

Investigations to Achieve Highest Efficiencies in Exhaust Gas After-Treatment for Commercial Vehicles using an SCR System

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Andreas Keuper, Hiie-Mai Ida Unger, Jia Huang, Harald Bressler and Wolfgang Albrecht
Bosch Emission Systems GmbH & Co. KG.

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ABSTRACT

To comply with the upcoming emission regulations for non-road applications, especially the TIER 4 Final emission legislation, a significant reduction in particulate matters and nitrogen oxide emissions is necessary. An exhaust gas after-treatment system with a good performance helps to meet these requirements.

The following paper focuses on the possibilities to reduce the nitrogen oxide emissions in exhaust gas after-treatment technology using selective catalytic reduction with AUS32. Using this technology and targeting a nitrogen oxide emission reduction of 90% the exhaust gas after-treatment system enables engine-out emissions of about 3 - 4 g/kWh nitrogen oxide. Considering an increase of only 5% reduction efficiency to 95%, a duplication of engine-out emissions could be acceptable for still meeting TIER 4 Final emission legislation. This would enable the engine manufacturer to avoid internal engine measures, such as exhaust gas recirculation, and therefore provide the opportunity to save on space, cooling, fuel and costs.

To achieve maximum reduction efficiency of nitrogen oxides it is important to understand the influential parameters and their interaction within the complex selective catalytic reduction system. An analysis to determine the influence of each parameter and its interaction on the overall efficiency within the TIER 4 Final emission tests for off-highway applications (the steady state C1 test and the non-road transient cycle - NRTC) has been set up on a theoretical basis. To determine the path to high reduction rates, the results of the theoretical analysis have been simulated with

computational fluid dynamics (CFD) analysis and tested on an engine test bench.

The paper describes this program and analyses the most influential parameters, how to achieve maximum nitrogen oxide conversion rates, and the limits of this technology within the scope of these investigations.

INTRODUCTION

The upcoming TIER 4 Final legislation sets very stringent emission limits, especially for nitrogen oxides (NO_x) and particulate matters (PM). Engine manufacturers must invest heavily to comply with these new limits. While previous emission standards could usually be met with a particulate filter (DPF) and various measures for NO_x reduction within the engine, the new emission standards will require additional activities to reduce NO_x. [Figure 1](#) shows that there are different approaches to meet this challenge. As a general rule, nitrogen oxides inside the engine can be reduced by optimizing combustion processes. The other option is exhaust gas aftertreatment and catalytic breakdown of the nitrogen oxides generated during combustion. Selective catalytic reduction (SCR) has proven to be the leading solution here in recent years and has established itself accordingly in the automotive sector. While engine-internal activities, such as exhaust gas recirculation (EGR), are limited as a matter of principle, the SCR technology theoretically offers the potential of converting significantly more nitrogen oxide. [Figure 1](#) also shows that higher SCR performance allows a greater degree of freedom for the layout of the entire system. If the TIER 4 Final regulations can be met despite high NO_x exhaust gas emissions before the catalytic converter, the engine out NO_x constraint is removed from the total cost

optimization process. Although high engine out NO_x emissions effect a higher AUS32 consumption, the gained degree of freedom leaves space to lower particle emissions, simplify the engine and decrease the fuel consumption.

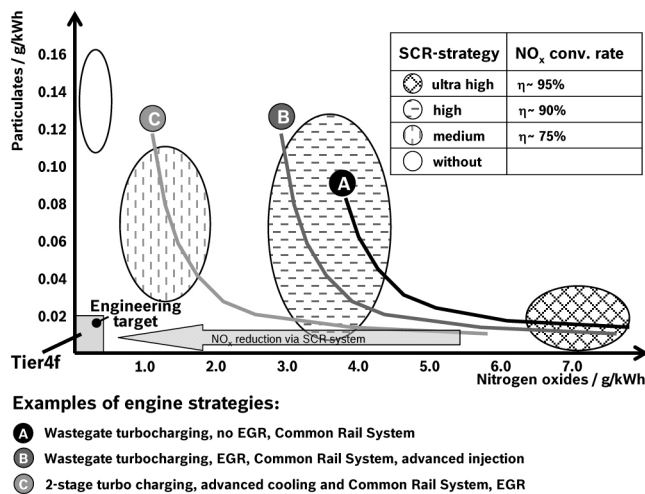


Figure 1. Possible engine and exhaust gas after-treatment strategies for TIER 4 Final systems

