1. Introduction

Selective catalytic reduction (SCR) of nitrogen oxides is a process that has been used successfully in power plants for decades. The first commercial vehicle test fleets with Siemens SinNOx technology were tested almost 20 years ago. However, automotive SCR systems did not enter serial production for another 15 years because improved engine designs were able to meet emission limits even without exhaust aftertreatment.

SCR technology was initially used only in EU V commercial vehicles but has now also found application in non-road mobile machines (NRMM), that is, tractors and construction equipment, and in passenger cars. The reducing agent is a standardised urea/water solution (AdBlue).

SCR systems usually consist of a reducing agent tank with an extraction pipe, a pump module and an injector. The precise amount of reducing agent that has to be injected into the exhaust system is determined either directly by the engine management or by a separate control unit.

Many years of experience have shown that there are two main challenges:

- Deposit-free injection of reducing agent under any operating conditions
- Evaporation and simultaneous distribution of the reducing agent

Future legislation will limit NO₂ emissions alongside the existing limits on NOx emissions. The ratio of NO₂ to NO in the exhaust gas in front of the SCR catalyst is a crucial factor in SCR efficiency, particularly at temperatures below 300°C or 250°C. Ideally, the ratio should be 1:1 to encourage a fast SCR reaction \cite{1}. If the proportion of NO₂ is lower, the light-off curve of the SCR reaction moves towards a higher temperature range. A similar but less significant pattern emerges if the NO₂/NO ratio is bigger than 1. Since the proportion of engine-based NO₂ is usually lower than required for an optimum ratio, an oxidation catalyst and/or a particulate filter with an oxidation coating are used to
oxidise the engine NO to NO₂ in order to ensure maximum NOx conversion rates in polluted urban areas. This can lead to proportionally higher NO₂ tailpipe emissions compared to raw emissions in certain operating ranges [2]. Ultimately, however, NO and NO₂ raw emissions are substantially reduced, especially at low exhaust temperatures.

In view of the fact that all NO is oxidised to NO₂ in the atmosphere [3], there is still a significant environmental benefit despite the higher NO₂ concentration in the exhaust gas. Consequently, there is no point in limiting the amount of NO₂ in total nitrogen oxide emissions.

The composition of the exhaust gas entering the SCR catalyst and the exhaust gas temperature are important factors that decide whether it is possible to inject the AdBlue without it forming deposits so that the SCR reaction can proceed. Due to the temperature losses along the exhaust system the reducing agent should be added at a position as close to the engine as possible. The optimum position is directly behind the turbocharger, or behind an oxidation catalyst installed at that position. In future, it may also be worth considering installation in front of the turbocharger, especially for engines or applications with lower dynamic engine performance requirements, such as hybrid vehicles. The limited installation space in the engine compartment requires new and innovative designs so that all components can be grouped together in very confined conditions. Since most future diesel applications will also include a particulate reduction filter, it would be best in these cases to combine particulate filter and SCR coating [4].

With technical options which allow to achieve NOx conversion rate above 95% [5], SCR technology is also the best way to operate diesel engines under fuel-efficient operating conditions and so reduce CO₂ emissions.

2. Gen III SCR dosing system

As mentioned briefly above, an SCR dosing system consists of a reducing agent tank with an extraction unit, a pump unit and an injector, if necessary. The tank, pump and injector are connected via heated pipes. In newer systems, the pump module is integrated in the tank itself. Figure 1 shows Emitec’s Gen III SCR dosing system.
Emitec’s SCR dosing system injects the reducing agent into the exhaust system and also functions as a complete tank extraction unit. In addition to the actual dosing pump and a lifetime filter, it also comprises the heating, a pressure and temperature sensor, and an supersonic-based level/quality sensor. The injection pressure is adjustable and can be adapted to the specific application [6].
As an option, a fully functioning SCR control unit can be installed at low cost to replace currently used separate SCR control units and prepare the system for the emerging markets and the retrofit market (figure 2).

The injector is connected to the system via a heated pipe. The system remains filled even during shutdown. This prevents fouling of the injector and the pressure line, which can be caused by back siphoning of dirt from the exhaust system.

2.1. Operation during shutdown (back sucking / non-back sucking)

A non-back sucking system is particularly suitable for future SCR designs, where the injector is positioned in the direction of the exhaust flow in front of the SCR-coated particulate filter. Figure 3 shows the particulate concentration in the exhaust system at the SCR injector position in front of the particulate filter after the engine has been switched off.

