} higher than 200°C](image)

**CONCLUSIONS**

Developed add-on underbody electrically heated SCR systems have been tested on two different applications: one Light Duty Commercial Vehicle and one Passenger Car. Emission results gained with and without heating have been presented and discussed in conjunction with an active thermal management of the SCR function.

It is shown on both vehicles that the electrically heated catalyst efficiently can improve the temperatures of the SCR systems.

The NOx emission results depend on the vehicle characteristic: Vehicle A with its shortage of NO\textsubscript{2} could not achieve EU 6 level, even with a very high energy supply. Therefore the improvement of the DOC function on vehicle A for a higher production of NO\textsubscript{2} is mandatory before to continue underbody SCR system development. Vehicle B with its high amounts of NO\textsubscript{2} can reach EU 6 NOx emission level, but due to its very low inlet temperatures, the required energy supply is relatively high.

In these investigations the energy management of the vehicles isn’t optimized with energy recovery systems. The presence of such systems would deliver free energy available for the heating and fuel penalties would be reduced.

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