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SCR SYSTEMS FOR NOx REDUCTION IN HEAVY DUTY VEHICLES

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Abstract

Air pollution has become an important worldwide problem. The European Commission credits road and water transport as the major source of NOx pollution, and of being responsible for around 50% of the total air pollution in urban areas. In Poland, around 45% of the country NOx emissions are attributed to transportation.

During the last decade, the use of SCR technologies have gained popularity as a method for NOx reduction, the technology is widely considered as one of the solutions for road transport emissions. SCR technology had previously been employed in stationary plants, maritime transportation and other installations using combustion processes in which exhaust conditions are easier to control. The advance on the technology led to the introduction of the first heavy-duty vehicle with an SCR system into the market in 2004.

New technologies and applications are constantly appearing, for example, SCR exhaust gas cleaning systems for reciprocating engines are still under development and compression ignition engines can be found in a number of different applications. The technology still needs to be studied and improved as constant problems and knowledge is required in issues such as urea injection, crystallization and NOx reduction efficiency. Moreover, the designs intended for heavy duty vehicles need to meet vehicle limitations and EURO emissions restrictions.

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.

Keywords: *NOx, 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 (O3) in the atmosphere [3]. NOx 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 popularised 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 [5].

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

Tab. 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
N_1	I	RM ≤ 1305	60	180	60	80
	II	1305 < RM ≤ 1760	75	235	75	105
	III	1760 < RM	82	280	82	125
N_2			82	280	82	125

PI = Positive ignition, CI = Compression ignition
M = 4 wheel vehicles for the carriage of passengers
N_1 = 4 wheel vehicles for the carriage of goods (RM < 3 500)
N_2 = 4 wheel vehicles for carriage of goods (3 500 < RM <12 000)

2. NOx 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 needs to be located after the oxidation catalyst and/or soot filter to avoid the oxidation of the injected solution before its catalytic reaction with NO_x contaminants [7].

The reduction of NOx 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 NOx [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 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 favoured 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 (NH3) into the exhaust mix, converting NO_x contaminants into N_2, NH_3, CO_2 and H_20 [7].

