# The Exhaust Aftertreatment for Future World-Wide Internal Combustion Engines; From Passenger Car to Trucks

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## Abstract

In the coming years, new emission standards for passenger cars and commercial vehicles will be introduced worldwide. The primary focus is on ensuring that future emission limits are met under all statistically relevant driving conditions.

Different vehicle classes require different technologies, including passenger cars, vans, and commercial vehicles. In particular Heavy Duty engines, with their wide range of applications, pose a unique challenge and require innovations in future exhaust aftertreatment. In addition to optimizing conventional catalyst substrates, there is significant importance placed on active solutions that can be used as add-ons. Specifically, newly developed electrically heated diesel (EHD) catalyst substrates for both passenger cars and trucks, in combination with existing exhaust systems or newly developed catalyst substrates, will be deployed.

## Content

## 1 Introduction

While market studies about electric powertrain penetration continuously change at quite a dynamic pace, one point remains pretty unchanged: ICE powertrains will continue to serve both individual and commercial mobility for decades. Similarly, while the phase-in date for EU7 package (both LD and HD vehicles) as well as some details in the limit values are still under discussion, one point remains pretty unchanged here too: thermal management in the EATS (Exhaust After-Treatment System) will be of utmost importance in order to securely comply with the emission limits under various operating conditions.

Additionally, $CO_2$ targets represent a crucial part of the entire Powertrain-EATS chain, as engines with improved fuel efficiency tend to have lower exhaust temperatures, which further complicates catalyst operation in low load condition.

It is well known that for gasoline engines most of the emissions are emitted in the very first seconds of the emission cycle. Moreover, the new Real Driving Emissions extended conditions will include use cases that could potentially require the use of a heater during cold start. For Diesel Engines the use of an exhaust gas heater is mandatory, not only to reach a fast light off of the oxidation and reduction catalysts, but also to keep the catalysts warm during low loads conditions.

In many cases EU-VI HD-Engines have the highest tailpipe nitrogen oxides ($NO_X$) emissions in the first 10% of the engine-work [g/kWh], while Stage V non-road mobile machinery (NRMM) operate in some RDE cases within extended idle mode. The tailpipe $NO_X$ -concentration has peaks at a power lower than 10% or higher than 75% of the nominal power.

Several studies have been conducted on thermal management of heavy-duty exhaust systems in order to get the catalyst-temperature into the window of best performance.

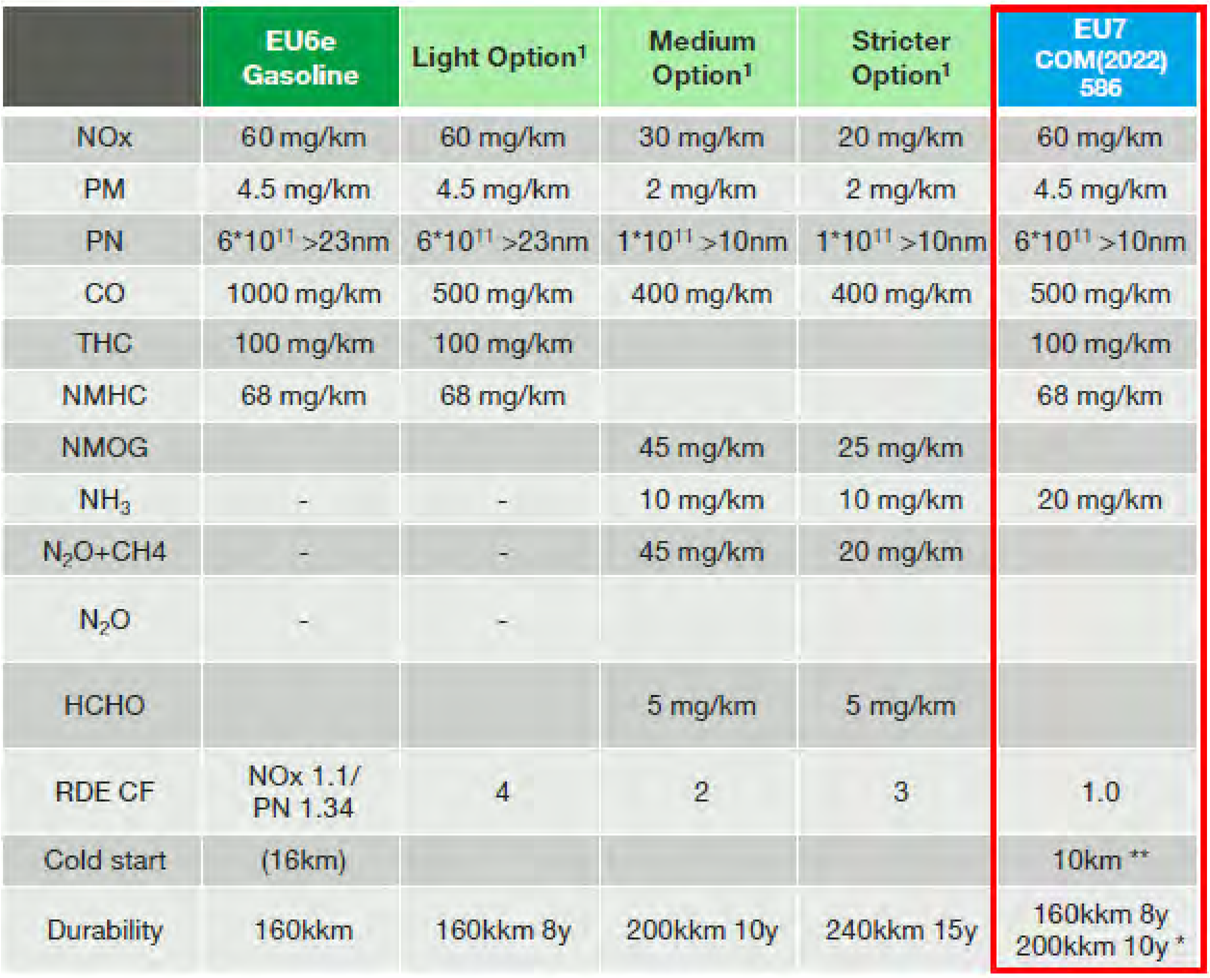
This paper deals with various application examples of Emitec Technologies products from the well-known Electrically Heated Catalyst (EHC) to the newly introduced Electrically Heated Disc (EHD) also in combination with the modern CS-Design in metallic substrates, which enable an optimized integration in LD and HD EAT Architectures. In particular, insights in the EHD development process will be given, describing both the mechanical durability aspects as well as the thermal performance of the product.

Application examples will be described both from a packaging integration perspective as well as from an emission performance perspective.

## 2 New Emission Legislation for Pass Car and Heavy Duty

The EU Proposal for EU7 limits has been published in October 2022 showing limited changes of emission limit in comparison to EU6e and a much more relevant modification of the test conditions.

In Table 1 a comparison of current passenger car limits for Gasoline, the three preliminary proposals (light, medium and stricter) and the final EU proposal for EU7 is shown. It is quite clear that the legislator's focus is more on the RDE, considering the conformity factor of 1, than on the emission limits themselves. In fact, the emission limits for THC, NMHC, $NO_X$ and PM remain unchanged (considering only Gasoline), CO has been reduced by 50%, PN includes particles starting with 10nm and a $NH_3$ limit has been introduced.

