

Innovative Substrate Technology for High Performance Heavy Duty Truck SCR Catalyst Systems

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ABSTRACT

Diesel engine emissions regulations throughout the world have changed dramatically over the last 20 years, with the most stringent phase for medium/heavy duty being implemented starting 2007 – 2010. The general perception is, that combination systems including PM reduction devices and NOx aftertreatment, likely SCR will be applied, hence significant additional emissions equipment will need to be added to a diesel engine. The consequences of this will be increased space for packaging and increased cost, to meet the demanding regulations. Traditional substrate technology, while developing extensively for gasoline engines by use of higher cell densities has limitations when applied to CI diesel engines. New developments in substrate and coating technology now enable considerable improvement in the efficiency and packaging space needed to meet certain limit values. A novel approach combining a continuously operating PM-reduction with advanced “turbulent” SCR-catalyst in a special system configuration has been investigated in an engine cell program with a HDDE, demonstrating the capability to approach US 2010 emission limits with an extremely compact and cost effective design.

INTRODUCTION

The U.S. 2007 and EU 4/5 emission limits for HD-trucks can be met with the on-going engine development successes and application of one exhaust emission control technology, either for PM-reduction (DPF, PM-Metalit) or for NOx reduction (SCR systems). For US 2010 and the announced but not yet finalized EU 6, it is considered common understanding in the industry that a combination of both PM and NOx reduction exhaust systems will be required, together with further advanced engine technology. It is generally expected that the engine will apply high-pressure EGR systems, dual stage turbo charging, high pressure common rail injection, and as well additional advanced features. While these developments will bring the engine-out emissions to a much lower level, they will also add cost. It will be necessary to reconsider the traditional approaches of emission control systems, to maintain the diesel engines perception as the highly efficient, durable,

cost-effective prime mover for trucks. Future emission control systems shall be designed in view of the control and emission performance possibilities of future engine technology, while minimizing space allocation in the truck and to keep the demands on maintenance and operator’s interaction to a minimum.

The future engines will emit NOx and PM at significantly lower levels as could be expected some years ago. Taking this into account, this paper will describe the status of an on-going investigation to apply the continuously operating PM-Metalit to a low emitting engine, minimizing the demand for active regeneration equipment and filter maintenance. Further, advanced catalyst and coating technology has shown the potential to offer a drastic reduction of diesel oxidation catalyst volumes. Similar advantages are demonstrated regarding the required SCR catalyst volumes when applying “turbulent” catalyst substrates and appropriate catalyst coating. In addition, for low load/low temperature operation, a system will demonstrate the application of “turbulent” substrate technology to aid in the hydrolysis of urea and to influence the flow within the system itself to enhance performance.

Based on the application of these advanced substrate technologies, a high-performance, yet extremely compact emission control system to approach the US 2010/EU 6 emission limits is introduced.

To understand how each new product can be used in an exhaust system, a “pre-development” section discusses different technological “pieces” and the relevant test work, and finally this is demonstrated by the presentation of results from different emission control systems tested on a Heavy Duty Diesel Engine at AVL.

PRE-DEVELOPMENT

BUILDING BLOCKS FOR DIESEL EXHAUST SYSTEMS – STRUCTURED FOIL SUBSTRATES

For both ceramic and metal substrates, the inlet flow can be characterized as “turbulent” while as the exhaust gas passes down the straight channel, very quickly a “laminar” flow pattern is established.

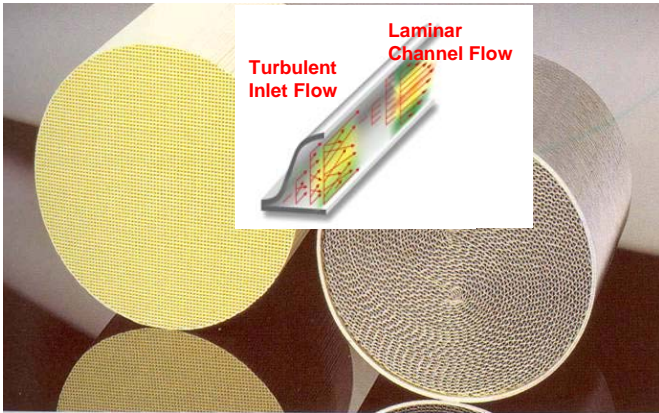


Figure 1. Traditional substrate technology, ceramic and metal, has historically been dominated by straight channels producing a laminar flow profile.

In the following paragraphs, different metallic substrate technologies are described along with a brief statement on benefits for each. In all structured foil substrates, the laminar flow regime is influenced to enhance and re-condition gas flow or to improve flow distribution.

Standard Substrates: with parallel channels, (metallic or ceramic), considered “standard” technology. Metal substrates use thin foils for backpressure optimization. This class of substrates is characterized by straight channels where laminar flow in the exhaust gas is the dominant factor controlling overall performance.

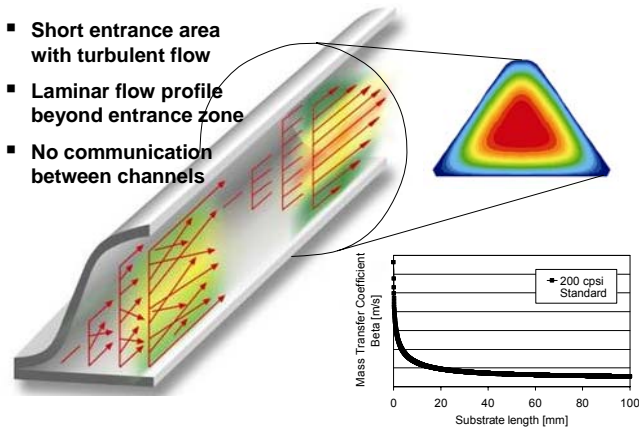


Figure 2: Standard foil design for metallic substrates.

LS Metalit®: Substrates with a “counter-corrugation” which is repeated along the length of each channel, with the objective to improve mass transfer.

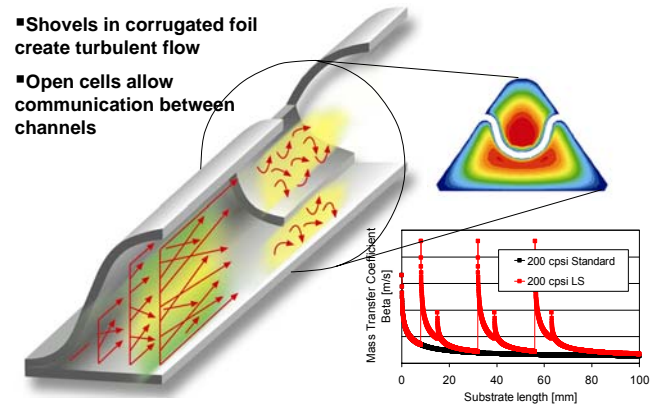


Figure 3: LS foil with counter-corrugation to improve mass transfer

LS/PE Metalit®: Substrates using a corrugated layer with the “counter-corrugation” technique, but adding a flat layer using perforated foil to increase the mass transfer and allow mixing of the exhaust gas from channel to channel within the substrate itself. Exhaust gas which can mix from each channel improves the potential that NO_x and NH_3 will come into contact in a reduction catalyst.