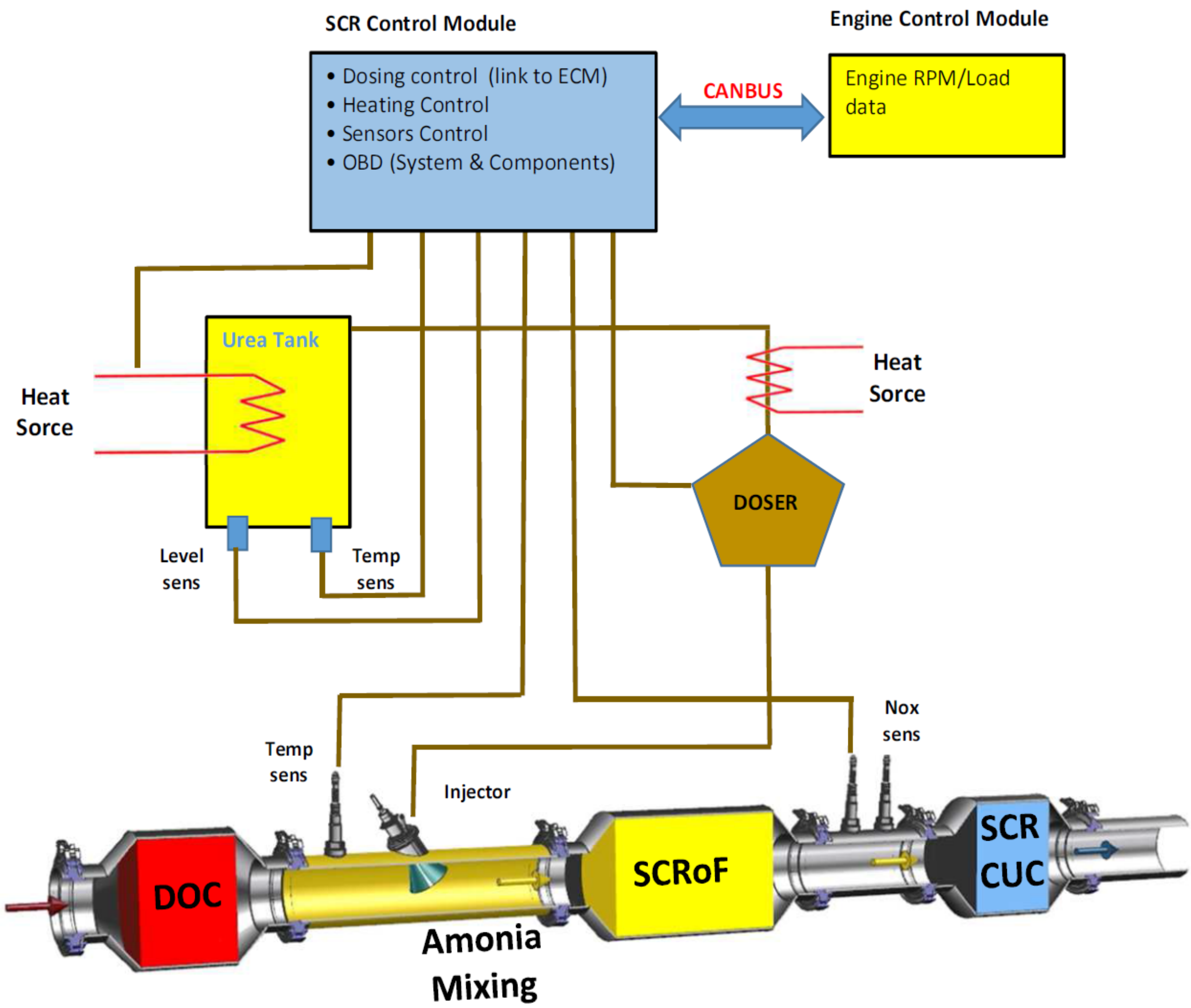

Fig. 1. Emission reduction system: DOC – oxidizing catalyst, SCR CUC – ammonia blockage filter

$$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2\,, \tag{1}$$

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O\,, \tag{2}$$

$$4NH_3 + 2NO + 2NO_2 \rightarrow 4N_2 + 6H_2O\,. \tag{3}$$

The effectiveness of and SCR system depends on many factors including the type of catalysts, the injection pattern of ammonia (NH_3), the mixing efficiency, and temperature [10]. 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/A12O3),
– 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.

4. HD state-of-the art

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].

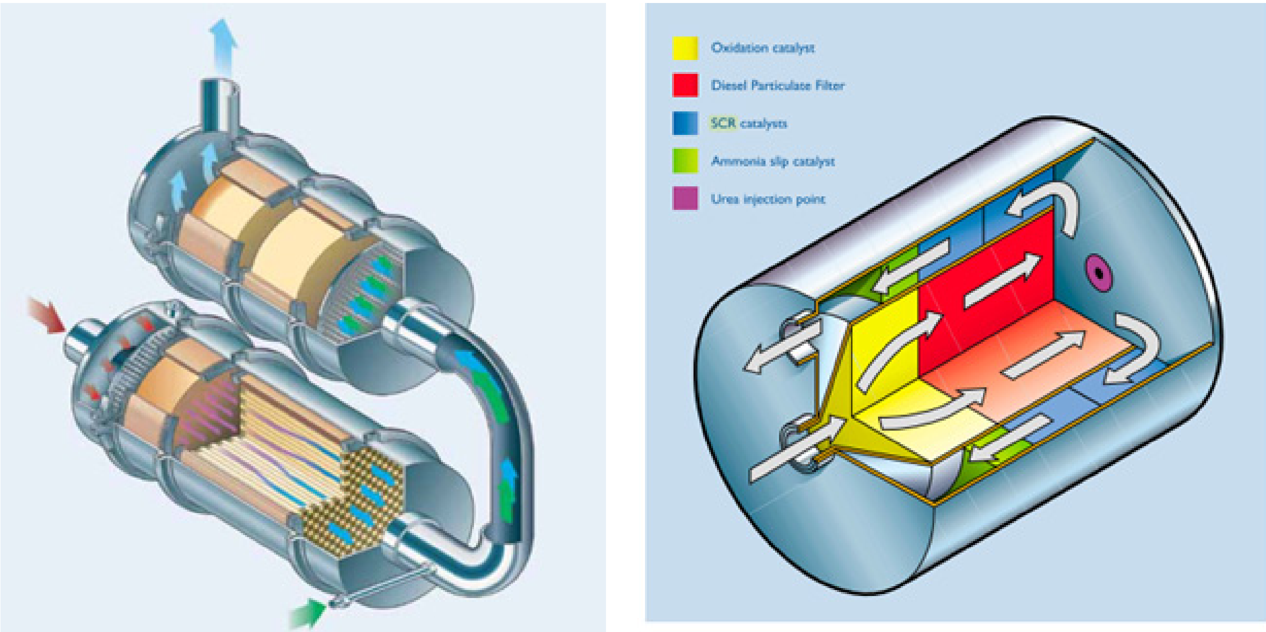

Fig. 2. First generation in-line SCRT system (left) and Compact SCRT system (right) by Johnson Matthey [13]

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). Furthermore, it has been found that using an oxidation catalyst after the SCR unit promotes a higher NO_x oxidation efficiency, this process has been referred to as fast SCR process [10].