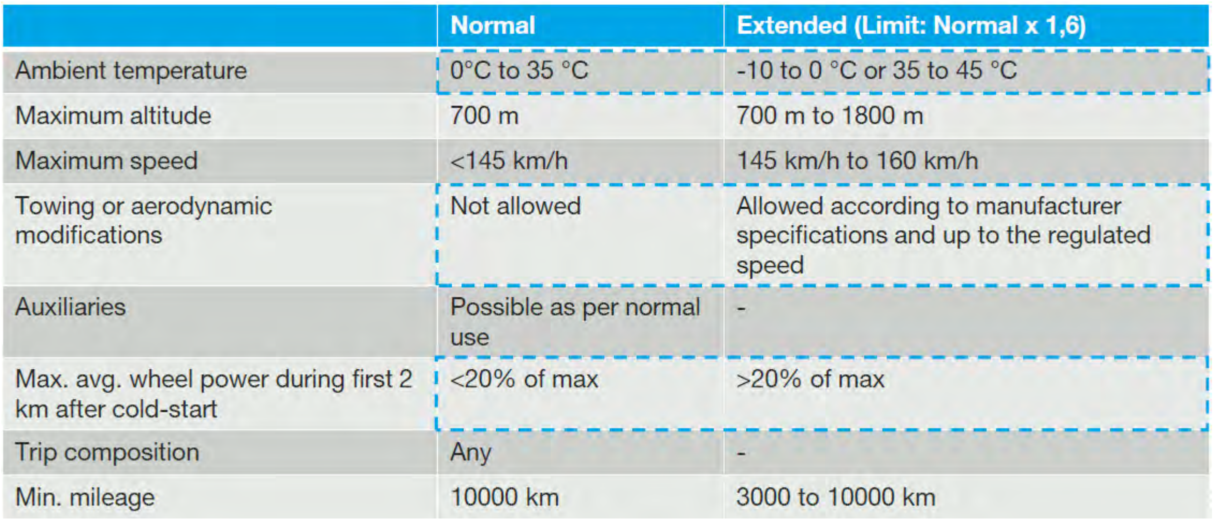


| | EU6e Gasoline | Light Option[1] | Medium Option[1] | Stricter Option[1] | EU7 COM(2022) 586 |
|---|---|---|---|---|---|
| NOx | 60 mg/km | 60 mg/km | 30 mg/km | 20 mg/km | 60 mg/km |
| PM | 4.5 mg/km | 4.5 mg/km | 2 mg/km | 2 mg/km | 4.5 mg/km |
| PN | $6*10^{11}$ >23nm | $6*10^{11}$ >23nm | $1*10^{11}$ >10nm | $1*10^{11}$ >10nm | $6*10^{11}$ >10nm |
| CO | 1000 mg/km | 500 mg/km | 400 mg/km | 400 mg/km | 500 mg/km |
| THC | 100 mg/km | 100 mg/km | | | 100 mg/km |
| NMHC | 68 mg/km | 68 mg/km | | | 68 mg/km |
| NMOG | | | 45 mg/km | 25 mg/km | |
| $NH_3$ | - | - | 10 mg/km | 10 mg/km | 20 mg/km |
| $N_2O$+CH4 | - | - | 45 mg/km | 20 mg/km | |
| $N_2O$ | - | - | | | |
| HCHO | | | 5 mg/km | 5 mg/km | |
| RDE CF | NOx 1.1/<br>PN 1.34 | 4 | 2 | 3 | 1.0 |
| Cold start | (16km) | | | | 10km ** |
| Durability | 160kkm | 160kkm 8y | 200kkm 10y | 240kkm 15y | 160kkm 8y<br>200kkm 10y * |

Tab.1 EU7 Emission Limits, EU Proposal, October 2022

Moreover, the definition of a valid RDE Test has been modified, introducing the Normal Condition (where the conformity factor has a value of 1) and Extended Condition (where the conformity factor has a value of 1.6).

At the time in which this work has been released, only one extended condition can be applied during a valid test. In case two conditions are valid at the same time, for example temperature between -10°C and 0°C and altitude between 700m and 1800m, the test is not valid anymore.



| | Normal | Extended (Limit: Normal x 1,6) |
|---|---|---|
| Ambient temperature | 0°C to 35 °C | -10 to 0 °C or 35 to 45 °C |
| Maximum altitude | 700 m | 700 m to 1800 m |
| Maximum speed | <145 km/h | 145 km/h to 160 km/h |
| Towing or aerodynamic modifications | Not allowed | Allowed according to manufacturer specifications and up to the regulated speed |
| Auxiliaries | Possible as per normal use | - |
| Max. avg. wheel power during first 2 km after cold-start | <20% of max | >20% of max |
| Trip composition | Any | - |
| Min. mileage | 10000 km | 3000 to 10000 km |

Tab. 2 Definition of Normal and Extended Conditions

For Heavy-duty vehicles, European emission standards have significantly reduced pollutant emissions over the past decades. In particular, Euro VI emission standards have reduced on-road $NO_X$ and PN emissions compared to the previous legislative step. A further tightening of emissions is, in any case, required, to achieve a better air quality. With the EU proposal for Euro VII, a Real-Driving Emissions procedure for trucks and buses in combination with reduction in limits has been introduced. Similarly, to the passenger cars, tailpipe emissions will have to be limited over a wider range of operating conditions, including cold-start and low-load operation in cities.

In addition to the regulated pollutants, in order to comply with climate change targets, the EU-Commission also proposed further tightening of the $CO_2$ regulation for heavy duty trucks. On one side, the two-faced challenge to achieve lowest emissions levels in conjunction with negligible impact on fuel consumption (hence $CO_2$) will lead to an acceleration towards electrification. On the other side, the long-term reliability, robustness and thermodynamic efficiency of the internal combustion engine, might lead to a revisitation of the role that synthetic fuels will play in the future.

## 3 EHC Status

The implementation of a 48V net on Passenger Cars is widely established for future platforms. Similarly, on Commercial Vehicles 48V net will at least partly replace the well-established 24V landscape. In both market sectors, this enables the adoption of high-power auxiliaries with viable cable diameters. Given the further reduction in future emission limits in the certification cycles, the development of advanced EATS is getting more and more importance.

Especially from an RDE perspective (PassCar) or simply during cold start and low load cycles (Commercial Vehicles), due to the limited conversion efficiency of catalytic converters at low temperatures, high tailpipe emissions would be expected.

In order to reach the required high conversion rates for nitric oxides in the SCR system it is essential to operate the exhaust aftertreatment in the optimal temperature window. Load points with low exhaust gas temperatures and especially cold starts will require (active) heating, which can be realized by means of the Electrically Heated Catalyst (EHC). The beneficial result of the EHC, a quicker catalyst light-off, can be further enhanced combining it, in some cases, with the additional fuel injection.

With active exhaust heating it is realistic to operate the engine a longer period of time in more fuel-efficient load points, with no penalty for exhaust heating. Pure electrical heating might be sufficient for many low load points.

