ABSTRACT

Engine manufactures’ and exhaust gas system suppliers’ engineers have successfully developed robust exhaust gas aftertreatment systems for on-road applications to achieve worldwide stringent emission standards for hydrocarbons and carbon monoxides, and - even more challenging ultra-low - NOx and particulate standards as well. Nonroad-Mobile Machinery (NRMM) will be subject to similar stringent emissions standards from 2010-2014 on.

The development of exhaust gas aftertreatment systems for non-road applications is expected to be extremely challenging due to the specific operating profiles, severe ambient conditions and the variety of duty cycles to be covered. Those diesel engines are installed in multiple vehicles and equipment such as agricultural and construction machines with very limited space allowance, adding a magnitude of complexity to the development in terms of packaging, thermal management and high transient load factors. The up-coming emission regulations require in a first stage reduction of particulate matter and in the following stage additionally lowest NOx tail pipe emissions.

This study summarizes a road map for modular aftertreatment systems for European Stage IIIA /US Tier 4 interim and finally Stage IV / US Tier 4 regulation, respectively. Such systems are engineered with advanced structured foil substrates for Diesel Oxidation Catalyst, PM-METALIT® and SCR catalysts in compact, functionally integrated arrangement, the so-called SCRi® system, resulting in minimum packaging requirements.

To meet this target, a detailed analysis of the functionality of the individual modules as well as the interaction between the particular components on system level leads to an optimum aftertreatment system efficiency. Especially the integration of the urea-water injection, including spray flow interaction (evaporation, thermolysis and hydrolysis) in the exhaust gas is regarded as particularly important. By means of a 3D CFD simulation based on the AVL code FIRE® [1] such phenomena can be investigated for a component (substrate) as well as for the entire aftertreatment system.

Based on the derived findings the overall functionality and performance of individual components was investigated in the regulated test cycles like NRTC, ISO 8178 C1. The results will be discussed with respect to performance, fuel efficiency benefits and system viability especially for NRMM.

1. INTRODUCTION

In the past, exhaust emission standards for NRMM were achieved by in-cylinder emission control measures. For example for European Stage 3 A emissions standards with best fuel consumption were achieved with cooled EGR. But, future emission regulations will require exhaust gas aftertreatment systems. Additionally, engine design development with 4-valve technology and variable geometry turbochargers (VTG), high-pressure fuel injection combined with cooled exhaust gas recirculation will continue to improve fuel consumption and minimize in-cylinder emission formation.

In view of the variety of NRMM applications, the optimization of engine maps is extremely challenging since engine operating conditions depend on the final engine / vehicle package.

The main objective of the work that led to this paper was the need for software based on the CFD tool AVL FIRE®, which would be able to perform calculations for a complete exhaust system for diesel engines. This paper describes the work
carried out in this context using the application of non-road diesel engines as an example.

It is the wide variety of non-road applications that demands a calculation program in particular because tests in this field would be extremely complex so that the potential for a simulation solution is especially high. It seems obvious that the best approach would be to extend the functions of an existing and well known and tested CFD program, AVL FIRE®, which has been successfully used to simulate complete exhaust systems, and so make it possible to perform calculations of relevant individual modules of such systems.

In accordance with the limits specified in EU Stage 3B and US Tier 4 interim the first stage of emission standards focuses on the reduction of particulates in 2011/2012 before setting lower NOx tail pipe emissions (figure 1).

![Figure 1: European and US emission regulations for stage 3B/Tier 4 interim and finally EU stage 4/Tier 4](image)

The solutions to meet these limits are those that combine NOx reduction with a soot filter system. Emitec's SCRi® aftertreatment system provides that potential. It consists of an oxidation catalyst, particulate filter, hydrolysis catalyst and SCR catalyst. Emitec's SCRi® catalyst system was developed to provide high NOx aftertreatment performance with high flexibility in application and model based control feature in combination with an efficient soot reduction device. Using the engine's NOx particle trade-off (fig. 2, point #3) engine raw emission can be set as an example to approximately 40 mg of PM/kWh and approximately 3-4 g of NOx/kWh. Under these boundary conditions and assuming the reduction rate of the SCRi® system is > 90% for NOx and > 60% for PM it becomes possible to meet the Stage 4 limit.