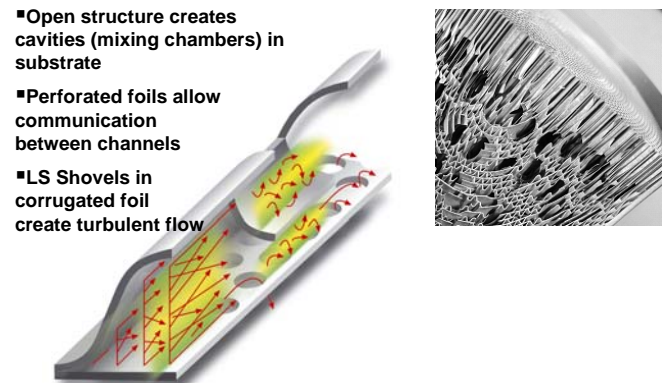


Figure 4: LS/PE foil with counter-corrugation and perforated flat layer

MX/PE Metalit®: Metal substrate using “shovels” on the corrugated layer combined with a flat layer with perforations. The objective of this substrate is to actively force the exhaust gas from one neighboring channel into the next channel and provide for a “micro-mixing” of the exhaust gas. This is useful to improve the flow distribution, destroy large droplets of remaining urea, and improve the distribution of urea/ammonia over the catalyst cross section. Reference Figure 5.

- Mixing shovels combined with PE Foil deflect flow
- Impact of droplets on shovels supports droplet evaporation

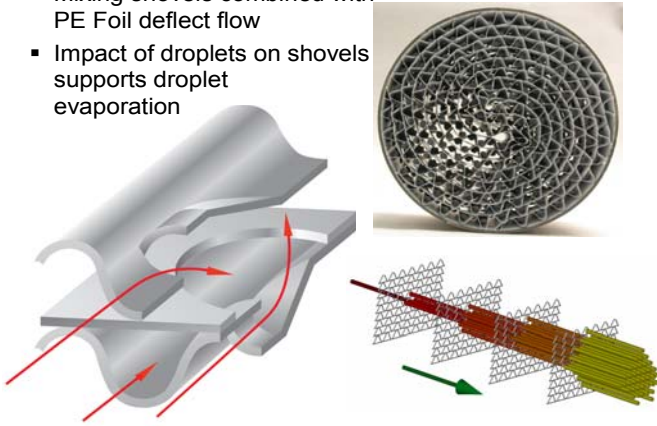


Figure 5: Mixing foil with corrugated “shovel” layer and perforated flat layer

PM Metalit®: Metal substrate using a corrugated layer of foil to divert the exhaust gas from each channel into the flat layer, constructed of stainless steel “fleece” material used to trap and reduce particulate matter [9, 10].

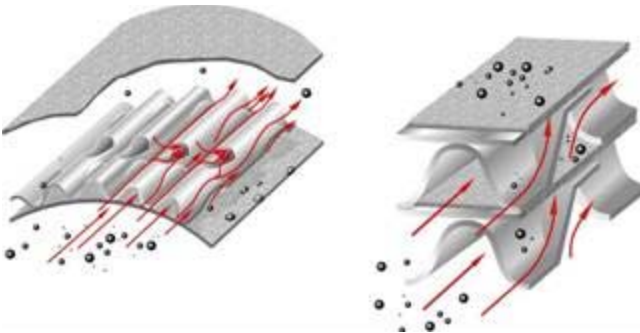
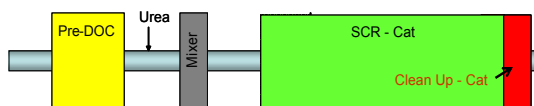


Figure 6. PM Metalit® deflects particulate matter into flat fleece layer for reduction of particles.

SCR FUNDAMENTALS

A typical layout of SCR systems is shown in Figure 7 below:

Typical SCR System



Modular SCR System

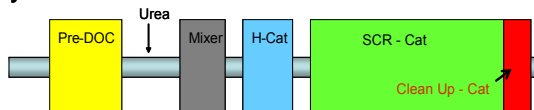


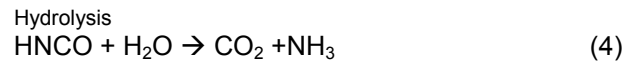
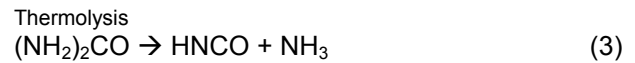
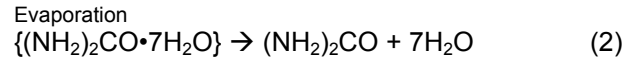
Figure 7. General layout of SCR aftertreatment systems.

DOC Function: A DOC in front of the SCR system is used to generate NO₂ with



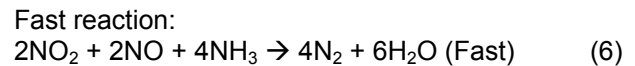
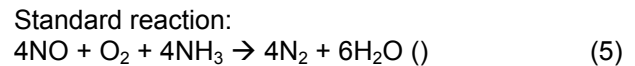
for facilitation of fast SCR reaction, which is especially important at low temperatures [1, 2]. Depending on system configuration, the DOC also plays an important role in passive and active regeneration of the downstream PM Metalit or DPF.

Hydrolysis Catalyst: The hydrolysis function is to complete the formation of NH₃ from the injected urea, and this is comprised of three steps as shown below:

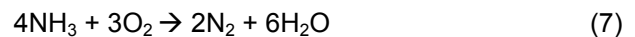


The hydrolysis catalyst can be integrated into the reduction catalyst or placed as a separate module between DOC and SCR substrate.

Reduction Catalyst: The function of this component is the selective reduction of NO_x with NH₃.



NH₃ Clean Up Catalyst: Typically an additional catalyst is placed behind the SCR substrate to oxidize excess NH₃ with O₂ to avoid objectionable odors.



SCR CHALLENGES – OVERVIEW

Successful SCR systems have numerous challenges, and several innovative substrate technologies have been developed with the ability to enhance performance as compared to current standard substrate technologies. In particular the following challenges are addressed:

- 1) NO₂ production
- 2) Urea evaporation and decomposition
- 3) Flow distribution

1) NO₂ PRODUCTION

NO₂ production is important during the “fast-SCR” reaction process occurring in the downstream reduction catalyst and for passive reduction of PM. Although for this set of experiments standard 300 cpsi substrates are used as pre-catalysts for NO₂ production, later experiments have shown the potential of structured foil (LS/PE) for improved volume specific NO₂ production. Figure 8 below shows a comparison of 200 cpsi, LS/PE 100/200 cpsi, and LS/PE 200/400 cpsi. Over a wide range of space velocities, the LS/PE 200/400 cpsi shows a significant advantage of 25-50% better NO₂ production.

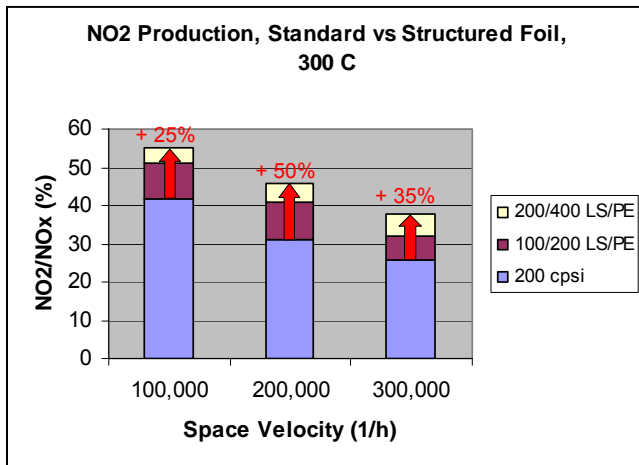


Figure 8: Comparison of NO₂ production for different foil technologies and cell densities.

The trend for NO₂ production of structured foil substrates is being studied further in additional programs as this is important not only for SCR systems, but also for passive and active regeneration of DPF systems, i.e. the higher the passive regeneration component the lower the fuel penalty due to “forced” regeneration events. In addition, structured foil substrates are being intensively studied for downsizing due the higher volumetric efficiency and subsequent cost benefits [3].

