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Piotr JAWORSKI
Sebastian JAROSIŃSKI
Azael CORTES CAPETILLO
Łukasz Jan KAPUSTA
Adam ZIÓŁKOWSKI
Robert GRZYWNOWICZ

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SCR systems for NO_x reduction in heavy and light duty vehicles

Air pollution has become an important worldwide problem. The European Commission credits road and water transport as the major source of NO_x pollution, and of being responsible for around 50% of the total air pollution in urban areas. During the last decade, the use of SCR technologies have gained popularity as a method for NO_x reduction, the technology is widely considered as one of the solutions for road transport emissions. This paper presents a review of the different SCR system designs derived from the various factors and regulations in the automotive industry which have influenced the technology, along with a parametric study of a proprietary SCR system for heavy duty application.

Key words: *NO_x, SCR, urea, ammonia, exhaust, emissions, after treatment, heavy duty vehicle*

1. Introduction

Considering that catalytic emission control has been around for more than 40 years, and Selective Catalytic Reaction (SCR) been widely used on stationary plants for the abatement of NO_x [1], its introduction into the automotive market dating to the last decade (around 2005-2008) is relatively recent [2].

The main purpose of SCR catalytic converters is the abatement of NO_x contaminants, which are poisonous for humans and largely responsive for the catalytic destruction of ozone (O_3) in the atmosphere [3]. NO_x is the generic term for mono-nitrogen oxides primarily NO and NO_2 which are produced during combustions at high temperatures [3].

Diesel engines operate lean, and at lower temperatures than stoichiometry gasoline engines [4], thus preventing the complete reaction of NO_x species. As catalytic technology developed, it was evident that Hydrocarbon (HC) based catalyst were not sufficient for the reduction of NO_x agents on low temperature engines such as the diesel operated ones [1]. This problem popularized the use SCR systems using urea based solutions as a conduct of ammonia (NH_3) for the reduction NO_x contaminants to nitrogen (N_2) over a catalyst composed of base metals on diesel engines. The technology has proved a great success showing efficiencies of over 90% NO_x reduction in laboratory conditions [5].

According to the Regulation (EC) No 715/2007, the Euro 6 norm for heavy, medium and light duty engine demands for more than a 50% reduction of NO_x contaminants in comparison to Euro 5 (Tab. 1). Such demanding reductions on NO_x contaminates demand for further investigation and improvement on SCR reduction methods for light and heavy duty engines [6].

2. NO_x reduction – SCR methodology

The SCR method consist in a controlled injection of a water/urea solution, that turns into ammonia (NH_3), into the exhaust gasses to promote the reduction of NO_x contaminants at low temperatures over a based metal catalyst (Fig. 1). The process used to be located after the oxidation catalyst to avoid the oxidation of the injected solution before its catalytic reaction with NO_x contaminants [7].

The reduction of NO_x in the absence of an oxidizing catalyst can be achieved in a narrow range of temperature between 1075 to 1175 K and over 1200 K the ammonia (NH_3) oxidize to NO_x [8]. Due to that it is not possible to combine the ammonia as a reduction fluid in high temperature region. It is a reason why a technique commonly used on SCR systems is to locate the SCR process (including the

Table 1. Oxides of nitrogen emission limits comparison of Euro 5 vs Euro 6 according to EC No 715/2007

Vehicle		Reference mass (RM) [kg]	Limit values: Mass of oxides of nitrogen (NO_x) [mg/km]			
			Euro 5		Euro 6	
Category	Class		PI	CI	PI	CI
M	–	All	60	180	60	80
N1	I	RM ≤ 1305	60	180	60	80
	II	1305 < RM ≤ 1760	75	235	75	105
	III	1760 < RM	82	280	82	125
N2			82	280	82	125

PI = Positive ignition, CI = Compression ignition
M – 4 wheel vehicles for the carriage of passengers
N1 – 4 wheel vehicles for the carriage of goods (RM < 3 500)
N2 – 4 wheel vehicles for carriage of goods (3 500 < RM < 12 000)