![Figure 2: Particulate (PM)- NOx trade-off and catalyst solutions to achieve stage 3B and 4](image)

The following chapters deal first with the fundamental functions of the system's individual components, followed by a description of the initial calculation results that reproduce the individual functions of each component. Finally, the test results are presented on the basis of a typical SCRi® system for a non-road application on the engine test bench.

2. CFD SIMULATION ON ENGINE AND CATALYST SYSTEMS WITH AVL FIRE®

CFD simulations have become increasingly important in modern engine development. The AVL CFD FIRE® program is a powerful tool that covers every engine-related CFD aspect, ranging from fuel mixture generation and combustion calculations to exhaust gas aftertreatment. Figure 3 provides an overview of the most common calculation tasks.

In addition, the use of CFD programs that support system design is becoming increasingly important to meet the growing requirements for exhaust aftertreatment (cf. figure 1). In response to this, FIRE® provides comprehensive models that can simulate exhaust aftertreatment systems. The tool reproduces all common system components, such as catalytic converters, diesel particulate filters, SCR systems and HC dosing systems.
As a result, system-related information on the behaviour of exhaust systems is already available in the early stages of the project. This information, which could not have been obtained in this form from measurements, permits a detailed assessment of system behaviour. The following phenomena can be assessed using an SCR system as an example (see figure 4):

- Prevention of Adblue® byproduct condensation and deposit forming
- Adblue® spray preparation (evaporation, thermolysis, hydrolysis) => uniform NH₃ admission in the catalyst
- Flow behaviour: equal catalyst intake flow
- Catalytic conversion (hydrolysis catalyst, SCR catalyst, slip catalyst): conversion rate, prevention of NOₓ slip, etc)

These findings make it possible to take specific optimisation measures that can be assessed in variant studies and also to carry out a quick assessment of system behaviour under changed operating conditions. CFD simulations that are able to quickly assess system quality under varying operating conditions are particularly useful and appropriate for NRMM applications, which are subject to great variance in the load spectrum.

Every relevant phenomenon was incorporated in the FIRE® models to make it possible to reproduce phenomena like for example spray preparation and SCR reactions in SCR systems. Figure 5 contains an overview of the modelling of both.

**UWS-INJECTION MODELLING**
- **Fluid Properties**
  - depending on temperature and urea concentration
- **Heat Transfer**
  - Heat transfer between droplets and wall
  - Lateral heat conduction in the piping
- **Urea spray/wall interaction model with 6 regimes**
- **Evaporation**
  - Multicomponent droplet evaporation
  - Multicomponent wallfilm evaporation
- **Gas Phase Reactions**
  - Thermolysis: \((NH₂O)₂CO \rightarrow HNCO + NH_3\)
  - Hydrolysis: \(HNCO + H_2O \rightarrow CO_2 + NH_3\)

**SCR Catalytic Reactions Modeling**
- **Hydrolysis**
  - \(HCNO + H_2O \rightarrow NH_3 + CO_2\)
- **SCR**
  - \(NH_3 + S \rightarrow NH_3(S)\)
  - \(NH_3(S) \rightarrow NH_3 + S\)
- **Oxidation**
  - \(2 \cdot NO + O_2 \rightarrow 2 \cdot NO_2\)

Figure 5  FIRE® modeling on spray preparation and SCR reactions
The numerical simulation of Emitec’s SCRi® system for the combined reduction of soot and NOx emissions (see section 3) requires additional adjustments and extensions to the model because of the special characteristics of the structured substrates:

- The radial permeability of the metal catalysts requires modified models to reproduce their physical and catalytic behaviour
- The specific use of the catalysts as vaporisers requires special consideration of the droplet behaviour inside the substrate. As part of this, particular attention has to be paid to the interaction between the droplets and the walls.