2) UREA EVAPORATION AND DECOMPOSITION

Urea spray consists of a distribution of droplets, some of which can be large. The first process in the formation of NH₃ from urea is the evaporation of the water. Larger droplets of urea can take much more “distance” in the exhaust pipe for evaporation, and in some cases beyond the available length of the exhaust system. Values have been calculated as a reference, using a mass flow of 200 kg/hr and 430 C a droplet of urea with diameter of 30 μm would evaporate in a length of 1.1m, while a droplet having diameter of 70 μm would take approximately 6.1 m for evaporation of the water.

Figure 9 below shows the measured distribution of droplet diameters for a tested airless urea injection

system. Typically, an ideal target range of maximum 30 μm is expressed for diameter based on available length in the exhaust system.

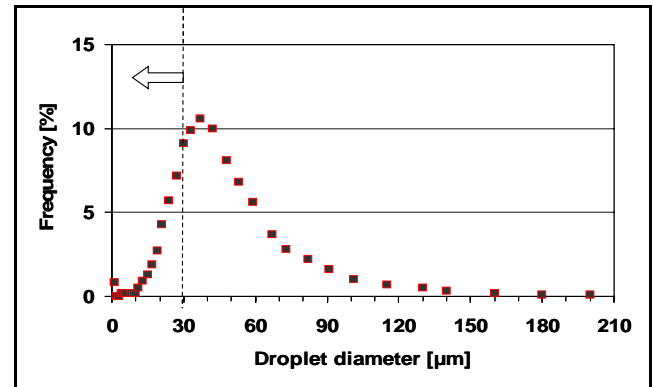


Figure 9: Typical distribution of urea droplets with an airless dosing system.

In this example, a significant amount of urea would reach the reduction catalyst still as aqueous urea and with a large droplet diameter. To demonstrate this effect, an experiment on a flow bench rig was constructed where a thermographic camera was placed on the exit side of a substrate used to simulate the reduction catalyst. The conditions for the experiment were limited based on the test equipment capacity, and included an exhaust temperature of 135 C with a volumetric flow of 250 m³. These green areas in Figure 10 are showing where large droplets hit the front face of the catalyst and have a “cooling” effect. This also coincides with the spray pattern of the particular injection system used. Although in practice, urea injection would not be advisable at 135 degree C, the experiment demonstrates the effect on the reduction catalyst if, under any operating conditions the injected urea is not fully evaporated within the given exhaust pipe length.

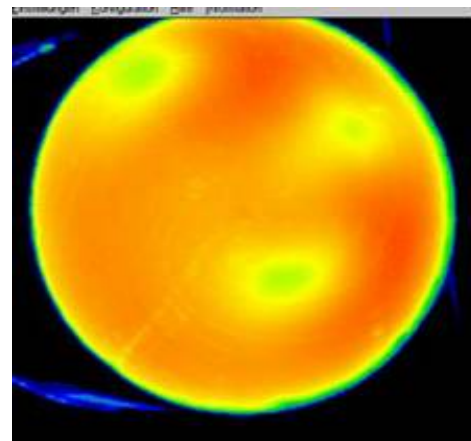


Figure 10: Cooling and distribution effects of large droplets and spray pattern of urea injection system.

For the present study, the challenge of evaporation and decomposition of urea was addressed by designing a special hydrolysis catalyst substrate with two stages.

The first stage was specifically designed to destroy the large remaining droplets of aqueous urea through a coarse cell density “mixing” device, and it is followed by second stage which is tuned for optimized hydrolysis performance.

To find the optimum foil types for best evaporation and hydrolysis performance, two experiments were conducted on a model gas test bench. First, three different foil types were compared for their efficiency to destroy the large urea droplets, evaporate the water, and to improve the distribution across the cross-section.

This experiment was conducted with CO₂ used as a tracer gas injected upstream of the catalyst – in the middle of the exhaust pipe. Downstream of the catalyst a probe was positioned which moved along the pipe radius and extracted gas samples for FTIR analysis. The sampling probe could be positioned in 0.5 mm increments along the radius starting from the center. Values for the CO₂ concentration were then recorded and fitted with a Gaussian distribution to calculate mixing efficiency as follows:

$$\eta = 1 - 0,5 \cdot \sigma \quad (8)$$

Sigma (σ) in this case is a measure of deviation from perfect mixing and can vary between 0 and 2, with the larger values representing a lower mixing performance:

$$\sigma = \sum_i \left(\left| \frac{c_i - \bar{c}}{\bar{c}} \right| \cdot \frac{V_i}{V} \right) \quad (9)$$

- ci: measured local concentration, volume specific [ppm]
- c: bulk-concentration, volume specific [ppm]
- Vi: Volume flow at measuring position [m³/h],
- V: Total-Volume flow [m³/h]

A Mixing efficiency of $\eta=1$ would represent perfect mixing, while $\eta=0$ means no mixing.

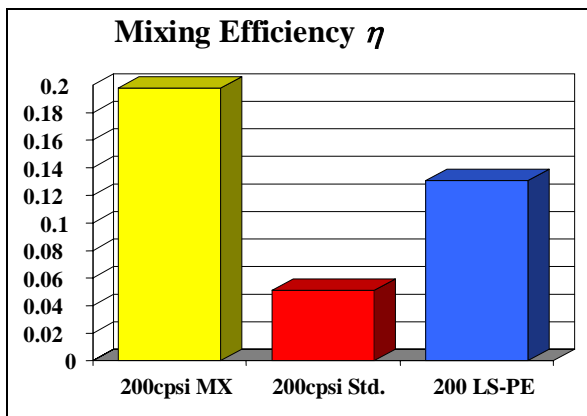


Figure 11: Mixing efficiency comparison and example equations.

As can be seen from Figure 11, MX or mixing structured foil attained the highest mixing performance. Based on

this result, MX foil was chosen for the first stage of the hydrolysis catalyst [4,6].

A second set of experiments, again conducted on a model gas test bench, was designed to compare different foil types for their ability to break down the injected Adblue mixture into Ammonia (NH₃) and Isocyanic Acid (HNCO). To characterize this performance, a “urea decomposition coefficient” is calculated:

$$Y_{(NH_2)_2CO} = 0,5 \cdot \frac{C_{NH_3} + C_{HNCO}}{C_{(NH_2)_2CO}} \quad (10)$$

which describes the quantity of urea that is transformed into its gaseous components. Figure 12 below shows the measured urea decomposition coefficient for the tested foil types.

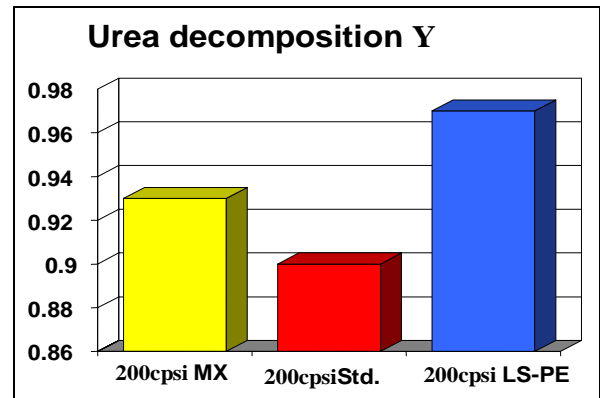


Figure 12: Urea Decomposition for different foil types.

Finally a second characteristic, the “Hydrolysis Coefficient”, was calculated:

$$\eta_{Hydrolyse} = \left(\frac{C_{NH_3}}{C_{NH_3} + C_{HNCO}} - 0,5 \right) \quad (11)$$

which describes the further conversion of the intermediate product Isocyanic acid (HNCO) into the desired Ammonia (NH₃).