![Graph showing soot concentration](image)

*Figure 3: Soot concentration in the exhaust system at the SCR injector position in front of the particulate filter*

This shows that the particle concentration in the exhaust system stays constant for a longer time after the engine is switched off. In back sucking SCR systems, these particles could enter the injector causing local fouling and in some cases malfunctions.

Another positive feature of non-back sucking SCR systems is the fact that, in contrast to back sucking systems, there is no AdBlue film remaining in the injector and the pipe. This film could lead to the formation of crystals when the application is not in use for extended periods. The crystals
could damage the injector because they are not dissolved quickly by the AdBlue when the system is started up and filled.

Since a non-back sucking system will be kept filled with AdBlue even under freezing conditions every component must be protected against freezing and allow for the expansion of the AdBlue volume due to freezing. This requirement basically also applies to back sucking systems because the system may remain filled under exceptional circumstances if the battery is disconnected or in case of malfunctions. However, back sucking systems require a smaller number of freezing cycles.

The following example illustrates the effect that freezing has on an SCR injector. A vehicle with an SCR system was fitted with thermocouples and tested in a climate chamber. Figure 4 shows the times until the AdBlue freezing point of -11 °C was reached in a vehicle tested in a climate chamber that had been pre-cooled to -20°C.

<table>
<thead>
<tr>
<th>Measure point</th>
<th>Temp. [°C]</th>
<th>Time [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>exhaust flow bottom</td>
<td>-11</td>
<td>3420</td>
</tr>
<tr>
<td>exhaust flow top</td>
<td>-11</td>
<td>3720</td>
</tr>
<tr>
<td>injector jacket bottom</td>
<td>-11</td>
<td>5610</td>
</tr>
<tr>
<td>injector jacket top</td>
<td>-11</td>
<td>6510</td>
</tr>
<tr>
<td>SAE connector</td>
<td>-11</td>
<td>8520</td>
</tr>
<tr>
<td>urea tube</td>
<td>-11</td>
<td>8580</td>
</tr>
</tbody>
</table>

*Figure 4: Times at which AdBlue freezes at different points of the SCR injector; vehicle in a pre-cooled climate chamber.*

The test results show that the injector begins to freeze from the side that is closest to the exhaust system. In the second stage the AdBlue freezes from the sides of the pressure line. The maximum temperature gradient during freezing is less than 0.5 k/min. Those results are used to calculate the freezing patterns of the injector and the entire dosing system. Figure 5 gives an example of the temperature distribution inside the injector just before the system is frozen solid. It becomes apparent that the upper third of the series SCR injector freezes last. The increase in the AdBlue volume caused by freezing is absorbed by an expansion volume at this point. The freeze protection
of the entire Gen III SCR dosing system was designed and implemented based on these calculations.

Figure 5: Temperature profile inside a water-cooled SCR injector just before it is frozen solid

3. Evaporation / mixing section

As mentioned in the introduction, the greatest challenges to an SCR system operating in the field are deposit-free injection and the evaporation and distribution of AdBlue or of the ammonia (NH₃) generated from it. This makes the mixing section a particularly important component of the SCR system.

In addition to the type of injection mode (air-assisted or airless), there are also the following possibilities for the injection:

- Injection into the exhaust pipe in front of the SCR catalyst
- Injection against a mixer (in the exhaust pipe or the catalyst casing)
- Injection against a hydrolysis catalyst [7]

In each case, the formation of deposits must be prevented across the entire engine map, as far as possible. The advantage of a hydrolysis catalyst is that it produces fewer deposits, especially at low temperatures, and also increases SCR efficiency. Figure 6 shows the result of a deposit test comparing an SCR system with a mixer to a system with a hydrolysis catalyst. The test was conducted under a constant load point at 1200 revolutions per minute and 215 Nm, at an exhaust gas temperature of 230°C and at an exhaust gas mass flow rate of 514 kg/h.
The system with the mixer showed some deposits in the area behind the mixer where the exhaust flow changes direction, which could block the exhaust system in the long term. However, these deposits could also, at least partially, evaporate at high temperatures under dynamic operating conditions, thus producing excess NH₃ and consequently NH₃ slip.
Figure 7 shows the efficiency of NOx reduction at an exhaust gas temperature of 230°C and a sharp increase in the AdBlue amount with and without a hydrolysis catalyst in an otherwise identical catalyst system. It becomes clear that the system with a hydrolysis catalyst reacts to the AdBlue injection much more quickly than a system with a mixer. The fact that the efficiency of the system with a mixer increases after dosing ends can be explained by the evaporation of the deposits shown in figure 6.