These model extensions are based on studies that model the channel structure with full resolution. The resulting findings relating to physical and chemical behaviour make it possible to extend the macroscopic models after validation with the experiment. Calculation time restraints mean that the detailed tests have to be carried out on small substrate sections.

3. THE EMITEC SCRi® CATALYST SYSTEM

The SCR process has established itself as an efficient and economical technology for nitrogen oxide reduction. Therefore, SCRi® technology was developed to reduce soot particles in the exhaust gas and maximise NOx efficiency through optimised ammonia preconditioning in compact arrangements [2,3,4]. The functions / designs of the individual components are briefly described below. The principal components are also shown in fig. 6:

- Oxidation catalyst
- Urea injection
- PM-METALIT® as hydrolysis catalyst and filter
- LSPE substrates as SCR catalyst

Oxidation catalyst

Oxidation catalysts are used to reduce HC and CO and simultaneously oxide NO to NO₂ at a temperature range of 200 to 450°C. The generated NO₂ is used for continuous particulate reduction in the PM-METALIT® and to enhance fast SCR reaction at lower exhaust gas temperatures [5]. Oxidation catalysts optimized for NO₂ production are typically coated with Platinum (Pt) or coated with Platinum/ Palladium (Pt/Pd) for HC and CO oxidation requirements.

Many publications [6,7] have highlighted the advantages of structured metal substrates such as LS when used in the catalyst substrates of this type of applications. The LS structure (figure 7) and/or the PE design are the most suitable substrate structures for these applications, because efficiency is substantially increased as a result of improved mass transfer. The LS structure has the following properties:

- Generation of “micro-turbulence”
- Repeated intake section
- Partial reduction of the channel diameter in the LS section

The following section illustrates the resulting advantages during operating conditions.
**Urea injection system**

The urea dosing system shown in figure 8 represents another important component of Emitec’s SCR® system. The dosing system consists of the following main components:

- Tank / uptake pipe
- Dosing unit
- Injection nozzle
- Sensors and control unit

The injection nozzle is usually installed downstream of the oxicat and injects the urea solution either onto the rear of the oxidation catalyst or down stream in the direction of the exhaust gas flow towards the hydrolysis catalyst. The layout and control of the system allow it to be installed as a stand-alone version (with its own sensors) or as original equipment (integrated in the vehicle’s electronic system). The individual components can be used in passenger cars (12-volt system) and commercial vehicles (24-volt system) and are easily adapted (e.g. a vehicle-specific tank).

The individual components of the SCR dosing system and their functions are described in a previous publication [8] in greater detail.

**PM-METALIT® as a hydrolysis catalyst and as particle filter**

This partial-flow deep-bed filter is maintenance-free for its lifetime and oxidises soot continuously on a CRT basis without raising fuel consumption (see figure 9). The basic properties of the substrate include:

- Flow direction change
- Generation of convective radial exchange
- Filter function in the sintered metal fleece
- Greatly increased geometric surface

Depending on the type of application PM-METALIT® is fitted upstream in combination with an oxidation catalyst or as stand-alone system unit when catalysed. Soot particles are reduced by the NO\(_2\) that is present in the exhaust gas or generated in the oxidation catalyst. The systems can reach efficiency levels of between 50% and 80% with respect to soot mass. The reduction rates for particulate numbers in the 23 to 300 nm range are between 60% and 90% [9,10].

In addition, PM-METALIT® with a hydrolysis coating can also be used to generate ammonia from the thermolytically gasified mass from urea injection. Further details are described in the next chapter.