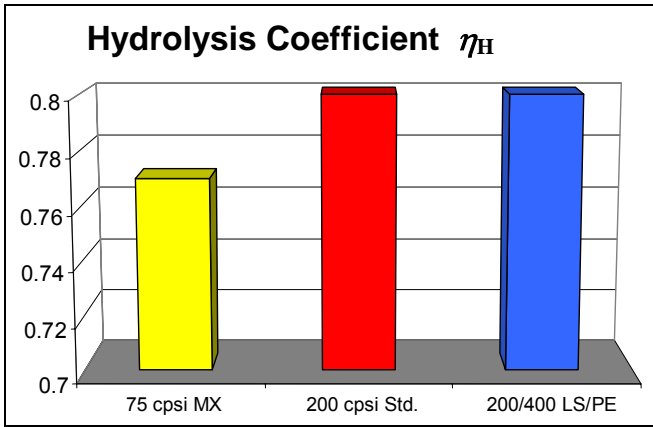


Figure 13: Hydrolysis Coefficient of different foil types.

The experiments to determine these two coefficients were run with a mass flow containing an AdBlue aqueous urea mixture so that NH_3 concentrations were in the range of 2,500 ppm downstream of the catalyst. Figures 12 and 13 above show the urea decomposition coefficient and the hydrolysis coefficient for the tested systems at a space velocity of 175,000/h.

Referencing Figure 12 and 13, the 200/400 cpsi LS/PE foil showed superior urea decomposition and hydrolysis efficiency compared to standard straight channel substrate technology. The results will vary as a function of temperature, but based on the overall performance of urea decomposition and hydrolysis, the final choice for the second substrate in the “two-stage” hydrolysis catalyst was to utilize the 200/400 cpsi LS/PE structure [4, 6]. Reference Figure 14 below.

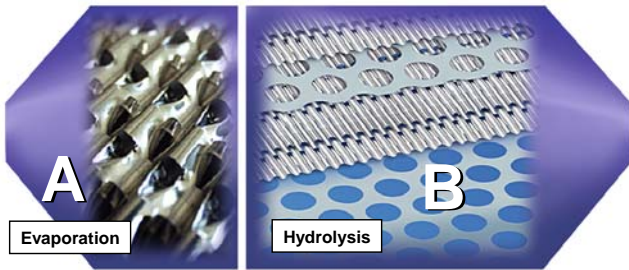


Figure 14: Two stage hydrolysis catalyst, first stage for destruction of large droplets of urea followed by 200/400 LS/PE substrate.

3) FLOW DISTRIBUTION

Flow distribution is an important element of all catalyst designs. For SCR catalysts, not only is it important to achieve a uniform distribution of urea/ NH_3 across the face of the reduction catalyst, its also needed that the flow distribution of the exhaust gas across the front face is optimized to avoid poor utilization.

An experiment on a cold flow bench was designed to demonstrate exhaust gas flow velocity distribution in a large diameter SCR substrate. For this purpose, the flow velocity at different points behind the SCR substrate is measured with a sensor. Measurements were conducted in increments of 5 mm in X and Y direction. Figure 15 depicts the test setup with a straight inlet cone in front of a SCR substrate.

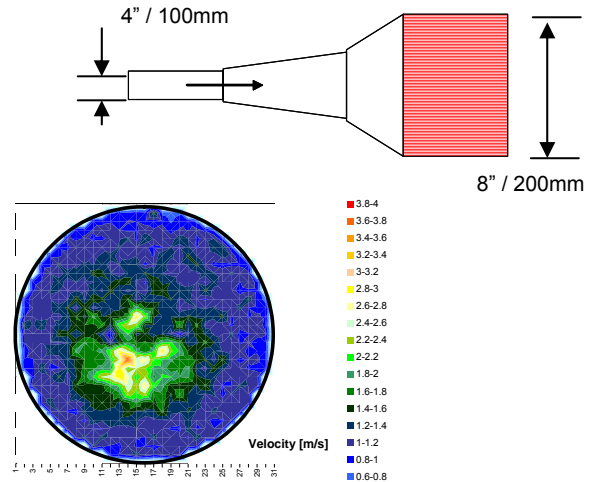


Figure 15: Flow velocity distribution behind SCR catalyst with standard empty cone.

In this case the flow is dominated by a pattern indicating “jet flow” where a large portion of the gas flow is in the center of the SCR substrate, while the gas flow near the cone walls is stalled.

A unique type of substrate, called the Conicat® for conical converter (Figure 16) is available to fill the space used by the empty cone. The Conicat® has been described in previous papers [7], originally as a close-coupled converter for fast light-off and improved flow distribution.

The system of Figure 15 was then re-tested with a Conicat® installed in the formerly empty cone. The results shown in Figure 17 show a much improved flow distribution over the front face of the large diameter SCR substrate.



Figure 16: Example of Emitec Conicat®.

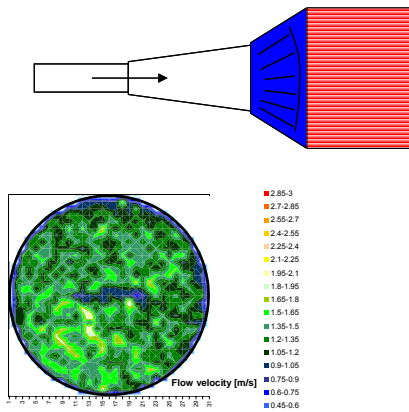


Figure 17: Flow velocity distribution with Emitec Conicat®

Both systems, with the empty inlet cone and with the Emitec Conicat®, were then tested on a cold flow bench for pressure drop comparison. The results show a lower pressure drop over the system with Conicat® at high exhaust flow rates. In high flow conditions, the flow stall near the walls of the empty cone causes a pressure drop which is higher than the pressure drop over channels of the Conicat®. At lower flow rates, the pressure drop from flow stall is slightly lower than the channel pressure drop in the Conicat®. Reference Figure 18 below.

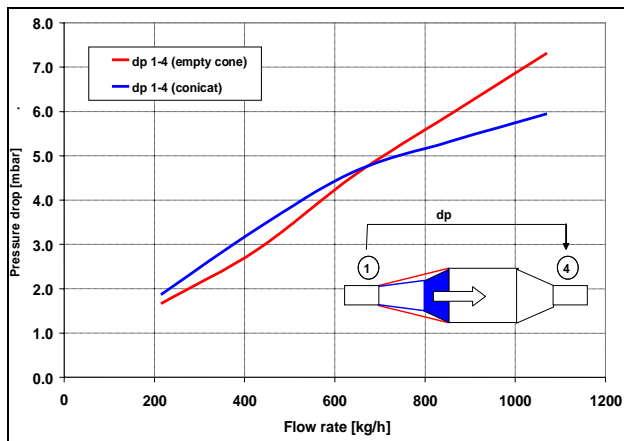


Figure 18: Pressure drop test results with Emitec Conicat®.

WASHCOAT PROCESS FOR TURBULENT CATALYSTS

With both the 40 cpsi Mixer substrate and the 200/400 cpsi LS/PE substrate, a coating of Titanium Dioxide is used to provide for a porous surface for effective evaporation (limit the effect of a “steam” insulation around the droplet), also having in the coating a high mechanical stability against erosion, and very importantly a high catalytic activity for HNCO- hydrolysis.