The Electrically Heated Catalyst (EHC) introduces “actively” heat energy at the “heating disc” into the exhaust system with high uniformity over the complete cross-section. The heating disc is attached to the insulated supporting pins and thus fixed to the support catalyst. The support catalyst itself is brazed to the outer mantle. This “assembly” (including the electrical connection of the heated disc) can be coated similarly to a conventional catalyst substrate with the appropriate wash coat formulation (usually TWC for PHEV or DOC for Commercial Vehicles).

Typical installation of an EHC in Diesel Passenger Car vehicles consists of the EHC mounted directly behind the turbocharger, mainly coated with DOC coating. The function of the EHC is twofold: quick light off and keep warm. The quick light off must be reached to allow early urea injection and reduce the HC and CO emissions during cold start. The keep warm function is on the other hand very important during low loads phases in which the exhaust gas temperature falls below the temperature range in which Urea can be injected.

The possibility to have a very tight angle between the two electrical connectors allows the use of the EHC also in the very crowded engine compartments, typical of modern vehicles. Moreover, the recently introduced two-pieces electrical connector (Figure 1) improve further the possibility to mount the EHC without or with minor impact on the existing canning.

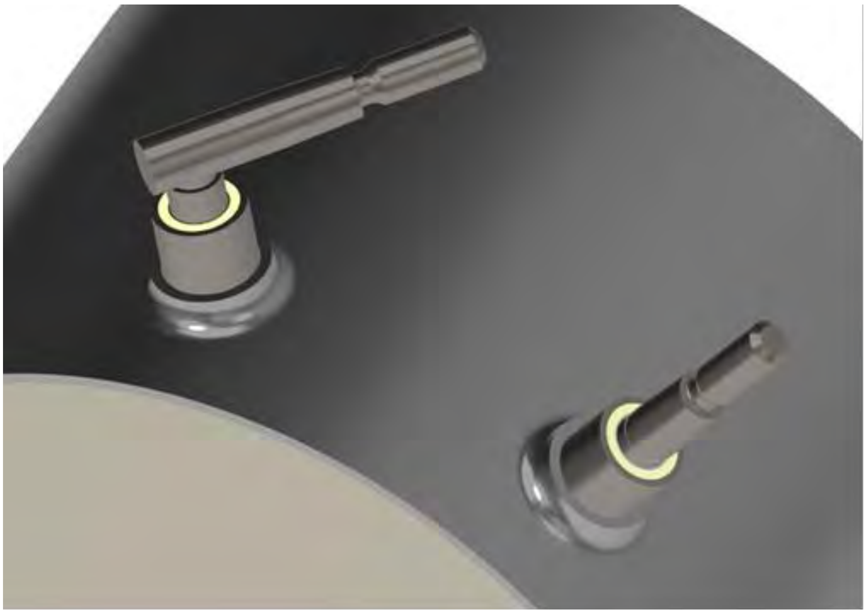


Fig. 1 Two-Pieces Electrical Connector

It is well known that in the Heavy Duty Vehicle market, there is a tendency to keep design changes to the EATS at a minimum, given the significant investment costs. The EHC can be seen as an extremely valid tool to optimize the thermal management of the entire EATS, by offering several installation positions as described in [5].

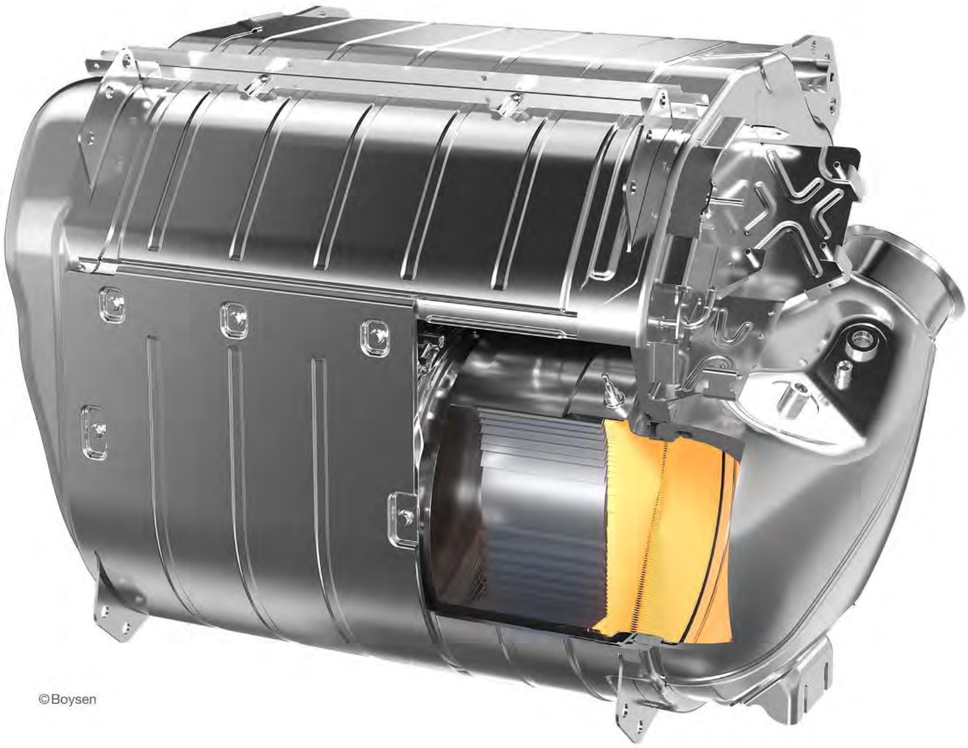


Fig. 2 Integration of into an existing silencer (source Boysen, [7])

In most cases, however, the integration of an electrically heated catalyst into an existing exhaust system is relatively easy for exhaust system manufacturers. The EHC replaces an existing catalyst volume with almost identical installation space. Only the electrical feed and cable routing needs to be adapted in addition.