**LSPE Structure as a SCR Catalyst**

Like the LS structure (see above) a “turbulent” LSPE structure has proven to be very effective at increasing the efficiency of the SCR catalyst or reducing installation size and hence costs (for design see figure 10). The basic properties of the substrate include:

- Repeated intake section
- Generation of micro-turbulence
- Reduction of thermal mass
- Provision of diffusive/convective radial heat and mass exchange
- Partial reduction of the channel diameter in the LS section
Application as an SCR catalyst depends especially on the ability to provide radial equalisation of velocity and concentration differences. Substantially improved mass transfer also makes out of these substrates highly suitable SCR catalysts.

**4. CFD SIMULATION AND FUNCTION ANALYSIS OF SCRi® SYSTEM COMPONENTS**

This chapter describes the calculation results that can currently be achieved with AVL FIRE® for the individual components of Emitec’s SCR system complemented by functional tests of the components. The main focus is on the coated PM-METALIT®.

**Oxidation catalyst**

As mentioned above, the main feature of the LS structure is its ability to substantially improve mass transfer. This advantage becomes particularly apparent at higher space velocities. This is exemplified by the conversion rates shown in figure 11, which use 200/400 LS instead of 200 cpsi in an oxidation catalyst at varying space velocities (60k 1/hr, 300k 1/hr, 650k 1/hr). Higher specific efficiency and lower thermal mass and therefore rapid heating up and light-off compared to standard technology makes the LS-Metalit an outstanding, cost-effective DOC product.

Following relevant extensions to the code, it will become possible to reproduce the improved mass transfer of structured substrates in the FIRE® CFD calculations. The necessary work is already in the planning stage. The implementation of the models and a subsequent calibration with actual measurements will make it possible to assess the catalytic activity of different structures.

![Figure 10 LSPE design and operating principle](image)

**Figure 10** LSPE design and operating principle

![Figure 11 Propene conversion in a 200/400 LS structure compared to a standard 200 cpsi, Ø 40 x 50.8 mm, 50g/ft³ Pt (stab.), 450°C](image)

**Figure 11** Propene conversion in a 200/400 LS structure compared to a standard 200 cpsi, Ø 40 x 50.8 mm, 50g/ft³ Pt (stab.), 450°C

Any application of the LS structure must generally consider which smooth-channel substrate is to replace.

![Figure 12 Suitable areas of application for various LS cell densities depending on flow speed compared to 400 cpsi standard (450°C)](image)

**Figure 12** Suitable areas of application for various LS cell densities depending on flow speed compared to 400 cpsi standard (450°C)

Since the advantages of the LS structure when compared to smooth channels increase with higher
space velocities, higher smooth-channel cell densities could – put simply – always be replaced by a (lower) LS cell density, as long as the average channel speed is increased and the system operates in a mass transfer-optimised range. Figure 12 shows the boundary flow speeds above which 400 cpsi can be replaced by 200/400 or 300/600 cpsi LS. For values > 1 on the y-axis LS is expected to perform better. Above a flow speed of 10 m/s a 200/400LS can replace 400 cpsi and increase performance; above 2.5 m/s same applies to 300/600 LS.

Urea dosing and injection system

The fact that the injection system has a great effect on the quality of NH₃ formation is well established.

This is primarily due to parameters, such as injection pressure, spray entry speed, achievable droplet diameter distribution, the spray cone and the geometry of the exhaust system. Of course, this also includes the boundary conditions of ammonia formation, such as gas temperatures, exhaust gas mass flow and UWS injection volumes.