In addition to its chemical function, a hydrolysis catalyst must, as shown, also evaporate all of the injected AdBlue to eliminate any droplets that could form deposits on pipe bends. For this reason, extensive research was carried out to test the droplet penetrability of different catalyst structures and find an optimum design. The aim was to ensure that all droplets were evaporated at the end face, where rapid cooling could lead to the formation of deposits, and to evaporate 100% of droplets with minimum backpressure. A comparison between three catalyst structures in figure 8 shows the specific lengths required for 100% evaporation.

![Figure 8: Evaporation properties of different catalyst structures and lengths](image)
The mixer structure (MX) exhibited the best properties. All droplets had been evaporated after a length of only 80 mm.

A dosing map for this MX structure was defined during the development stage. The dosing map describes the maximum volume of AdBlue that can be injected without deposits as a function of exhaust gas temperature and exhaust mass flow (figure 9). Airless injection was performed with a water cooled SCR-injector at a pressure of 8 bar. The injector delivered a round, slightly centre-weighted spray pattern with a Sauter mean diameter of 90 µm for the droplets.

![Figure 9: AdBlue dosing map for a hydrolysis catalyst with an MX structure and airless dosing with a water cooled SCR-injector](image)

Using a NOx raw emission map it is possible to calculate whether the SCR mixing section can supply sufficient NH₃ in all map points.

If the ammonia volume is not sufficient, especially at low temperatures, it will become necessary in order to increase the temperature level at the hydrolysis catalyst to activate engine-based heating or install an electrically heated catalyst. Figure 10 shows an electrically heated catalyst in the mixing section.
Due to the heating function the surface of the catalyst (heat source) is hotter than the exhaust gas so that the amount of injected AdBlue can be increased. Figure 11 shows the extension of the dosing range in the dosing map.
An alternative process, which is described in more detail below, is reverse injection onto a zone-coated oxidation catalyst.

4. Close-coupled, compact SCR system

Installation space is a critical factor, especially in passenger cars, but also in non-road applications. In order to be able to inject AdBlue even at low loads and low temperatures the injection point should be located in the engine compartment close to the engine. The point closest to the engine is directly behind the diesel oxidation catalyst. However, since there is often no space in the engine compartment for the installation of a conventional mixing section, a possible alternative would be the application of a hydrolysis coating to the rear of the diesel oxidation catalyst (DOC) with injection of the AdBlue droplets against the rear end face (figure 12).

![Figure 12: Close-coupled, compact SCR catalyst system with rearward AdBlue dosing](image)

The droplet size can be adapted to flow conditions by adjusting the injection pressure. Lower injection pressure is associated with bigger droplets. Figure 13 shows the effect of injection pressure on the ammonia distribution in a close-coupled system for two different load points. It becomes clear that the optimum injection pressure depends on the load point. Emitec’s SCR system offers extra flexibility when it comes to meeting the requirements of different applications.
The compact catalyst design means that the transition of the canning between the DOC and the SCR catalyst is optimized for additional mixing function. Figure 14 shows NH$_3$ distribution measure on the flow test bench for the catalyst system shown in figure 12.
The measured uniform distribution of $\text{UI} = 0.96$ creates good conditions for high SCR conversion rates. Emissions were subsequently measured on a dynamic dynamometer at constant load points. The test engine was a 6.8 liter NRMM engine (figure 15).

![Figure 15: NOx efficiency of a close-coupled SCR dosing system at different constant load points of the engine map](image)

Conversion rates between 80 and 98% were achieved.

5. Summary

The requirement for highly effective NOx exhaust gas aftertreatment arises primarily from existing and planned CO$_2$ limits, which lead to an increase in NOx raw emissions from fuel-efficient engines. As a result, SCR catalysts will have to be fitted to the majority of passenger cars and commercial vehicles.

Emitec has added a compact, in-tank Gen III dosing system to its highly successful NoNOx product range. The Gen III dosing system includes all the necessary functions, such as dosing, filtration, level and quality measurement, and defrosting, in one single unit. The system can be used both in passenger cars and commercial vehicles.

These compact and highly efficient complete SCR systems are based on existing metal structures for hydrolysis, mixer and SCR catalysts.

The strength of the components in connection with Emitec’s engineering deliver innovative solutions, such as close-coupled, compact SCR catalyst systems with rearward injection and universal mixing sections with hydrolysis catalysts that are particularly effective at low temperatures.
Bibliography


[4] Dr. Martin Dieterle¹, Dr. Sam Boorse¹, Dr. Kenneth Voss¹, Dr. Susanne Stiebels², Dr. Claudia Wendt², Dr. Torsten Neubauer², 1 BASF Corporation, 2 BASF Catalysts Germany GmbH: „Two in One : SCR on Filter“; MinNOx Konferenz 2010, Berlin