As these considerations show, there are enough reasons to have a closer look at the possibilities and limits of an SCR system - an effort which Bosch Emission Systems GmbH & Co KG supports with this paper. Along with laboratory tests and simulative considerations, engine test bench experiments form the core area of this work. So in addition to the essential question of feasibility, practical implementation is also a main focus. A brief consideration of the factors leading to series implementation is shown at the end of this paper.

THEORY

BASICS OF SELECTIVE CATALYTIC REDUCTION

Every combustion engine produces nitrogen oxides as a matter of principle. Due to the lean combustion of diesel engines the oxidation of pollutants can easily be obtained with a platinum-based oxidation catalyst. In contrast, nitrogen oxides cannot be reduced within a surplus of oxygen. To solve this problem the SCR system injects AUS32 into the exhaust gas. On an SCR catalyst the AUS32 is converted into gaseous ammonia which is a strong reducing agent and enables the final reduction of nitrogen oxides via the SCR catalyst. As ammonia is a toxic gas it should be consumed completely in order to avoid ammonia slip [23][19]. Thus the accurate dosing of AUS32 is essential for environmentally friendly operation.

The principle set-up used for this investigation is illustrated in [figure 2](#). It operates with a diesel oxidation catalyst, followed by the AUS32 dosing system, a mixer and the SCR

catalyst. Later the SCR catalyst can be designed with an integrated ammonia slip catalytic zone at the end of the monolith. Several sensors are used to regulate and control the system. [Figure 2](#) shows a NO_x sensor before the SCR catalyst to detect the content of NO_x in the exhaust gas - the most important value to calculate the required amount of AUS32. The NO_x sensor at the end of the system is needed to monitor the remaining NO_x content. Two temperature sensors are used to detect the temperature within the SCR catalyst as precisely as possible.

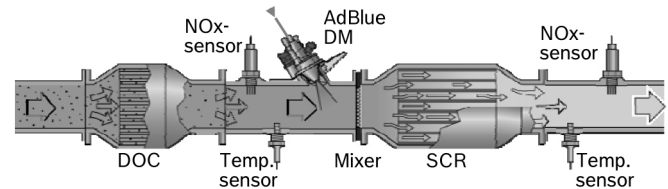


Figure 2. Setup of the analyzed selective catalytic reduction system

Most important within such a system is the appropriate selection of the SCR catalyst technology. There are different technologies that can be used according to the overall performance needed, temperature conditions and other influential parameters (see also [figure 6](#)).

CATALYTIC CHARACTERISTICS

There are different SCR technologies available today, each with particular strengths, designed for different applications and system configurations[1]. Along with vanadium-based catalysts, zeolite technologies on a copper or a ferric basis are available. All 3 types of catalysts have been screened on a synthesis gas test bench first in order to understand their functionality and the interrelationship between different influencing parameters.

[Figure 3](#) shows the conversion performance of the three common representatives at different temperatures. The behavior illustrated here is the most important decision criterion for a catalyst technology. The conversion performance at high temperatures will prove to be crucial here. As shown in [figure 3](#) the ferric zeolite SCR is best suited for this requirement, and thus is used for this investigation [10][13]. This technology performs well at temperatures up to 500°C and the coating can also endure even higher temperatures, enabling the use of an actively regenerated particulate filter (DPF) in front. This type of catalyst has also already proven its reliability in serial application [14].