The interaction of the injected spray with the exhaust gas results in highly three-dimensional effects. This high level of complexity makes FIRE® a particularly important and valuable tool in this area because it is able to reproduce the quality of the evaporation of the urea solution and the thermolysis and hydrolysis of the urea contained in the gas flow post injection. Following a detailed examination of the CFD simulation suitable countermeasures can be developed to prevent a number of undesired effects:

- Unequal NH₃ admission in the SCR catalyst
- Excessive and unequal admission of UWS in the SCR catalyst
- Adblue® byproduct condensation including the additional risk of deposit forming

In order to highlight the need for CFD simulations by way of an example the droplet evaporation distances of 50 µm urea droplets after injection depending on a passenger car’s engine torque and revolutions was examined using AVL 1D tools (figure 13). It is clearly apparent that the evaporation distance would have to extend to several meters under unfavourable conditions. This shows that in the absence of suitable measures excessive amounts of liquid phase would hit the hydrolysis or SCR catalyst in a wide range of the engine map and that evaporation inside the SCR catalyst would reduce the valuable catalytically effective length. If the liquid phase is unequally distributed at the catalyst intake it will not always be possible to achieve the necessary NOx conversion rates even with corresponding overdosing.

This forms the basis from which appropriate measures, that are essential to meet the emission target, can be developed. The measures may involve an increase in injection pressure to reduce droplet size or the use of a PM-METALIT® as a vaporiser and mixer.

Figure 13 Droplet evaporation distances of 50 µm urea droplets post injection depending on engine parameters; AVL 1D tool

Emitec’s SCR dosing system allows for variable injection pressure so that the resulting droplet size
can be precisely adjusted to the specific application and its boundary conditions. Figure 14 shows the average droplet diameter (SMD) that can be achieved under variation of injection pressure between 4 and 8 bar. Due to its internal structure the PM-METALIT® is able to evaporate the injected aqueous urea solution effectively and distribute the generated ammonia across the surrounding channels.

**PM-METALIT® as a hydrolysis catalyst and as particle filter**

In the SCRI® system the PM-METALIT® is located in a unique position, because it carries out two distinct functions. It is used to reduce soot particles and as a more effective means of converting the injected aqueous urea solution to NH₃. This means that the volume of the SCR catalyst can be reduced. For this purpose, a hydrolysis coating is applied to the PM-METALIT®. Studies have shown that the integration of a hydrolysis coating in the PM-METALIT® enhances this effect because the exhaust gas is able to mix with the urea solution inside the substrate (equal distribution). Furthermore, this concept supports the evaporation of urea droplets, because they are being absorbed by the coated metal wire fleece of the PM-METALIT®. The great internal surface of the fleece and the fact, that droplets are not able to bypass a channel without coming into contact with an absorbing surface, substantially increases hydrolysis efficiency.

For a function analysis of a coated PM-METALIT® following tests have been carried out:

- Ability of absorbing, evaporating and distribution of urea droplets
- Hydrolysis activity / ammonia creation
- Filter function in coated condition

**ABSORPTION, EVAPORATION AND DISTRIBUTION OF UREA DROPLETS**

With regard to the first task, figure 15 shows the effect of substrate length and substrate coating depending on injected urea mass (tested by using water) and load point. Relevant tests were carried out on the engine test bench using a SCRI® dosing system and a digital camera to monitor the droplets behind the substrate. After a typical PM-METALIT® length of 150 mm almost no droplets were detected with or without coating. The effect of coating is clearly apparent in shorter substrates.

![Figure 15](image)

The CFD simulation of the hydrolysis behaviour initially required the mapping of the flow-through behaviour of the PM-METALIT® in CFD with respect to gas and liquid droplets. The operating points, or the prevailing boundary conditions for which the calculations were performed, are summarised in table 1 below.

<table>
<thead>
<tr>
<th>Load Point 1</th>
<th>Exhaust gas mass flow [kg/h]</th>
<th>Gas temperature [°C]</th>
<th>Urea dosage [g/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>300</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Load Point 2</td>
<td>600</td>
<td>400</td>
<td>612</td>
</tr>
</tbody>
</table>