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) or compact (Fig. 4),

- Boundary conditions such as mass flow and temperature,
- Demand of emission limits (NH_3 distribution and conversion efficiency),
- Demand on pressure drop (pressure drop for each included elements),
- Costs.

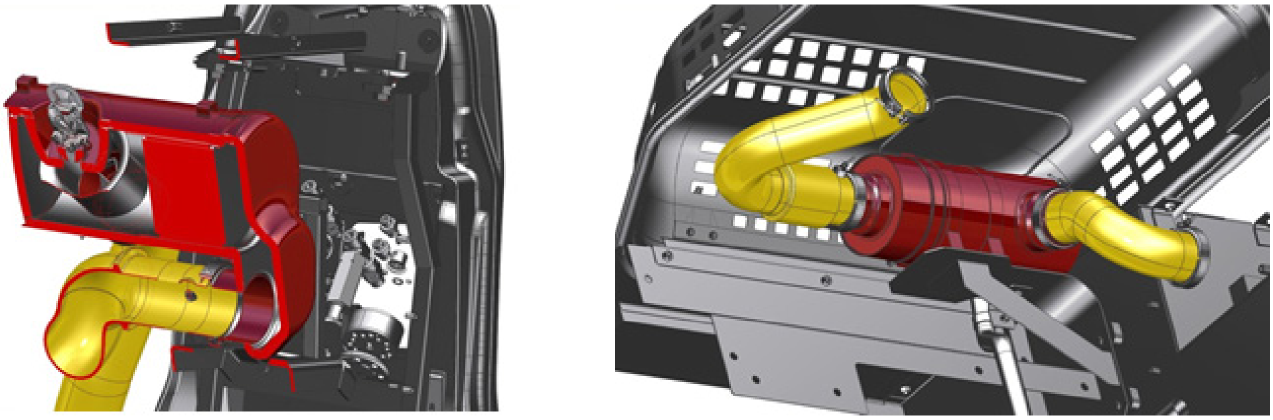

Fig. 3. Inlince concept of SCR system in HD application, left , right

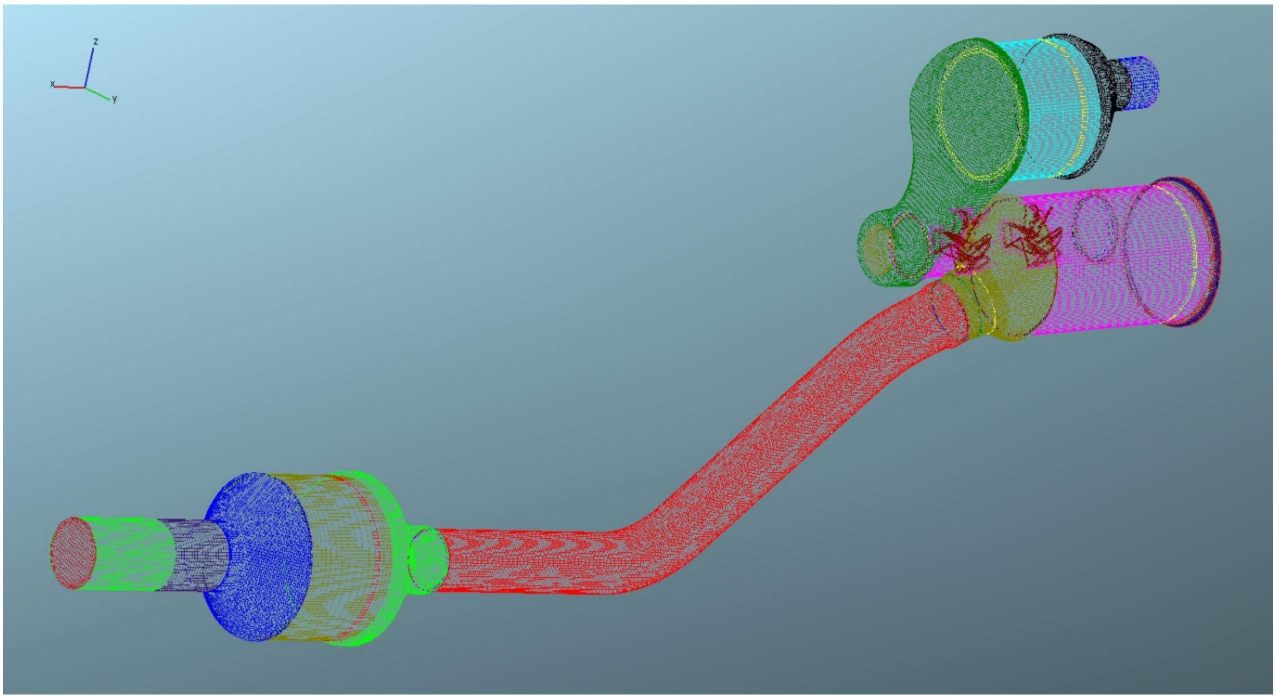

Fig. 4. Compact concept of SCR system in HD application

The design process of a compact SCR system such as the one in Fig. 5 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. 2). 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 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 3 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 accurately crucial to 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 its long pipe directing the flow. 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.

Tab. 2. 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	92.6% − S	>95%
SCRoF	95.3%	96.4%	94.9%	95.0%	>98%
SCR + CUC	93.6%	93.9%	98.4% − PP (perforated plate)	92.9%	>98%

Tab. 3. 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]	Max ATS DP [mbar]
Inlet cone	25.8	11.4	11.4	11.4	
DOC	49.0	42.4	42.4	43.0	46.0