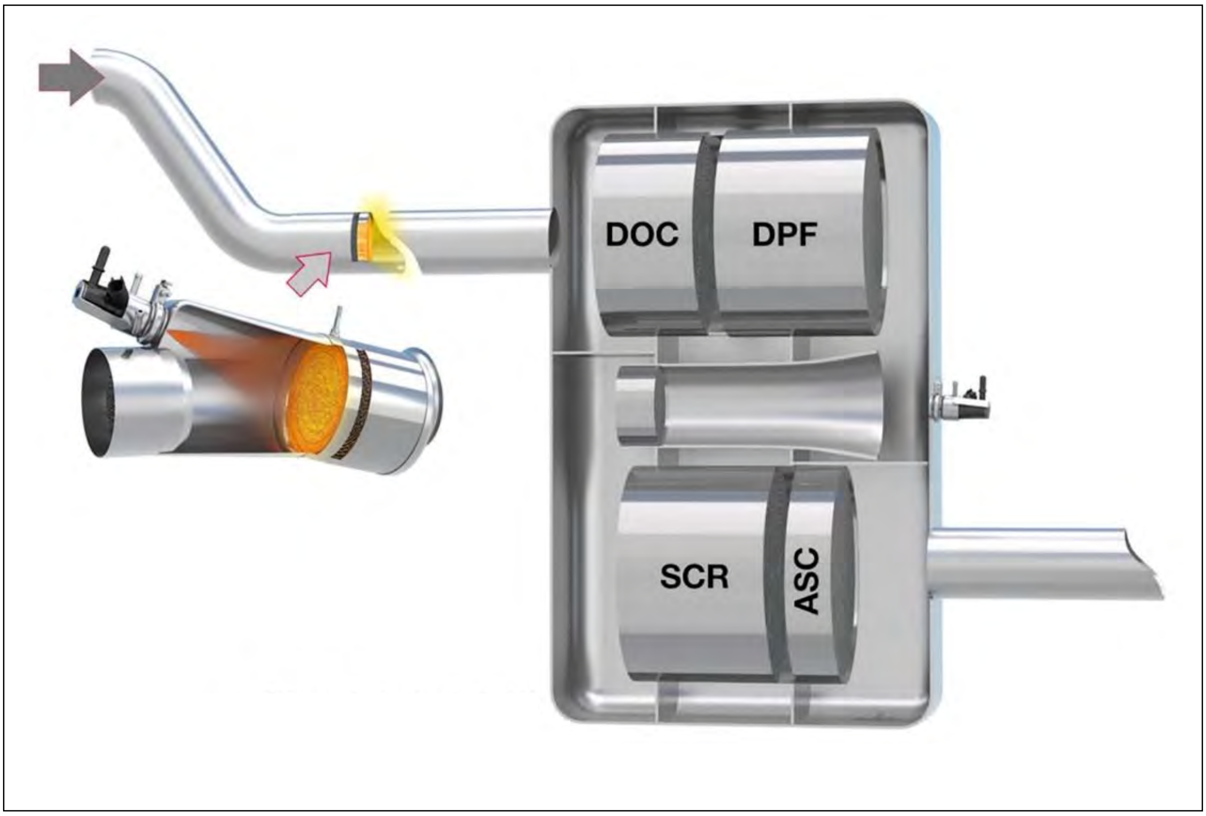


Fig. 3 EHC in front of an existing muffler

Alternatively, it is possible to position an EHC as an additional component in front of the existing exhaust system (Fig. 3). This makes it easier to optimize fuel dosing directly on the EHC – especially for cold start.

Thus, already proven exhaust systems or components can be partially reused. This reduces development and testing effort as well as tool costs for new configurations.

## 4 EHD Description

### 4.1 Basic Design - Similarities and Differences Between EHC and EHD

The Electrical Heated Catalyst (EHC) is a well-known and field-proven component and has been in serial production for several years already in different applications. The flexible design of the EHC allows a wide range of dimensions in diameter and length as well as different voltage applications from 12 to 48V. The EHC is available for an electrical power consumption from 1 to >10 kW.

The main EHC components are the heated disc, electrically isolated support pins to fix the heating disc to its surrounding components, the support catalyst matrix and electrical pins to connect the EHC to the power supply.