This was followed by a description of the interaction between the droplets and the walls. As a result, using those newly implemented software functions important aspects of the PM-METALIT® hydrolysis function can already be simulated. Figure 16 shows the vectors of the gas flow passing through the fleece layer. Radial flow velocities up to 3 m/s were obtained in the simulation especially in channel regions with deep blade impressions. This correlates to an amount of air mass flow of 25% passing through the fleece at one blade. Calculations have shown that this amount increases with increasing channel velocity.
The radial porosity and the active redirection of the gas flow and the liquid droplets into the fleece caused by the blades results in a macroscopic distribution of droplets and their resulting product beyond the individual channel and into adjacent channels, which may require equalisation due to objection with urea solution. Figure 17 shows a corresponding two-dimensional ammonia concentration profile in a channel grid consisting of 5x3 channels where urea was injected only into the central channel.

The radial distribution of the tracer gas across an area of up to three channels in width and five channels in height is clearly apparent. As a result, unequal admission in adjacent cell areas can be equalised.

The simulation describes the interaction between the flow and the spray droplets and also the interaction between the droplets and the wall according to Birkhold [11]. Based on findings from previous tests [12] in the simulation the droplets come into contact with the fleece where they are absorbed, stored and evaporated depending on boundary conditions.

With regard to the total evaporation at this operating point in the 32-mm long system shown here (equal to 1 blade per channel), it became clear that depending on the load point as much as 76% or 56% of the droplet mass can be evaporated inside the substrate (figure 18). At actual substrate lengths of 150 mm it is likely that this proportion can be substantially increased to achieve 100%.

A comparison between the simulation (figure 18) and the actual measurement of the droplet mass leaving the substrate (figure 15) at a substrate length of 32 mm (uncoated) shows good correlation in load point 2, where approximately 10-15% of the mass leaves the substrate. However, at low massflow and temperature as in load point 1 the results differ clearly, which highlights the need for additional validation effort.

Differences between measurements and calculations (figure 18) also exist in the reproduction of the liquid mass stored in the substrate. While the above-mentioned tests revealed no extraction of liquids in this respect and similar findings were reported in earlier studies [12], the CFD produces mass fractions between 10% and 30% depending on the load point. Work on a more detailed technical validation and parameter adjustment in the program is already underway.
HYDROLYSIS ACTIVITY AND AMMONIA GENERATION

In the next step, the hydrolysis activity and ammonia creation were examined. Tests were carried out on the engine test bench using a 3.0 l light truck engine. In a constant load point the concentration of Ammonia behind PM-METALIT® was monitored with a variation of injected urea mass. The coating applied on PM-METALIT® Ø 150 x 150 mm was a 30 g/l Hydrolysis Coating, especially designed to create a thin coverage on the metal wires in the fleece.

Figure 18 Calculated amounts of evaporated, unevaporated and remaining urea droplet mass, catalyst length = 32 mm, load point 1 and load point 2

Behind the PM-METALIT®, 95% of the maximum achievable amount of ammonia was obtained. This provides good conditions for high SCR conversion rates downstream. This concept will also prevent deposits of urea by-products, which could be converted catalytically in the PM-METALIT®.

FILTER FUNCTION IN COATED CONDITION

In the final step, the filter efficiency of the coated PM-METALIT® was tested in an identical setup as the one shown above, using a micro soot sensor in front of and behind the PM-METALIT®. The resulting filter efficiencies are plotted in figure 20. The injected urea mass was not found to have any effects on filter efficiency.

Figure 19 Ratio NH₃ created in H-catalyst relative to NH₃ max. achievable by thermo-and hydrolysis, 50 and 100 mg urea / s, 160 kg/h exhaust flow, 340 °C in front H-catalyst

Figure 19 shows the conversion resulting from the injection of urea with 50 mg/s resp. 100 mg/s.

Figure 20 Soot mass reduction of coated PM-METALIT® Ø 150 x 150 mm, 30g/l hydrolysis coating, engine test bench, 160 kg/h, 340 °C

LSPE Structure as SCR Catalyst

Most modern standard SCR catalysts are coated with vanadium pentoxide or zeolite coatings. Zeolite coatings are still relatively sensitive to the NO/NO₂ ratio in the exhaust gas at low temperatures. These systems include an upstream oxidation catalyst to increase efficiency to the highest level (NO/NO₂ ratio of 1:1) because the engine exhaust gas contains mostly NO.