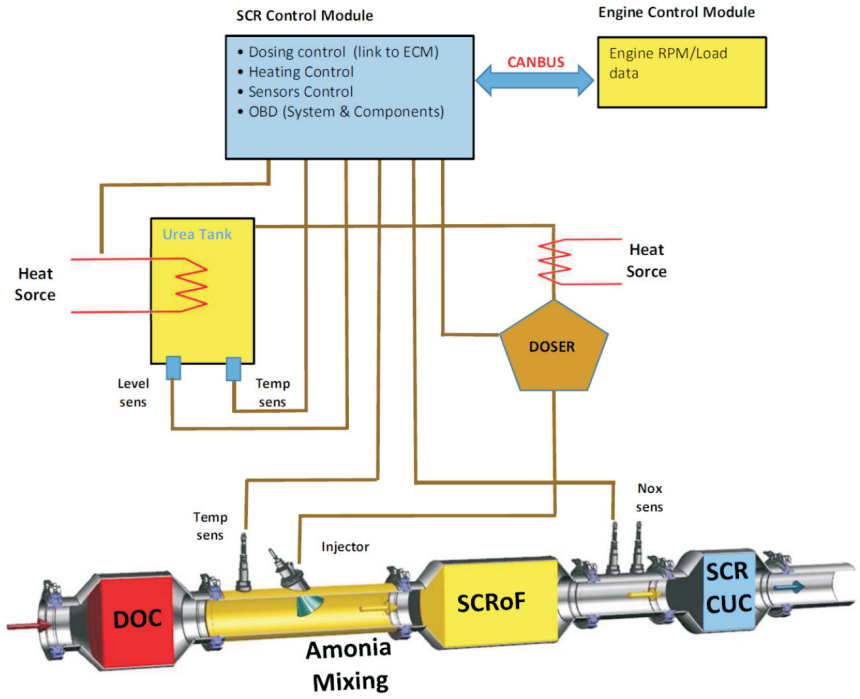

Fig. 1. After-treatment system

solution injection, mixing and catalytic converter) away from the engine to lower its temperature of operation.

NO is the most simple odd-electron molecule with a thermal stability and represents the major NO_x component in exhaust gases [9]. The catalytic decomposition of NO has been favored as the most desirable method for its removal [9].

NO releases oxygen during its decomposition, and in turn, this oxygen competes for adsorption sites over the catalyst surface, this is the reason why an additional liquid or gaseous reductant is required during the SCR process [6, 9]. SCR catalysts selectively decompose NO_x species by an hydrolysis process after adding urea as the source of ammonia (NH_3) into the exhaust mix, converting NO_x contaminants into N_2, NH_3, CO_2 and H_2O [7].

$$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2 \quad (1)$$

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \quad (2)$$

$$4NH_3 + 2NO + 2NO_2 \rightarrow 4N_2 + 6H_2O \quad (3)$$

The effectiveness of SCR system depends on many factors including the type of catalysts, the injection pattern of ammonia (NH_3), the mixing efficiency, and temperature. Depending on the catalyst, the temperature of operation varies ranging from 300–800 K. There are three main groups of SCR catalysts [10]:

– Those supported by noble metals (Pt/Al_2O_3)
– Those with a base metal oxide (containing vanadium)
– Those of metal ion exchanged zeolites–crystalline silicate (Cu-ZSM-5).

The use of an external agent for the catalytic reaction of NO_x contaminants has always been considered the weak aspect of the SCR technology [1]. To start it is necessary the inclusion of a storage tank for the ammonia solution (NH_3) with all the complexities involved such as its maintenance and refilling [11]. Moreover, the injection system needs to be designed and adjusted for optimal operation to avoid overloading and crystallization [1, 12]. Finally the technology requires of an efficient ammonia distribution to ensure optimal efficiency [1].

Future advances on the technology needs to focus on compact designs that ensure a complete mixture of the ammonia solution in the air flow. In parallel the catalytic converters need to be develop to fulfill the need of simultaneously reduction of soot and NO_x contaminants.

3. SCR construction

Taking the above into account a clear design path for the SCR technology points toward an in-line SCR catalysts solution, able to provide a full emission reduction of HC, CO, NO_x and Soot at low temperatures under a single packaging (Fig. 2). An example of these designs is the SCRT® catalyst from Johnson Matthey which incorporates an SCR catalytic system as well as a CRT® (Continuous Regenerating Trap) to deal with NO_x and Soot at the same time [13].