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	150.0
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	54.0
Outlet SCR‘s Cone	14.5	14.1	10.7	10.1	
Overall	435.0	392.2	398.4	374.7	350.0

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 includes the testing of one or two stage mixer solutions (Fig. 5). As shown by Tab. 4, 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 Tab. 5.

Tab. 4. Gamma NH3 distribution in two stage mixer concept

Operating Point [2000rpm − 65kW → 350kg/h, 380°C, 0.3kg/h DEF]	
Cases	Gamma NH3 (two Mixers)
Case 1	94.57 %
Case 2 (−10mm)	91.97%
Case 3 (+10mm)	94.12%
Case 4 (+20mm)	92.63%

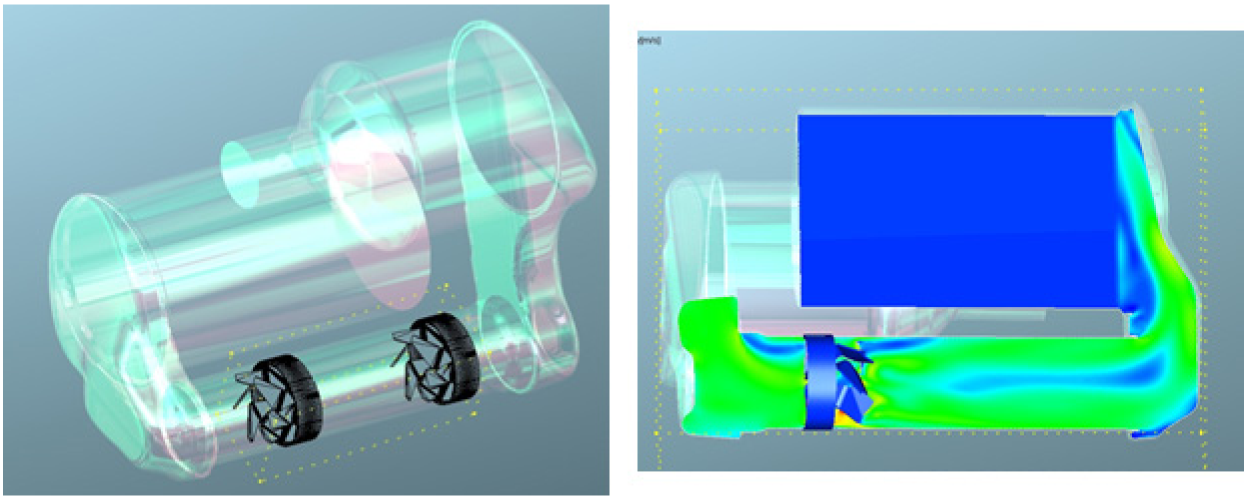

Fig. 5. Mixer models for CFD tests, on the left the two stage, on the right one stage mixer conept

Tab. 5. Gamma NH3 distribution in one stage mixer concept

Operating Point [2000 rpm – 65 kW → 350 kg/h, 380°C, 0.3 kg/h DEF]	
Cases	Gamma NH3 (two Mixers)
Case 1	82.3%
Case 2	82.83%
Case 3	84.69%
Case 4	86.68%
Case 5	94.60%

5. Conclusions

Tightening emission regulations are expected to continue. 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 optimisation techniques a solution which meets the required emission limits, design limitations and at an affordable production cost could be achieved.

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