Based on the above-mentioned boundary conditions of actual systems the substrate has to meet the following requirements in addition to a high...
selectivity of coating with respect to N₂ generation and a minor tendency towards ammonia oxidation:

- Ability to radially mix gases (ammonia) over the substrate length to overcome unequal gas distribution in front of SCR
- Efficiency improvements due to the increased mass transfer inherent in the LS structure

To assess the equalisation of the concentration in a radial direction across several cells measurements were carried out on a gas test bench, during which the concentration distribution of CO₂ as a tracer gas was measured over substrate expansion in a radial direction (as in chapter 4.3). Figure 21 contrasts the results of standard substrates and LSPE substrates with the same basic cell density of 200 cpsi.

To illustrate the equalisation of a tracer gas injected into the centre cell, the CO₂ objected substrate’s outlet surface is 4 times higher in case of using LSPE. As demonstrated with PM-METALIT®, this local equalisation is sufficient to equalise concentration differences between individual channels or entire channel areas effectively.

Figures 22 and 23 show the conditions based on CFD calculations:

The higher distribution coefficient of the LSPE structure is clearly apparent when compared to the standard structure. After injection of CO₂ into the centre cell, the CO₂ objected substrate’s outlet surface is 4 times higher in case of using LSPE. As demonstrated with PM-METALIT®, this local equalisation is sufficient to equalise concentration differences between individual channels or entire channel areas effectively.

Figures 22 and 23 show the conditions based on CFD calculations:

Figure 22 shows the model setup and the equalisation of concentration of a tracer gas injected into a single cell over the substrate length of 18 mm – about one subdivision of the LSPE structure (the current model does not allow for greater lengths). As with the measurement values in figure 21 an initial equalisation of the concentration, which has already covered 7 cells, is clearly apparent despite the short substrate length.
By contrast, Figure 23 shows the resulting radial flow velocity components in operation point 1. Radial velocities reach up to 3 m/s, which corresponds to approximately 10% of the axial velocities in load point 1.

The next step is the implementation of global models derived from detailed models and measurements in order to be able to simulate complete systems comprising structured substrates. For this purpose, the model will incorporate wall reactions so that the catalytic reactions can be examined in the detailed model. This will make it possible to examine the catalytic behaviour as well as flow and droplet behaviour in detailed models. The findings could be used in addition to measurements to aid the development of global models.

5. OVERALL PERFORMANCE OF A PM-METALLIT® AND SCR® SYSTEM IN A NON-ROAD APPLICATION; NRTC, ISO 8178 C1

As mentioned in the previous chapter the functions shown are not available in a global model so that it is as yet impossible to perform calculations for a complete SCR® system in technical dimensions. Instead at this point measurement results relating to NOx and particulate reduction, which were established using a prototype SCR® catalyst system on the engine test bench under non-road conditions will be presented. Figure 24 shows the relevant test bench setup.

![Figure 24 Engine test setup on engine dynamometer](image)

The test was carried out on a production engine with 107-kW used in mobile machinery. The engine was installed on an engine dynamometer equipped with an exhaust gas sampling line pre and post SCR® system. In addition, micro-soot sensors were used to record soot concentrations pre and post system during transient and steady state cycles. The AdBlue® injector was installed 200 mm upstream of the PM-METALIT® front face in order to simulate a system which has to be installed under limited space. Therefore mixing of Urea solution was limited.

Table 2 summarises the dimensions and technical data of the catalysts used in the tests.