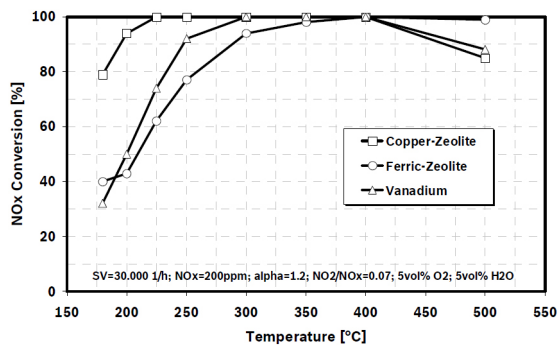


Figure 3. Comparison of different SCR catalyst technologies: NO_x conversion rates at different temperatures

Several further aspects, such as the space velocity and the NO₂/NO_x ratio of the upcoming exhaust gas, have to be considered when using a ferric zeolite catalyst. The following sections will show and explain these aspects.

The results illustrated in figure 4 show a high dependency on the catalyst's temperature and the space velocity. This is a common characteristic for almost all kinds of catalysts [12] [22][24]. A minimum temperature is needed to start the reaction. Higher temperatures accelerate the chemical reaction. However competing reactions can start and lower the NO_x conversion performance. Each catalyst technology has its own optimal temperature. In terms of catalyst performance a lowering of the space velocity has a similar effect because it gives the reaction more time and hence allows higher NO_x conversion rates [27][21].

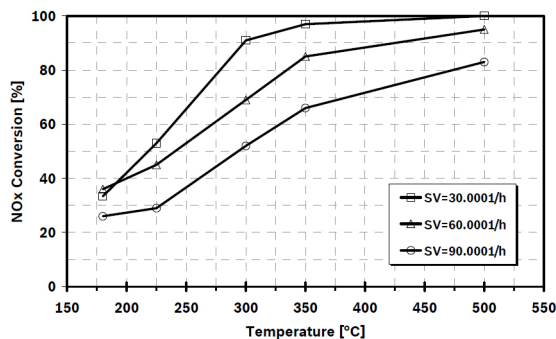


Figure 4. SCR catalyst technology: ferric zeolite - dependency of the space velocity on the NO_x conversion rate

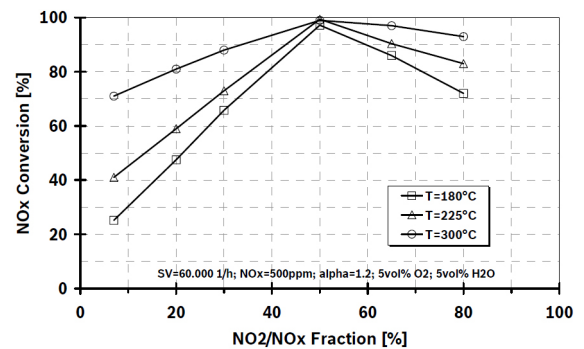


Figure 5. SCR catalyst technology: ferric zeolite - dependency of the NO_x conversion rate on the NO₂/NO_x ratio

Specific for a ferric zeolite catalyst is a strong dependency on the NO₂ / NO_x ratio shown in figure 5. The reason for this lies in the reduction of nitrogen oxides within the SCR catalyst, which is roughly based on the three basal reactions shown below (1, 2, 3). Depending on the NO₂ fraction in the exhaust gas different reaction paths are possible. [13][20] If there is none or only few NO₂ present reaction (1) will be prior, whereas reaction (3) takes place if there is mostly NO₂ present. With a balanced NO₂/NO_x ratio of around 50% reaction (2) is the preferred reaction path. In addition to a different stoichiometry factor, the main difference between them is the reaction speed. Reaction (2) is much faster than the others and hence shows the best performance - especially at low temperatures [16]. An NO₂ to NO_x ratio of 50% is therefore an important basic requirement to achieve a good NO_x conversion performance.

Due to the fact that the exhaust emissions of a diesel engine usually do not contain much NO₂, it must be generated afterwards by using a diesel oxidation catalyst (DOC). In order to get a 50% ratio of NO₂ to NO_x in the most relevant areas of the engine map, the choice of a suitable DOC technology is fundamental for high NO_x conversion rates. However, this is the reason for always assessing both catalysts together: ferric zeolite SCR and DOC.