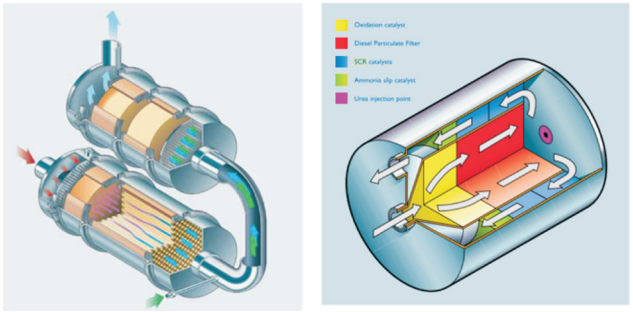

Fig. 2. First generation in-line SCRT system (left) and Compact SCRT system (right) by Johnson Matthey [13]

Initial SCRT development focused on 'linear' configurations where the CRT was followed by an in-line SCR unit, and further iteration lead to the compact SCRT design (Fig. 2).

Currently in the market, there are catalyst designs with incorporated reduction functions for CO, HC, NO_x and Soot into a single component or a single housing, capable of working at a range of temperatures, from 300–700 °C, and with a mixture of catalytic material.

To achieve this four-way function, it is necessary to have a coherent substrate arrangement, sufficient SCR catalytic loading and low levels of backpressure produced by the substrate.

Exhaust gases must pass first through the SCR catalyst and then through the oxidation catalyst. If exhaust gases bypass the SCR catalyst, and are exposed in first instance to the oxidation catalysts, the reductant, in this case ammonia, will be oxidise to NO_x contaminants, compromising the effectiveness of NO_x reduction [5].

It is necessary to account for certain parameters during the design process including:

– Packaging, which defines possible constructions solutions, like inline (Fig. 3, 4) or compact (Fig. 5)
– Boundary conditions such as mass flow and temperature
– Demand of emission limits (NH_3 distribution and NO_x conversion efficiency)
– Demand on pressure drop (pressure drop for each included elements)
– Cost.

Fig. 3. Concept of Close Coupled SCR system in HD application

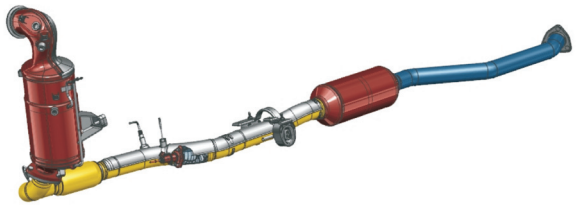

Fig. 4. Inline concept of SCR system in LD application

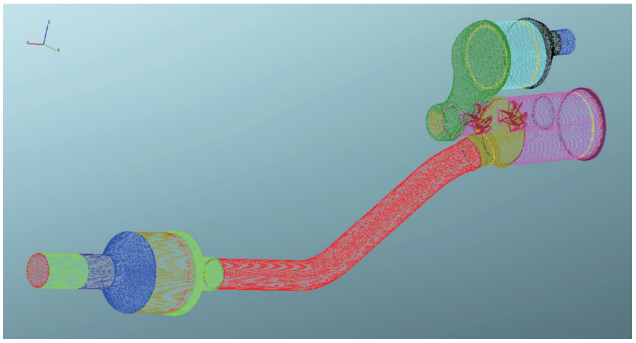

Fig. 5. Compact concept of SCR system in MD application

4. LD state of the ART

The design process of a compact LD SCR system such as the one in Fig. 4 involves various iterations in order to find the optimal solution that meets packaging, emissions and boundary condition limits. The different flow conditions state in relation to real drive conditions need to be considered. Two important parameters that also need to be validated during the design process are pressure drop (Tab. 2) and velocity uniformity (Fig. 6). It is of major importance to limit the pressure drop of the SCR design, which in many cases is mainly generated by the mixer.