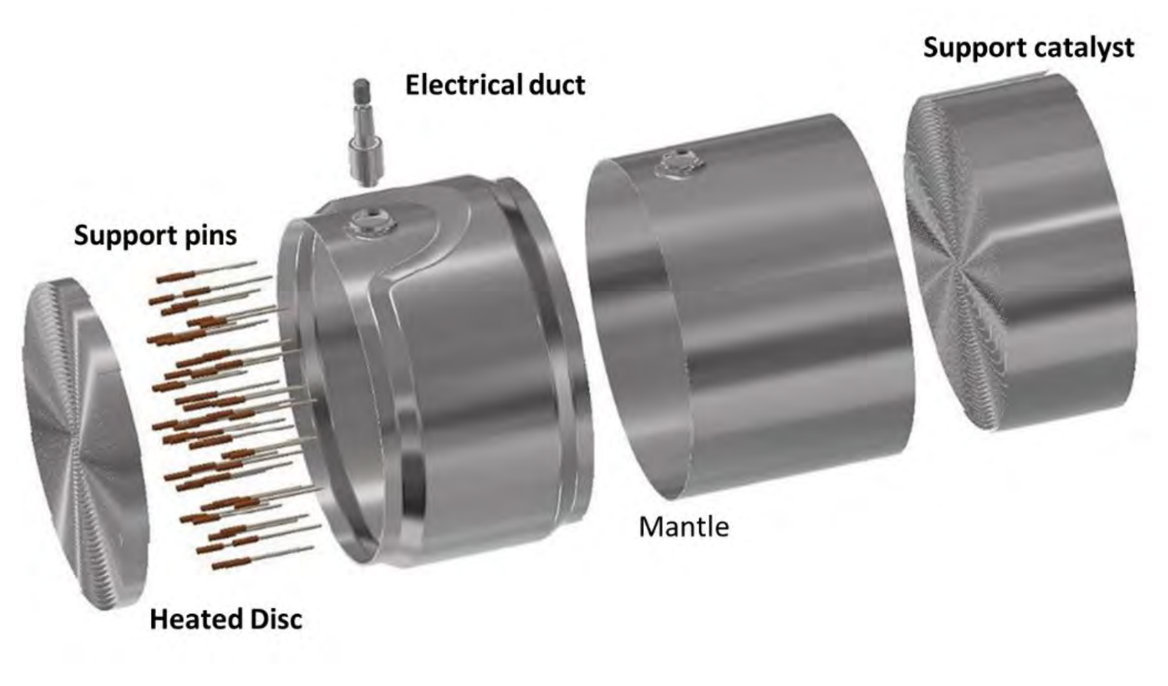


Fig. 4 Design of the electrical heated catalyst EMICAT®

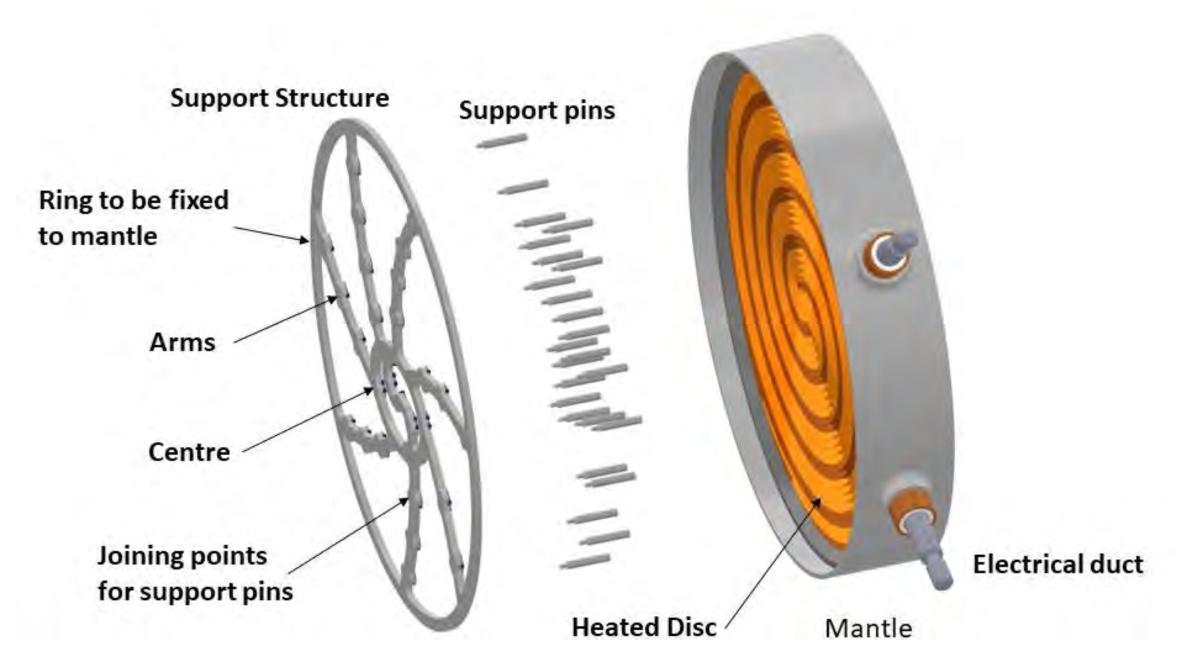


Fig. 5 Design of the Electrically Heated Disc

The EHD is a new product, based on the same field proven components as the EHC. Based on extensive voice-of-customer interviews, a new shorter heater was developed to allow flexible installation at different locations in the exhaust aftertreatment system. To achieve this, the support catalyst matrix was removed, and replaced with a stainless-steel frame, also called the support structure.

All other key components were carried over from the EHC in order to design a robust heater while keeping the number of new components to an absolute minimum.

## 4.2 Support Structure, Parameter, Design and Simulation

The support structure has the following significant design characteristics:

- Outer Ring to fix the structure to the mantel
- Regular Curved Arms which allow the needed stiffness and flexibility to compensate mechanical and thermal loads
- To connect the heated disc to the support structure via isolated support pins

Mechanical and thermal Simulations are showing that the design is not exceeding the allowed limits in terms of stress and movements.

A simulation was conducted to calculate the stress inside the heater unit under simultaneous mechanical and thermal loads. The mechanical loads were based on a PSD-Profile which is used also for the KLT (key life test) to validate the mechanical robustness. This Profile was developed over many years and is based on measurements and experiences out of different application and covers real life loads. The thermal load in this case was a steady state condition of 500 °C.

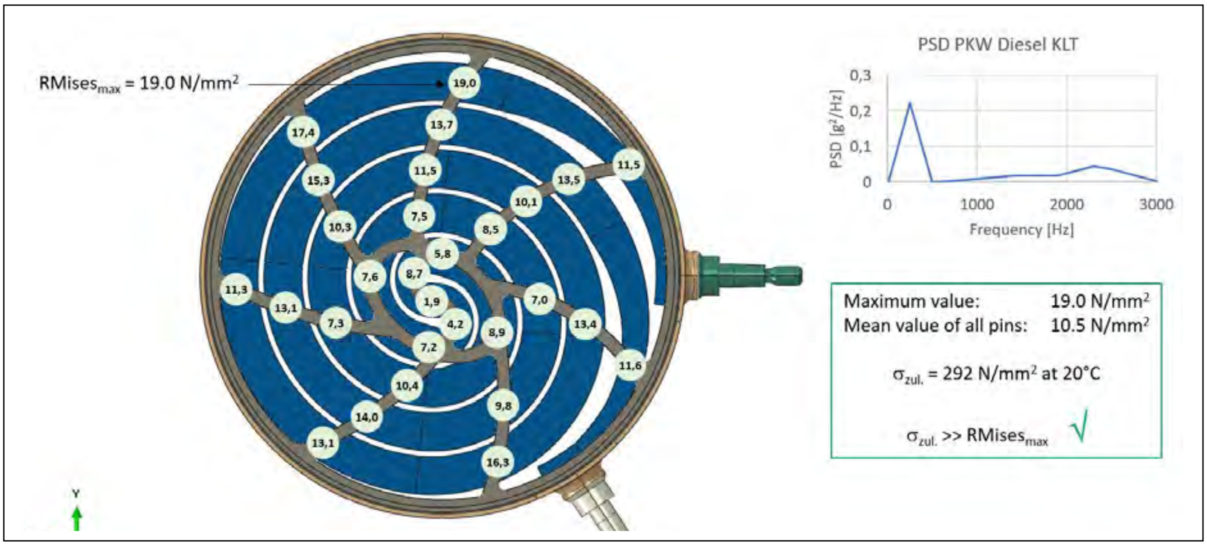


Fig. 6 Thermomechanical simulation / loads

The simulation result shows that the stress inside the components is far below the limits of the material and joining points. The green spots are showing the stress in-between the support pins and the support structure, which is the most sensitive area inside the EHD.

The excitation spectrum in the simulation was selected analogously to the generic investigations in chapter 4.4.

## 4.3 Flow Distribution, Electrical Power Map and Back Pressure

One key challenge was to develop a robust support structure that provides the lowest possible flow disturbance and allows best possible flow distribution over the heater.

The new heater design was validated on a flow bench under different flow rates with ideal inlet flow distribution. The result shows a good flow distribution measured directly behind the heater with very minimal impact of the support structure.

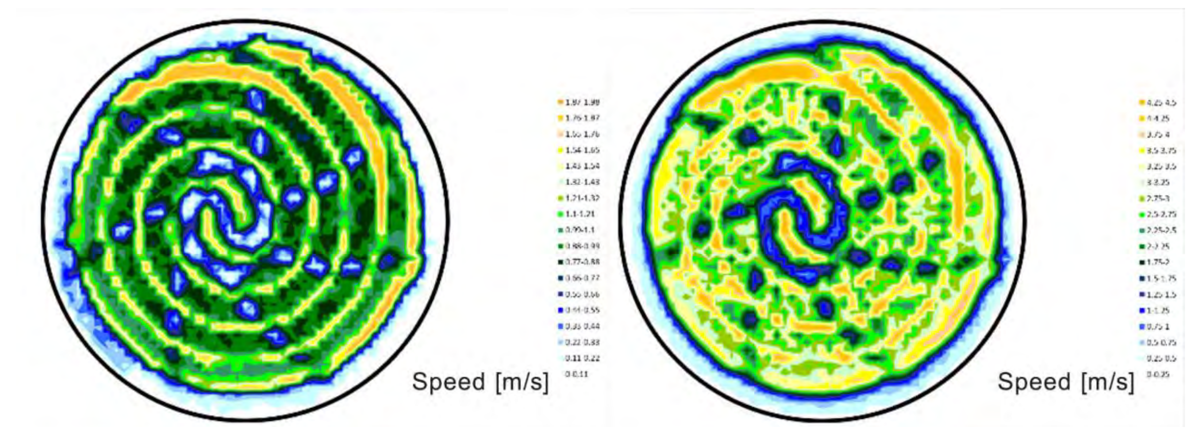


Fig. 7 Flow distribution EHD at 60 kg/h (left) and 170 kg/h (right) mass flow

Another very important design goal was quick heat up and uniform heat distribution over the heater. Infrared camera tests were conducted to evaluate the maximum electrical power that can be applied to the heater at low flow conditions, such an engine idle. The results with the newly developed EHD are shown below.

While these first results indicate a good power capability at low flow, opportunities for further improvement have been identified. An updated heating disc shape is currently being designed and tested.