To apply this washcoat technology, a new production process was developed. Coating of standard substrates with parallel channels is a process that is well established and in high production volumes. Different methods exist, either by applying exact quantities in a “precision” process, or by a waterfall of washcoat and subsequent blowing out excess material to clear the channels. Substrates which utilize structured foil present new challenges due to their interrupted channel wall and internal cavities, as present with LS, LS/PE, PE, and MX type foils. For these technologies, blowing out the excess washcoat material with compressed air for example may not work as the air follows the path of least resistance. To eliminate the excess material, a process which relies on centrifugal forces has been developed and shown to be effective in providing a uniform and consistent washcoat layer.

EXPERIMENTAL TEST SET-UP AND RESULTS

EXPERIMENTAL SETUP

The following section describes the test set-up comparing SCR systems using Structured Foil substrates and a baseline SCR system currently available in European Trucks (fully extruded reduction catalyst). A heavy duty truck engine developed to meet Euro 5 emissions limits ($\text{NO}_x = 2 \text{ g/kWh}$ and $\text{PM} = 0.02 \text{ g/kWh}$ (ESC) and 0.03 g/kWh (ETC)) was utilized. The baseline SCR system (Vanadium type, fully extruded) was designed to meet the Euro V emissions requirements. The testing was designed to demonstrate the benefits of new foil technologies for significant reduction in space and system cost. The building blocks for this test program included: a) a DOC for low temperature performance, b) structured metal substrates for both urea mixing and hydrolysis, and c) Vanadium type coated structured metal substrates for the NO_x reduction catalyst to investigate enhanced mass transfer and internal mixing, and the PM Metalit® in an extended step of the program for continuous reduction of particulate matter.

The investigation was carried out with a heavy duty engine in the range of 2 ltr/cylinder. Due to the use of an SCR system the engine was calibrated for lowest particulate matter emissions and optimized fuel consumption, and did not have an EGR system. The engine was installed in a fully dynamic and transient operation test cell at AVL. The test rig set-up is shown below in Figure 19.

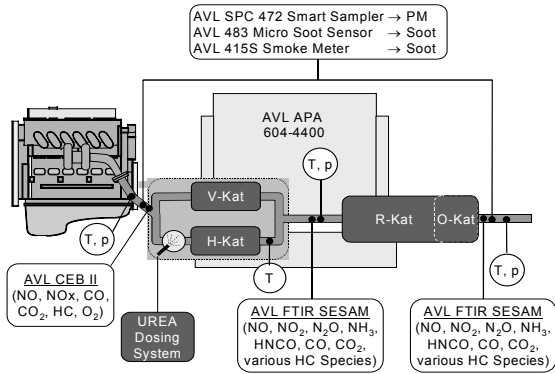


Figure 19: Test rig and exhaust set-up at AVL.

Points where temperature and pressure were monitored are marked as T and p. At the turbine outlet location gaseous engine-out emissions were measured (NO, NO_x, CO, CO₂, HC, O₂) with standard analyzers (ref AVL Combustion Emissions Bench II). The exhaust gas composition downstream of the V (oxidation) and H (hydrolysis) Catalysts and as well in the “tailpipe” location was measured simultaneously to the engine out emissions by FTIR SESAM technology.

Table 1 below reviews the specific system configuration, system 0 is the baseline, systems 1, 2, and 3 all integrate different elements for comparative testing. As a final step, the PM Metalit® is added before the reduction catalyst and is described in a later section.

System #	Hydrolysis Cat	Pre-DOC	Reduction Cat	Clean-up
0 (baseline)	Serial Production	No	300cps V- Extruded 100% Volume	Zone Coated
1	40cps MX + 200/400 LS/PE	No	300cps V-Extruded 100% Volume	Zone Coated
2	40cps MX + 200/400 LS/PE	300 cps	300/600 LS/PE V-coated 70% Volume	Zone Coated
3	40cps MX + 200/400 LS/PE	300 cps	300cps V-Extruded 100% Volume	Zone Coated

Table 1: System description for comparative testing

All testing was carried out at AVL’s laboratories in Graz, Austria. The tested systems are defined in Figure 20.

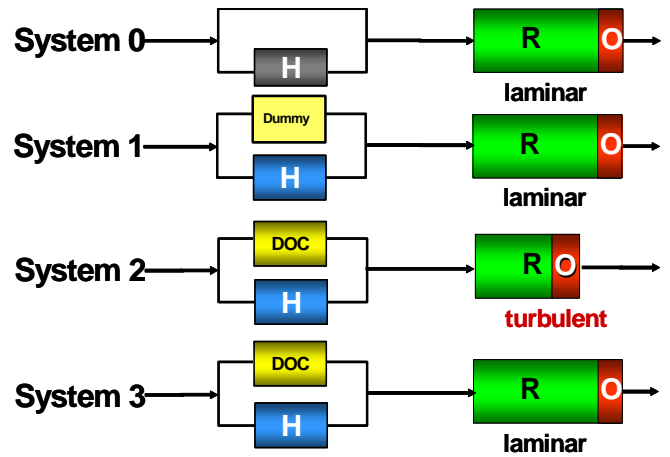


Figure 20: System layout and description.

The baseline system, System 0 in the test matrix, consisted of a hydrolysis catalyst followed by a large volume of fully extruded reduction catalysts. This system did not use a pre-oxidation catalyst. The outlet side of the reduction catalysts was zone coated to integrate the slip cat function.

In system 1, the hydrolysis catalyst was substituted with an advanced two-stage hydrolysis catalyst (reference Figure 14) with approx. 10% larger volume. At the same time, a dummy catalyst was placed in a parallel pipe to allow a direct comparison to a system with pre-oxidation catalyst later. The benefits in system performance with a parallel arrangement of pre-DOC and hydrolysis cat has been demonstrated in previous studies [6,8,10]. The reduction catalysts remained the same.

System 2 used the same hydrolysis catalyst as system 1, and a pre-oxidation catalyst replaced the dummy cat in the parallel exhaust pipe. Second, the reduction catalysts were removed and substituted with a smaller volume of 300/600 LS/PE substrates, which were also zone coated for integrated slip cat function.

Finally, for System 3 the 300/600 LS/PE reduction catalysts were removed again and replaced with the original fully extruded reduction catalysts. This system used the same hydrolysis catalyst and pre-oxidation catalyst as in system 2. This setup allowed a direct comparison of the fully extruded and the turbulent reduction catalysts.

All systems were tested for backpressure and showed similar overall system backpressure within 5%.

The urea dosing system was not modified and represented the production equipment and calibration. All catalysts were degreened on the test engine with a specific proprietary test cycle.

TEST RESULTS

INFLUENCE OF HYDROLYSIS CATALYST

For the first part of the test program, the influence of the hydrolysis catalyst was analyzed by comparing systems 0 and 1, as shown in Figure 21 below.

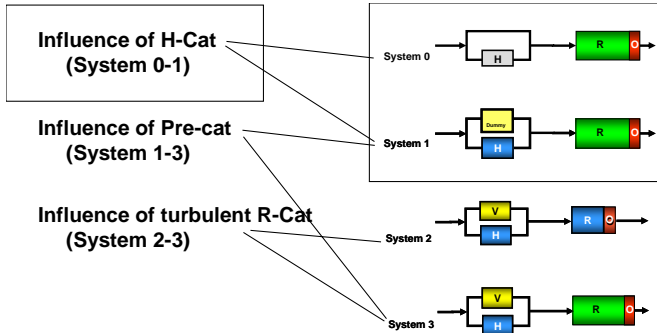


Figure 21: Influence of hydrolysis catalyst is compared between systems 0 and 1.

System 0, the baseline production system, included a hydrolysis catalyst, with the urea injection located approximately 150mm upstream. System 1 used an advanced hydrolysis catalyst in the two stage design (40 cpsi mixer foil followed by 200/400 cpsi LS/PE). While in the model gas bench a 200cpsi mixer was used, a lower cell density of 40cpsi was chosen for the engine tests to keep backpressure optimized.