Table 2. Pressure drop results for different flow conditions

Operating points	Mass flow	Back pressure	Press drop mixer only	Press drop mixer + pipe	Temperature @ mixer	
	kg/h	Pa	Pa	Pa	K	°C
1	300	7710	623	1121	571	298
2	125	2567	110	192	520	247
3	50	755	17	29	443	170
max	620	15910	2821	5021	815	542

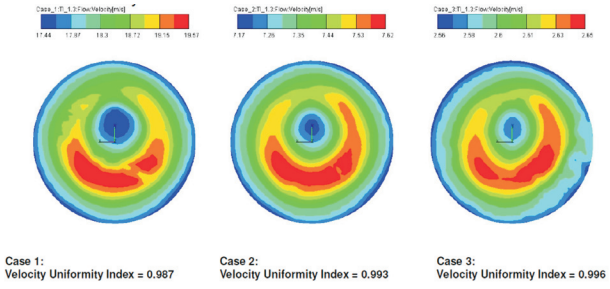

Fig. 6. Velocity uniformity at 25 mm of SCR for different flow conditions

The optimization of urea mixing process is the most challenging one, especially due the different flow conditions such as idle, medium and full load. Even if the uniformity of NH_3 can be achieve the conversion parameter can be still low (Fig. 7).

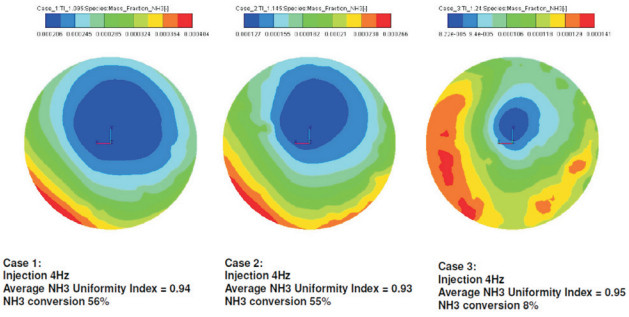

Fig. 7. NH_3 uniformity at 25 mm of SCR for different flow conditions

The reason for that is limited mixing and evaporation efficiency due to the low flow conditions. The droplets of urea water solution are to heavy to be drag by the flow and are deposed on pipe wall generating the wall film (Fig. 8). The vaporistion is limited in such flow conditions which will afftect the maximum conversion parameter. For presented LD application the conversion parameter is not a critical one, but it becomes critical for close coupled solutions.

Table 3. Velocity uniformity results for developed design

Bricks	I CFD Flow Uniformity	II CFD Flow Uniformity	III CFD Flow Uniformity	IV CFD Flow Uniformity	Flow Uniformity
DOC	83%	78%	87.5% 92.5% – S (swirl)	92.6% – S	> 90%
SCRoF	95.3%	96.4%	94.9%	95.0%	> 95%
SCR+CUC	93.6%	93.9%	98.4% – PP (perforated plate)	92.9%	> 92%

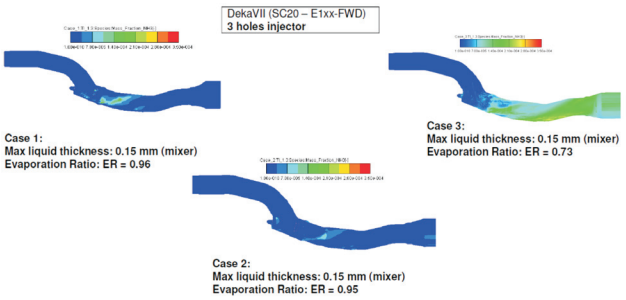

Fig. 8. Wall film generation in the exhaust pipe for different flow conditions

5. HD state of the ART

The design process of a HD or MD compact SCR system such as the one in Fig. 5 also involves various iterations in order to find the optimal solution that meets packaging, emissions and boundary condition limits. Two important parameters that also need to be validated during the design process are pressure drop and velocity uniformity (Tab. 3).

Table 4 shows the velocity uniformity percentages of the compact SCR design here presented. It can be seen how as iteration advanced, the velocity grew more uniform within the design.

Table 4 presents the results of pressure drop created by each component in each of the design iterations. For the computational fluid dynamic (CFD) analysis of the SCR system, it is crucial to accurately define the boundary conditions such as the inlet flow pattern, which is located directly after the turbine and results in the swirl flow (S). It is important to highlight how difficult it is to achieve a reliable uniformity on the SCR+CUC element due to different diameter of pipe and catalyst in-cone. The use of a perforated plate (PP) could be a solution to improve the flow uniformity, however, the addition of this component will be a source of pressure drop.

At the final stage of the design of the SCR system, the injection characteristics of the water/urea solution, commercially known as ad-blue, and the distribution of ammonia (NH_3) need to be validated numerically and experimentally. Typically this stage include the testing of one or double mixer solutions (Fig. 9). As shown by Table 5, the influence of the mixer position has a significant impact. By redesigning the mixer into a single stage design it was possible to obtain improved results as presented in Table 6.