Backpressure was tested on a cold flow bench under uniform inlet flow conditions. The EHD with its low-profile support structure exhibited a very low flow restriction, see results below.

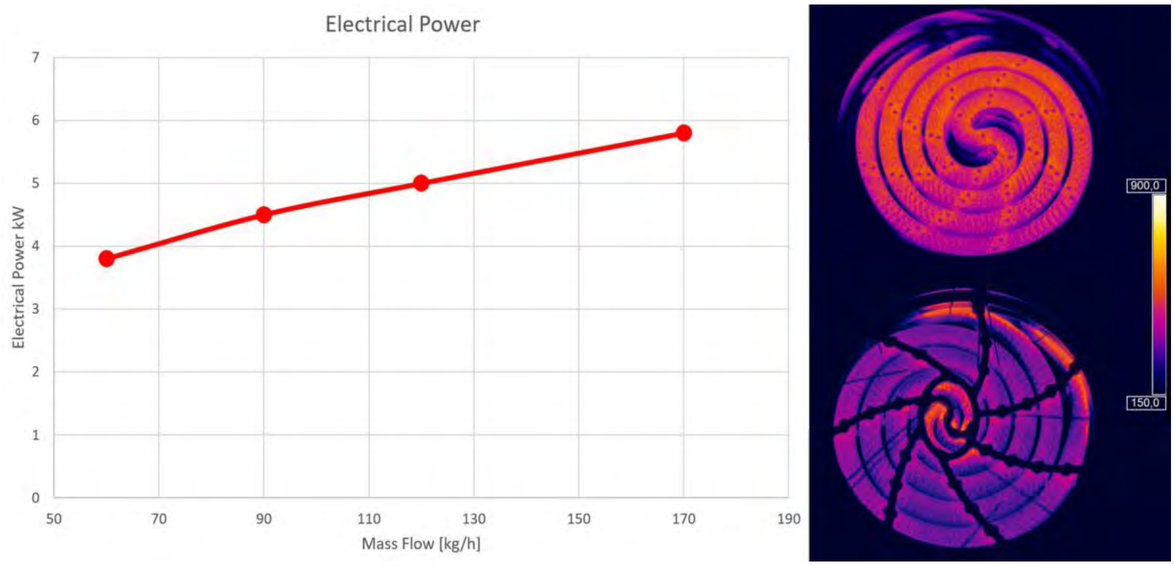


Fig. 8 Electrical power map from 60 to 170 kg/h mass flow

## 4.4 Generic Tests

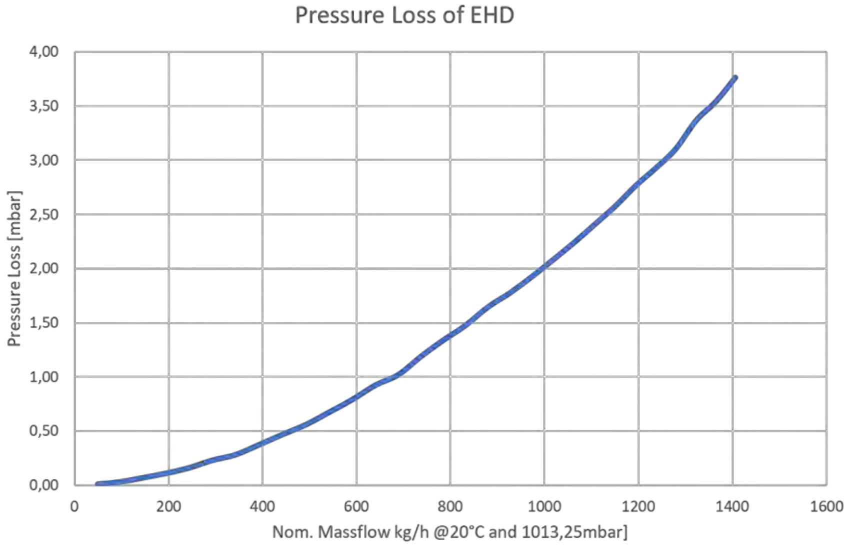


Fig. 9 Nominal pressure loss of EHD

Emitec has used two different key tests to validate the robustness of the new EHD.

The first durability test is the KLT (Key Life Test). In this test, the substrate is tested simultaneously under high mechanical and thermal load conditions.

The EHD is fixed in a specially developed rig to an electromagnetic shaker device. The test specimen is positioned under 45° to achieve a simultaneous mechanical excitation in horizontal and vertical direction. The mechanical load profile was developed over 20 years based on collected measurements and applied for generic testing. But also, customer specific profiles can be tested. In this case we tested with 11,7 gRMS PSD. The thermal load is generated by a gas burner. In this case the temperature and flow rate of the burner was kept constant (400 kg/h flow and 500°C gas inlet-temperature)

The target test duration of 100h for Heavy Duty Applications was achieved without any damage.

The second generic test is an EITC (Electrical Inner Thermal Cycle). In this test the specimen is exposed to a high number of electrical load cycles (frequent power on and off) to represent an accelerated usage cycle.

In the present EITC Test the substrate is periodically switched on and off under certain flow conditions. By switching the electrical power on the substrate is heated up and by switching off it is cooled down rapidly. This thermal shock generates a thermal stress inside the heated disc. In this specific test the EHD was heated with 5,5 kW at 60 kg/h mass low for 5,5s (achieving his max. allowed temperature) and cooled down with 170 kg/h mass flow for 12,5 s. After 60.000 cycles the test was stopped without and damage or derating in the mechanical and electrical functions.