Figure 22 below shows the total decomposition of the injected urea into NH₃ and HNCO during the ESC test. Both systems have a similar rate of urea decomposition.

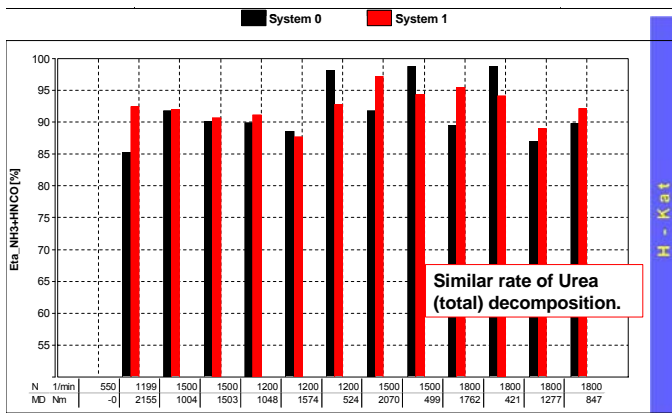


Figure 22: Rate of Urea decomposition for Systems 0 and 1

While the total decomposition of urea was similar, it was found that system 1 with the two stage hydrolysis catalyst shifted the concentration of the decomposition products more towards NH₃.

As more NH₃ was formed in the advanced hydrolysis catalyst of system 1, the amount of intermediate HNCO was reduced. Figure 23 shows the NH₃ Yield for both tested systems.

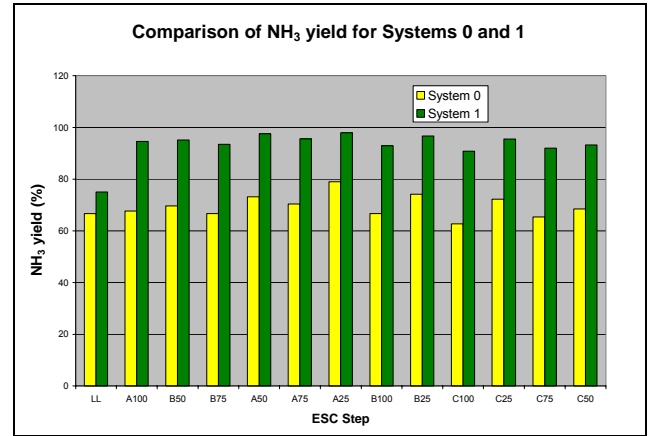


Figure 23: Comparison of NH₃ yield for systems 0 and 1.

This result could be confirmed also for transient operation during following ETC tests. It can be concluded that the substitution of the baseline hydrolysis catalyst in system 0 with the proposed structured foil design (1st stage mixer foil + second stage LS/PE foil) in system 1 resulted overall in similar total urea conversion (NH₃ + HNCO), but the break down yielded a more complete conversion of urea to NH₃. This test result was consistent with the experience discussed earlier on the model gas test bench.

With the modifications in system 1, the urea injection nozzle was moved to a location 700mm upstream of the hydrolysis catalyst. In the baseline system, the nozzle was located only 150mm upstream of the hydrolysis catalyst. To understand the influence of the greater distance in system 1, a second set of experiments was carried out comparing nozzle positions of 150mm and 700mm upstream of the hydrolysis catalyst in system 1.

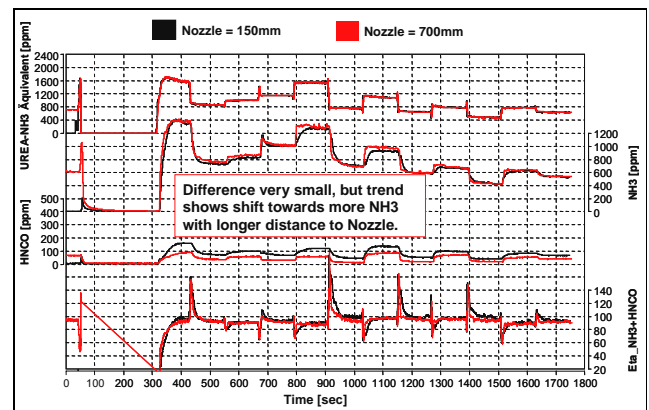


Figure 24: Comparison of system 1 with urea injector located at both 150 and 700 mm from front face of hydrolysis catalyst.

Figure 24 illustrates the urea decomposition and hydrolysis of the two-stage hydrolysis catalyst at different nozzle positions. As expected, the longer distance from injector nozzle to front face of hydrolysis catalyst slightly improved urea conversion towards more NH_3 . It is notable, that the use of the two stage hydrolysis catalyst allowed for a wide range in placement of the urea injector.

INFLUENCE OF PRE-OXIDATION CATALYST

In the second phase, the influence of the pre-catalyst was investigated by comparison of systems 1 and 3, reference Figure 25 below.

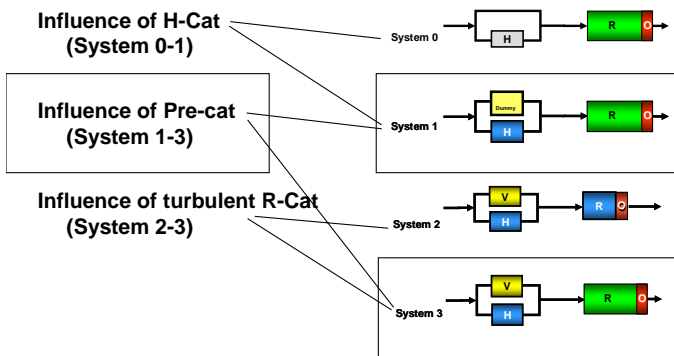


Figure 25: Comparison of systems 1 and 3 to understand the effect of a pre-catalyst

For this experiment, the dummy catalyst of system 1 was replaced with a 300cpsi oxidation catalyst.

As it was expected, the pre-catalyst had the effect of increasing the NO_2 concentration in the exhaust stream, The NO_2 production during both the ESC and ETC testing are presented in Figure 26 and Figure 27.

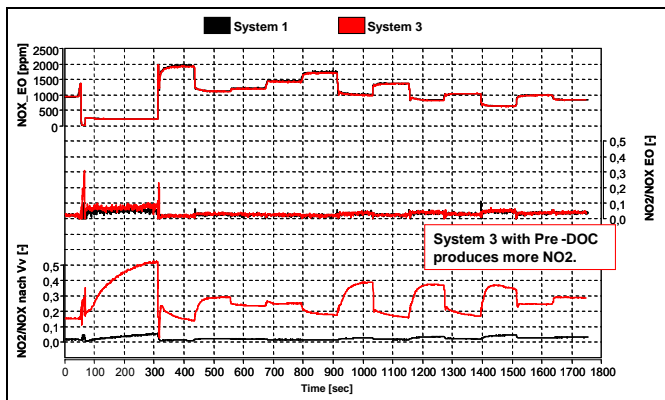


Figure 26: NO_2 production with pre-catalyst, ESC test.

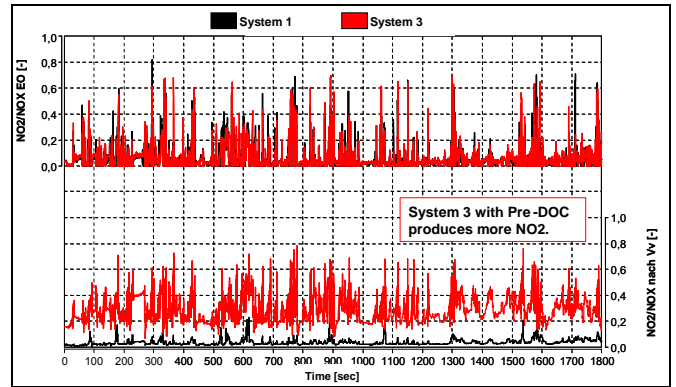


Figure 27: NO_2 production with pre-catalyst, ETC test.