<table>
<thead>
<tr>
<th></th>
<th>Dimensions</th>
<th>Volume</th>
<th>Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation Catalyst</td>
<td>Elliptical (177,8 x 114) x 101,5 mm</td>
<td>1,85 l</td>
<td>50 g/ft³ Pt</td>
</tr>
<tr>
<td>PM-METALIT®</td>
<td>Ø 174,6 x 174 mm / 200 cpsi</td>
<td>4,16 l</td>
<td>30 g/l Hydrolysis</td>
</tr>
<tr>
<td>SCR Catalyst</td>
<td>Ø 230 x 101,5 mm / 300/600 LS + Ø 230 x 63,5 mm / 300/600 LS</td>
<td>7,23 l</td>
<td>150 g/l SCR-HT + 150 g/l SCR LT</td>
</tr>
</tbody>
</table>

Table 2 SCR® System Components

The oxidation catalyst was designed with an elliptical shaped Metalit with 50 g/ft³ Pt-only coating. The PM-METALIT® downstream of the AdBlue® injection point was coated with Titanium-Oxide coating to support the hydrolysis and thermolysis process and support uniform ammonia distribution upstream of the SCR catalyst. The SCR catalyst was divided into two parts: a 300/600-LS Metalit coated with HT-SCR coating technology followed by a section using LT-SCR technology.

![Figure 25 Exhaust gas temperature and NO₂ generation rate during the ISO 8178-C1 test cycle](image)

The exhaust system was installed and the catalyst was degreened for 50 hours prior to testing. Figure 25 shows NO₂ generation for each test mode, depending on the engine out temperature level. Since the temperature level was relatively high, NO₂ generation was between 20% and 50% depending on the temperature level. The oxidation catalyst was...
designed to limit NO₂-production below 50% in most load points in order to keep tailpipe NO₂ emissions as low as possible.

Secondary emissions such as N₂O, isocyanic acid (HCNO) and NH₃ tail pipe emissions are shown in figure 27. Ammonia concentrations are well below 20 ppm and could be further reduced by adjusting the dosing strategy or fitting an oxidation catalyst downstream. The results are very impressive considering the distance between the urea injection point and the SCR rear face of less than 600 mm.

The overall soot and NOx efficiency is plotted in figure 28. The results show similar effectiveness with respect to soot reduction at 65 to 75% and NOx reduction of 80% at an NH3 average level < 2 ppm and NH3-peak below 25 ppm.

6. SUMMARY AND CONCLUSION

The aim was to develop powerful CFD software to reproduce complete exhaust gas aftertreatment systems so that the number of complex tests can be reduced, especially for non-road applications. Future legislation in this area will above all require a reduction in particulate and NOx emissions. The modular Emitec SCRi® aftertreatment system offers a perfect solution to this problem.

Against this background the calculation capacity of the AVL CFD tool FIRE® was expanded and optimised for the individual components of Emitec's SCRi®-systems.

It is possible to perform calculations on the PM-METALIT®, especially when used as a hydrolysis catalyst and soot filter, with respect to axial and radial flow, droplet separation and evaporation. The LSPE structure, which makes an ideal SCR substrate, can also be reproduced with respect to radial equalisation of velocities and concentrations.
Further steps in the development of the program include the porting of the functions to the scale of a global model, which would make it possible to perform calculations for complete SCRi® systems. Smaller parameter adjustments within the scope of the evaporation function are also required.

With regard to the function of the substrates the LS and LSPE structures increase efficiencies, when used in oxidation and SCR catalysts under appropriate conditions due to a strong increase in mass transfer.

A coated PM-METALIT® with a length of 150 mm has been shown to operate as an almost perfect absorber and vaporiser for liquid droplets. As a consequence, it would be possible to convert 95% of the injected urea to ammonia.

The LSPE structure has been shown to be able to homogenise unequal distributions of ammonia in front of the catalyst and at the same time increase mass transfer to improve catalytic efficiency.

This paper described a prototype SCR system for non-road applications with an NOx conversion rate of 90% and a particulate reduction rate of 70%.

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