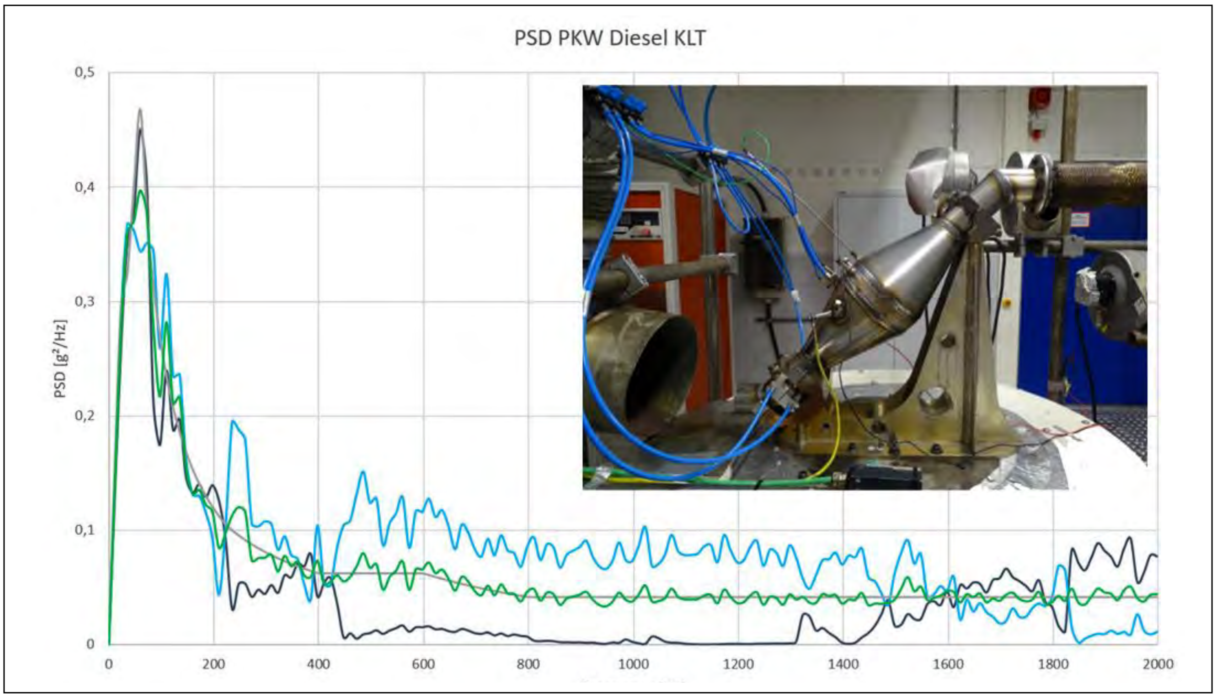


Fig. 10 KLT setup with a spectrum comparable to that in the simulation

The simulation results and test results demonstrate that the EHD is a robust design that is suitable for passenger car or heavy-duty applications. Its compact design allows flexible installation in close coupled and / or downstream position, such as turbo downpipe or muffler. The use of proven components that were carried over from the EHC make it a well suited and low risk product for implementation in the next generation of aftertreatment systems.

The high performance of the EHD, can be enhanced by installing downstream a highly efficient substrate. In the following chapter, the Cross Corrugation (CS) technology will be presented.

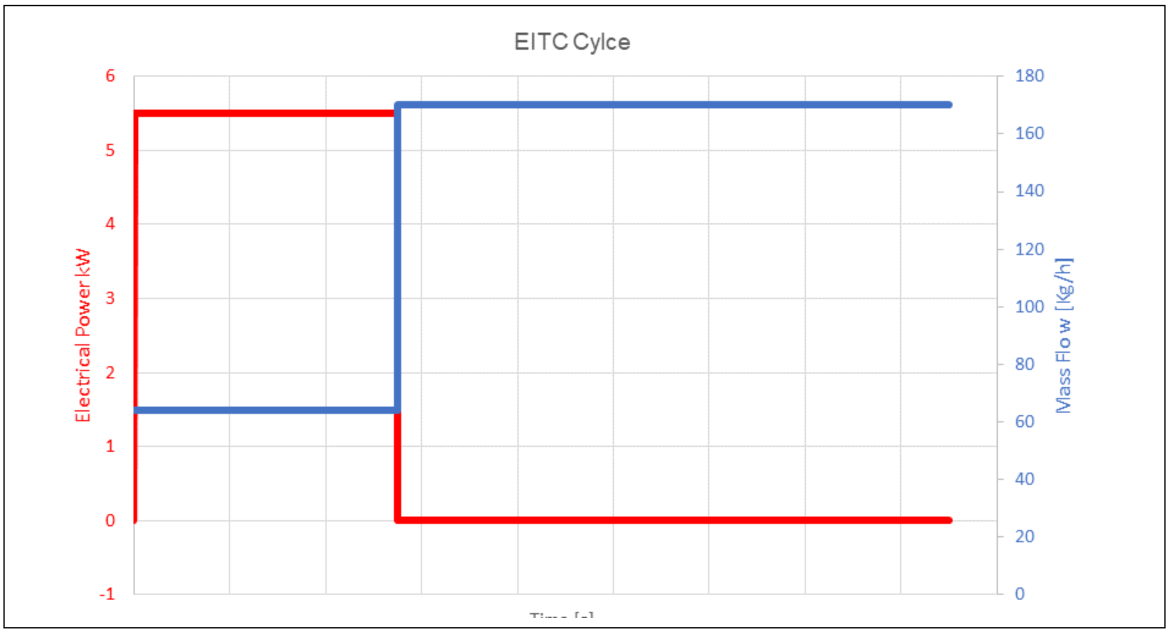


Fig. 11  EITC cycle

# 5 Cross Corrugation Description

## 5.1 Description of the Cross Corrugation Design

The Cross Corrugation (CS) Design consists of corrugated metal foils stacked one on the other, successively wound and inserted in the outer mantel. The corrugation of the CS structure is not parallel to the longitudinal axes of the mantle but has a certain angle (Figure 12). The angle is necessary to prevent the collapse of the foils once stacked, in this case it was decided to have an angle of 5°. In recent years, Emitec has successfully developed a corrugation and a brazing technology that allows the production of the CS Design for mass market [6] for passenger cars, heavy duty, and non-road mobile machinery.

One of the advantages of the CS Design is the elimination of the flat foils between corrugated foils, which is possible due to the angled channels. The deletion of the flat foils changes completely the inner structure of the metallic matrix. Usually in the metallic matrix the exhaust gas flows through channels, in the CS Design there are not real channels considering that the foils have contact points (Figure 12). For this reason, the exhaust gas is not forced to flow through a single channel in axial direction but can flow also in the radial direction.

Another interesting point is the wash coat distribution, once the matrix has been coated. In standard substrates, in the areas near the contact lines between flat and corrugated foils the wash coat is usually not well distributed, the same applies also for ceramic substrates. In the CS Design, these areas are not present, and the wash coat can be evenly distributed on almost the entire surface. Moreover, the deletion of the flat foils increases the usable surface and decreases the matrix weight.

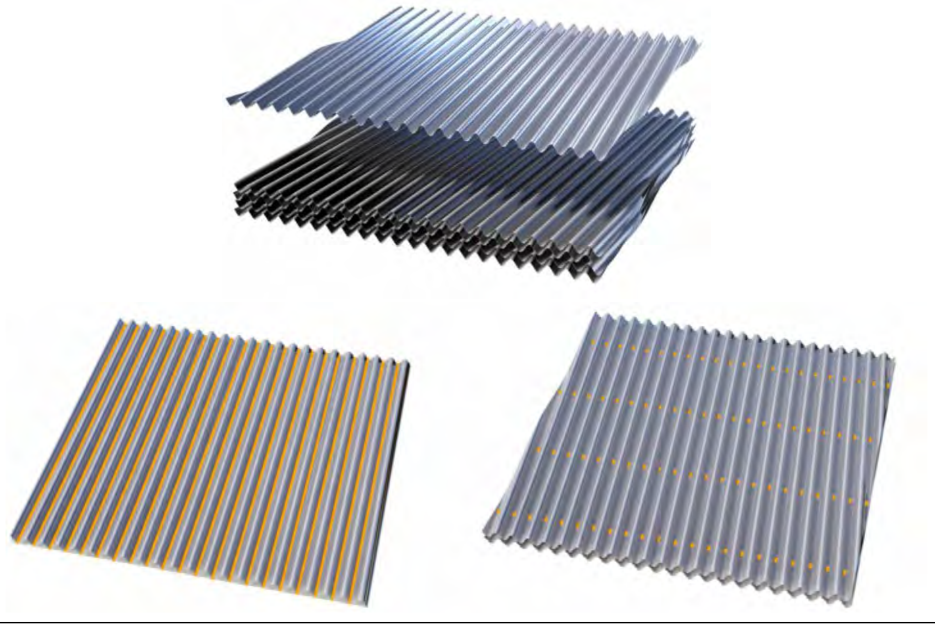


Fig. 12 Cross corrugation (CS-Design) Representation of the contact surface (standard on the left / cross corrugation on the right)

## 5.2 Physical Characteristics

A typical EU6 substrate has been compared with an advanced EU7 substrate with CS Design. The dimension of the outer mantel has been kept constant while the foil thickness has been reduced from 40 microns for the baseline EU6 substrate to 30 microns for the CS Design and the matrix length has been increased from originally 74,5mm to 90mm. The baseline substrate has a cell density of 600 cpsi using the well-known PE Foils, the CS Design has a cell density of 1.000 cpsi.