Previous studies have shown that increased NO_2 level have the effect of improving the low temperature performance of the reduction catalyst system by using the so called "fast SCR reaction" [1, 2]. The effect of increased NO_2 production for overall system efficiency in this experiment is discussed later on. NO_2 production is also important for continuous PM reduction and this is also discussed in a later section.

INFLUENCE OF TURBULENT REDUCTION CATALYSTS

The 3rd phase of the test program was designed to study if turbulent substrates, such as LS/PE foils, can be used to reduce the required SCR volume because of their better mass transfer and internal flow mixing. Thus, system 2 utilized a structured foil reduction catalyst with 300/600 LS/PE foil that was downsized by approximately 30% compared to the baseline which utilized a fully extruded 300 cpsi reduction catalyst. In each case the last 20 mm of each reduction catalyst was coated with a DOC washcoat for function as a slip catalyst. For this phase, System 2 was compared to system 3. Both systems used the identical pre-oxidation and hydrolysis catalyst, reference Figure 28.

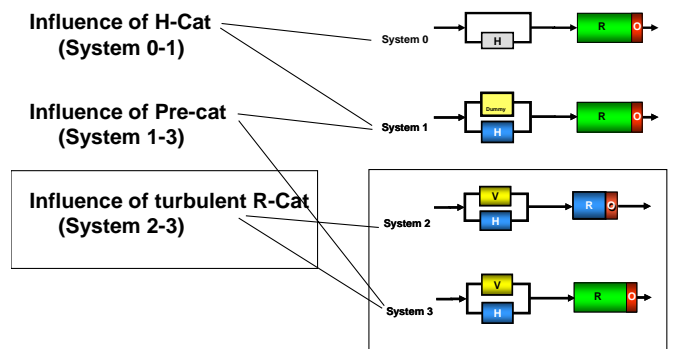


Figure 28: Comparison of Systems 2 and 3, reduction catalyst of System 2 approximately 30% smaller than baseline System 3.

The smaller volume of the turbulent reduction catalysts in system 2 lead to a higher space velocity and reduced resident times in the channel, reference Figure 29. The goal was now to investigate, if this higher space velocity leads to reduced SCR performance, or if the use of turbulent 300/600 LS/PE substrates allows for volume reduction at equal or similar performance.

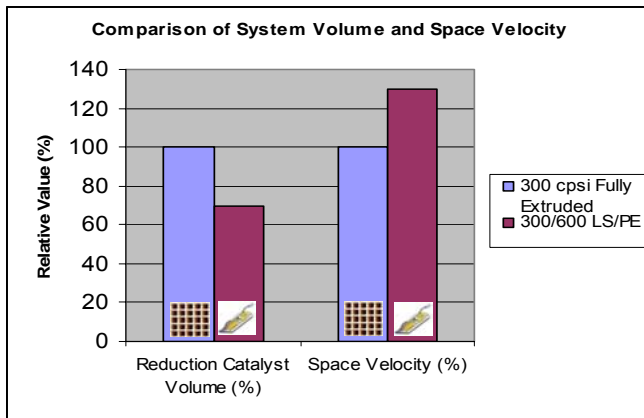


Figure 29: Space velocities in reduction catalyst for systems 2 and 3

First, tailpipe NH_3 , HNCO and N_2O emissions were compared in an ESC test for system 2 and system 3, reference Figure 30 below.

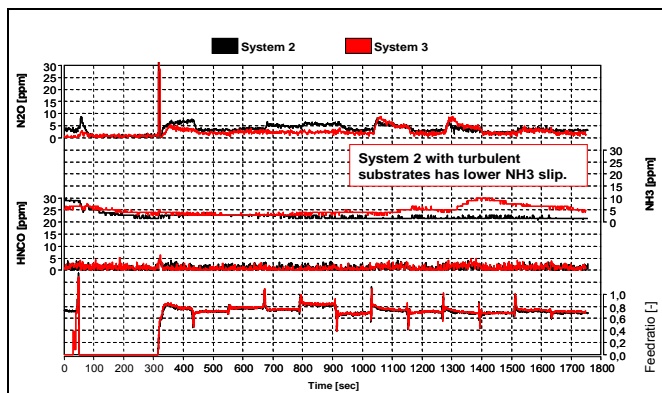


Figure 30: Comparison of System 2 and 3, ESC test.

It was found that at equal urea feed rate the ammonia (NH_3) slip was reduced with the turbulent reduction catalysts of System 2. At the same time, the HNCO concentration was nearly identical for both systems. These results could be confirmed also during transient ETC tests.

The N_2O emission of both systems was with maximum 7 ppm very low. However, it was notable, that system 2 had a slightly increased N_2O tailpipe concentration. Because of its higher volumetric efficiency, it is possible to reduce the Pt loading of the NH_3 slip catalyst, which would further reduce the N_2O production of system 2.

DISCUSSION OF SYSTEM PERFORMANCE

The comparison of overall system performance shows a similar NO_x reduction for all tested systems reference Figure 31 and Figure 32 below. Each system was tested 4 times. For all the testing, the dosing strategy was the same as the baseline production system.

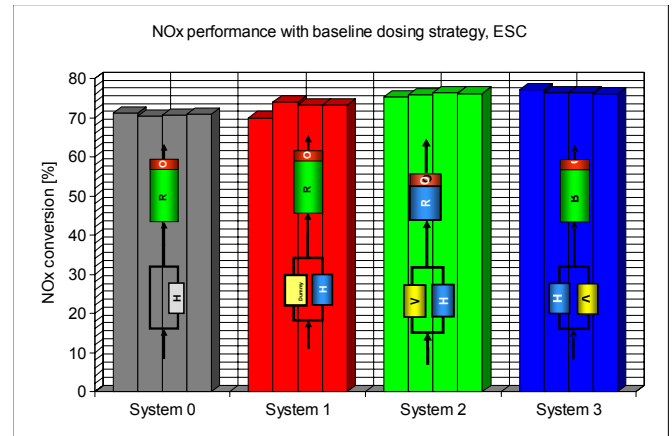


Figure 31: NO_x efficiency over different systems for ESC test.

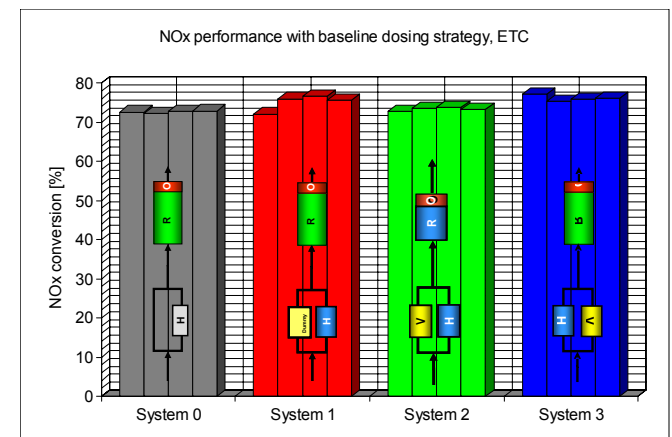


Figure 32: NO_x efficiency over different systems for ETC tests.

Comparing system 0 with system 1, it is apparent that the better NH_3 production of the two-stage hydrolysis catalyst did not lead to a significant improvement of NO_x reduction.