Table 4. Pressure drop results for developed design

Pressure drop @1050 kg/h 580°C	Concept 1 (one mixer) [mbar]	Concept 2 (two mixers) [mbar]	Concept 2 (two mixers + pp) [mbar]	Concept 3 (two mixers) [mbar]
Inlet cone	25.8	11.4	11.4	11.4
DOC	49.0	42.4	42.4	43.0
Injector cone	75.9	33.8	33.8	18.1
Mixer pipe	20.9	30.4	30.4	33.1
Midcone	24.7	37.8	37.8	37.4
SCRoF	151.0	151.1	152.1	153.2
Outlet cone	6.3	2.3	2.0	2.3
Tube	4.5	8.0	6.2	5.4
Inlet SCR‘s Cone	7.8	7.6	21.1	8.7
SCR+CUC	54.4	52.4	50.6	51.9
Outlet SCR‘s Cone	14.5	14.1	10.7	10.1
Overall	435.0	392.2	398.4	374.7

Table 5. Gamma NH_3 distribution in double mixer concept

Operating Point [350 kg/h, 380 °C, 0.3 kg/h DEF]	
Cases	Gamma NH_3 (two mixers)
Case 1	94.57%
Case 2 (–10 mm)	91.97%
Case 3 (+10 mm)	94.12%
Case 4 (+20 mm)	92.63%

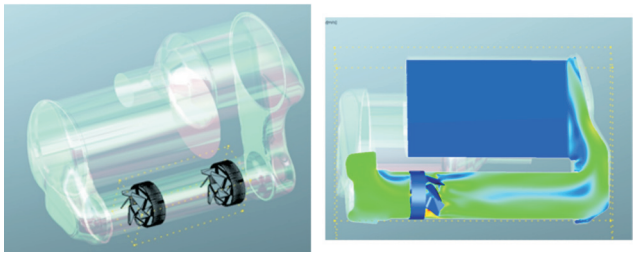

Fig. 9. Mixer models for CFD tests, on the left the double mixer, on the right one stage mixer concept

Table 6. Gamma NH_3 distribution in one stage mixer concept

Operating Point [350 kg/h, 380°C, 0.3 kg/h DEF]	
Cases	Gamma NH_3
Case 1	82.3%
Case 2	82.83%
Case 3	84.69%
Case 4	86.68%
Case 5	94.60%

6. Conclusions

Tightening emission regulations are expected to continue but not only for emission levels. For future Euro 7 regulations emissions levels will not change, changes in test methodology will continue to push depollution efforts on 2 levels:

– NO_x reduction level independent from driving conditions (urban, extra urban, uphill, highway),
– Optimization of fuel efficiency impact caused by AFT devices,
– Optimization of thermal management to minimize cold phase duration independent form driving conditions.

Such trend will demand for a continuous development of exhaust gas after treatment systems. The design of an SCR concept that meets the envisaged regulations will required a significant research process, nevertheless, if the task is followed employing the right analytical tools such as CFD and optimization techniques a solution which meets the required emission limits, design limitations and at an affordable production cost could be achieved.

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Piotr Jaworski, MSc. Eng. – research fellow, The Faculty of Power and Aeronautical Engineering at Warsaw University of Technology, Poland.
e-mail: *piotr.jaworski@itc.pw.edu.pl*

Sebastian Jarosiński, MSc. Eng. – Product Engineer, KATCON.
e-mail: *sebastian.jarosinski@katcon.com*

Azael Cortes Capetillo, DEng. – R&D and Innovation, KATCON.
e-mail: *azael.capetillo@katcon.com*

Łukasz Jan Kapusta, DEng. – Assistant Professor in the Faculty of Power and Aeronautical Engineering at Warsaw University of Technology, Poland.
e-mail: *lukasz.kapusta@itc.pw.edu.pl*

Adam Ziółkowski, MSc. Eng. – Design Engineer, KATCON.
e-mail: *adam.ziolkowski@katcon.com*

Robert Grzywnowicz, MSc. Eng. – Chief Engineer, KATCON.
e-mail: *robert.grzywnowicz@katcon.com*