Also, a comparison of system 1 with system 3 does not yield a significant increase in NO_x performance with the elevated level of NO_2 as it was expected. The reason is that in the exhaust gas temperatures of this engine during european HD test cycles are already in the optimum range for a SCR reaction, see Figure 33.

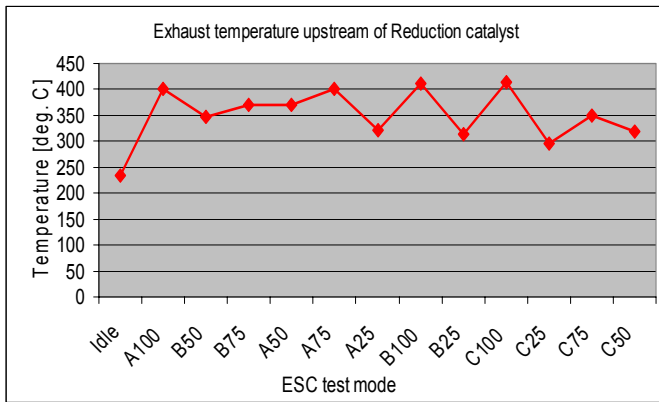


Figure 33: Exhaust temperatures upstream of SCR catalyst during ESC test

In test cycles and under real world driving operation with lower exhaust temperatures, the advantage of the system with pre-oxidation and two-stage hydrolysis catalyst is expected to be greater.

A comparison of system 2 with system 3 shows also a similar NO_x performance during ESC and ETC test runs. Here, system 2 utilizes the turbulent reduction catalyst with approximately 30% lower volume compared to the fully extruded reduction catalyst of system 3. The result confirms that it is possible to reduce the SCR catalyst volume using turbulent foil substrates such as 300/600 LS/PE, while maintaining similar NO_x performance.

At the same time, system 2 with the 300/600 LS/PE substrates had lower tailpipe NH₃ levels which allows for additional optimization of the system calibration. For instance, a modified dosing strategy could be used which can be optimized for higher dosing rate at equal NH₃ slip levels.

A further study to investigate the potential of downsizing the baseline reduction catalyst was considered, however the higher NH₃ slip of system 3 indicates that it may not be possible to downsize the reduction catalyst as it was done with the 300/600LS/PE.

INTEGRATED PM REDUCTION SYSTEM

Many studies have been conducted to investigate the potential integration of particulate reduction devices into SCR systems. Most of these systems include a combination of DOC and DPF positioned upstream of the SCR catalysts to use available NO₂ for continuous regeneration of the DPF. Such layout requires special high temperature SCR technology and protection measures to avoid damage to the SCR catalyst during active DPF regeneration. Other systems have been introduced where the DPF was positioned downstream of the SCR catalyst. Depending on the engine out and

tailpipe emissions this approach may still be feasible, however for certain applications such as U.S. 2010 the DPF would then need to be actively regenerated, leading to slightly higher fuel consumption.

As part of an on-going study, this test program was extended and system 2 was modified. Each module of the SCR catalysts was combined with an upstream PM Metalit as shown in Figure 34 below. A "Photo Acoustic Soot Sensor" (PASS) system was used to record PM emissions behind each catalyst system.



Figure 34: Combination System with PM Metalit and SCR catalysts

Previous laboratory tests have reported that PM reduction can be improved when NH₃ is present [8]. It was shown that it is necessary to completely convert the injected urea into NH₃ to avoid deposits from intermediate products such as HNCO in the filter.

The results of this experiment confirmed the previous experiences. Over a wide range of the ESC, a PM reduction of 50% could be achieved. Figure 35 shows the PM reduction, of the combined system compared to system 2 in the ESC test.

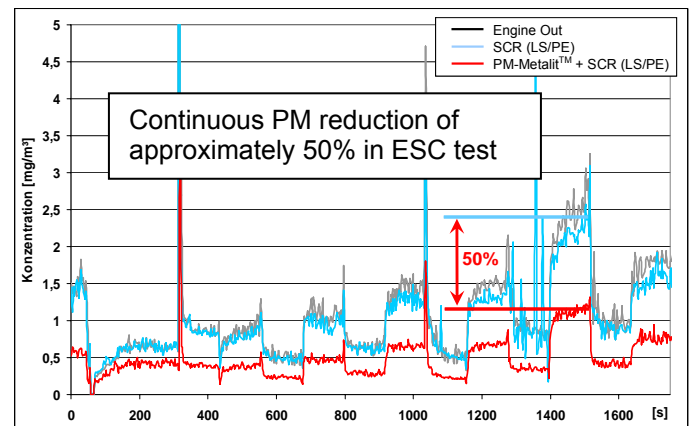


Figure 35: PM reduction in ESC test with System 2 and combined system

This result was repeated also in the transient test using gravimetric PM measurement. To determine a degradation of PM reduction from possible deposit of urea on the PM Metalit® filter, the ETC tests were conducted first without urea injection, then with the baseline injection calibration, and finally with a modified higher dosing rate. Figure 36 below shows the achieved PM reduction for all test runs.

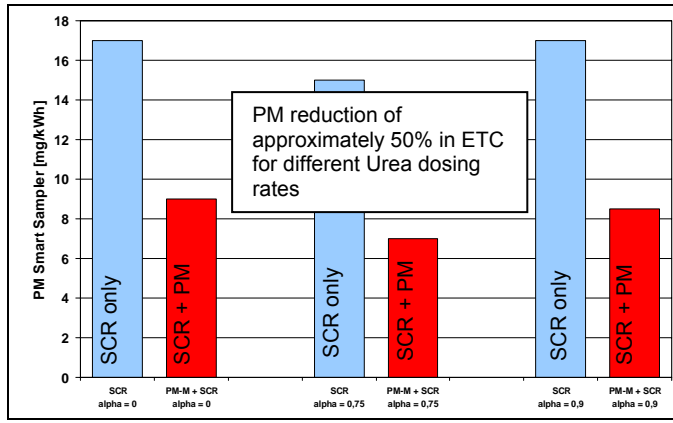


Figure 36: PM reduction in ETC test

Even with increased urea dosing rate, no negative effect from deposits in the PM Metalit® filter could be found. Further studies are planned to demonstrate long term durability and robustness against degradation of this ultra compact PM Metalit® SCR combined system.

CONCLUSIONS

Different modular SCR systems were designed and tested on a Heavy Duty Euro V diesel engine. The systems utilized a pre-oxidation catalyst, a two-stage hydrolysis catalyst, and either a fully extruded or turbulent 300/600 cpsi LS/PE reduction catalyst. An additional system utilized a PM Metalit® in combination with the optimized SCR system.

- The two-stage hydrolysis catalyst using MX + LS/PE foil and a newly developed washcoat process produced a more complete conversion of urea to NH₃.
- The SCR system using the turbulent 300/600 LS/PE substrate achieved similar NOx performance with 30% less catalyst volume while also having a lower NH₃ slip at the tailpipe.
- A significant space savings could be achieved with reduced volumes, enabling the packaging of SCR systems in areas with tight space requirements.

- Further system optimization is possible through changes to the urea dosing strategy and using the internal mixing benefits of LS/PE foil in the reduction catalyst.
- An additional test was conducted to understand the potential of combining the advanced SCR system with the PM Metalit®. The results yielded an additional 50% reduction in PM in a very compact combination SCR/PM aftertreatment system.
- Future testing is planned to demonstrate long term robustness of a system which can meet US2010 and EU VI requirements.
- Development of combustion and fuel economy optimized engines allows the application of the PM Metalit®, a device which continuously reduces the PM in the exhaust stream, without the need for active regeneration or the ash service cleaning needed for the majority of today's systems.

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