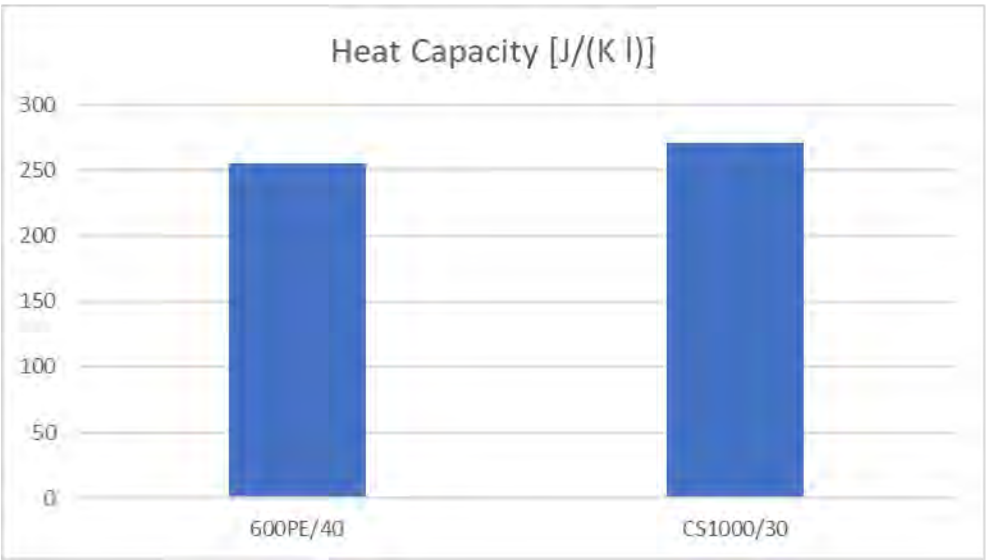


Figure 13 shows the thermal mass of the PE and CS Substrate.

Fig. 13 Substrate thermal mass, uncoated

On the other hand, the CS Design has a much higher Geometrical Surface Area (GSA), as shown in Figure 14.

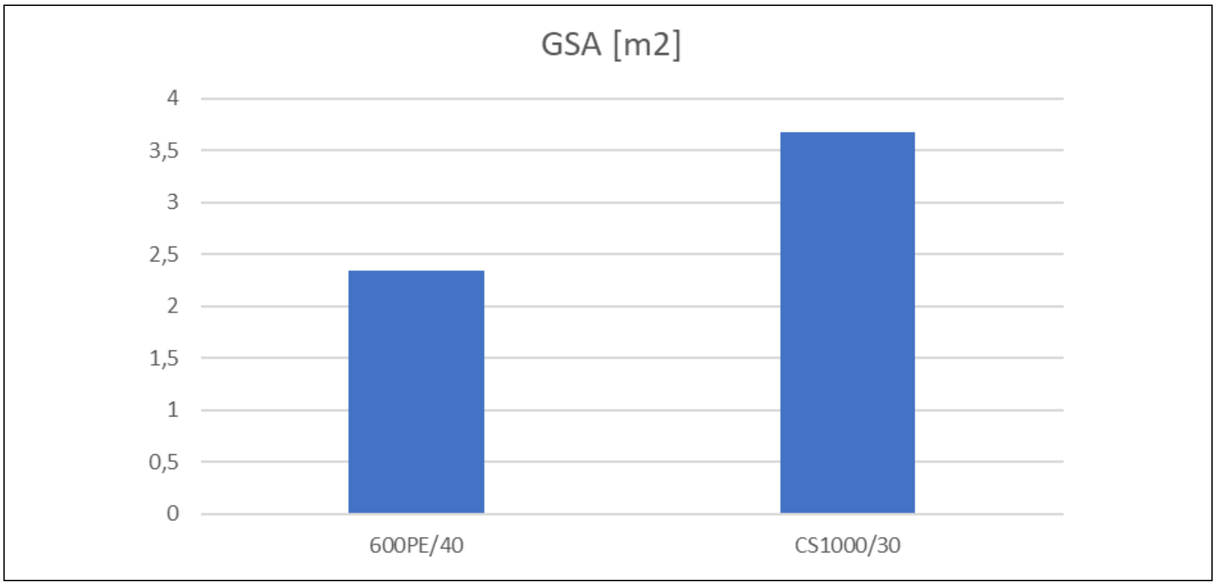


Fig. 14 Geometrical surface area, uncoated

In the following chapter the results of the emission measurement will be investigated, to better understand the influence of thermal mass and GSA during cold start, using the above presented substrates.

## 5.3 Emission Results Gasoline

The emission measurements were performed on a Jeep Renegade (gasoline engine 4 cylinders, turbocharged) on the chassis dynamometer. It is a 48“four-wheel chassis dyno with a maximal velocity of 250 km/h, maximal permanent power of 153 kW (and maximal power for 10 s of 258 kW). It is equipped with a climatic chamber that allows to perform measurements in a temperature range from - 20 °C up to + 35 °C. This makes it possible to perform Real Driving Emission measurements also under extreme temperatures.

Exhaust emissions can be measured with devices both for diesel and gasoline vehicles: HORIBA Mexa-7400 and Mexa-7500 (for measuring CO, $CO_2$, $O_2$, HC, $NO_X$) and HORIBA PMU 7000 and full flow dilution system (for measuring the particle mass). In addition to that there are several stand-alone measuring devices available that can be used when needed: AVL Sesam FTIR (simultaneous measurement up to 20 components like CO, $CO_2$, NO, $NO_2$, $N_2O$, $H_2O$, $NH_3$, $SO_2$, $CH_4$, etc.; some of these FTIR devices with two additional analyzers for the measurement of THC and $O_2$), HORIBA Mexa-1400QCL-NX (simultaneous single measurement with Quantum Cascade Lasers for NO, $NO_2$, $N_2O$ and $NH_3$), particle counting systems AVL APC 489 and HORIBA SPCS 2100, AVL Micro Soot Sensor 483 with diluter, Particle size distribution measuring device Cambustion DMS 500 and partial flow dilution systems Control System PSS20.

Emission measurements were performed with different driving cycles: RDE City Cycle and RDE Falkenstein. In both cases the tests were carried out at 0° and -7 ° C. The RDE City Cycle (Figure 15) is a real driving emission cycle simulating the driving conditions in a city, whereas the RDE Falkenstein (Figure 16) is a real driving emission cycle simulating the driving conditions in a country road.

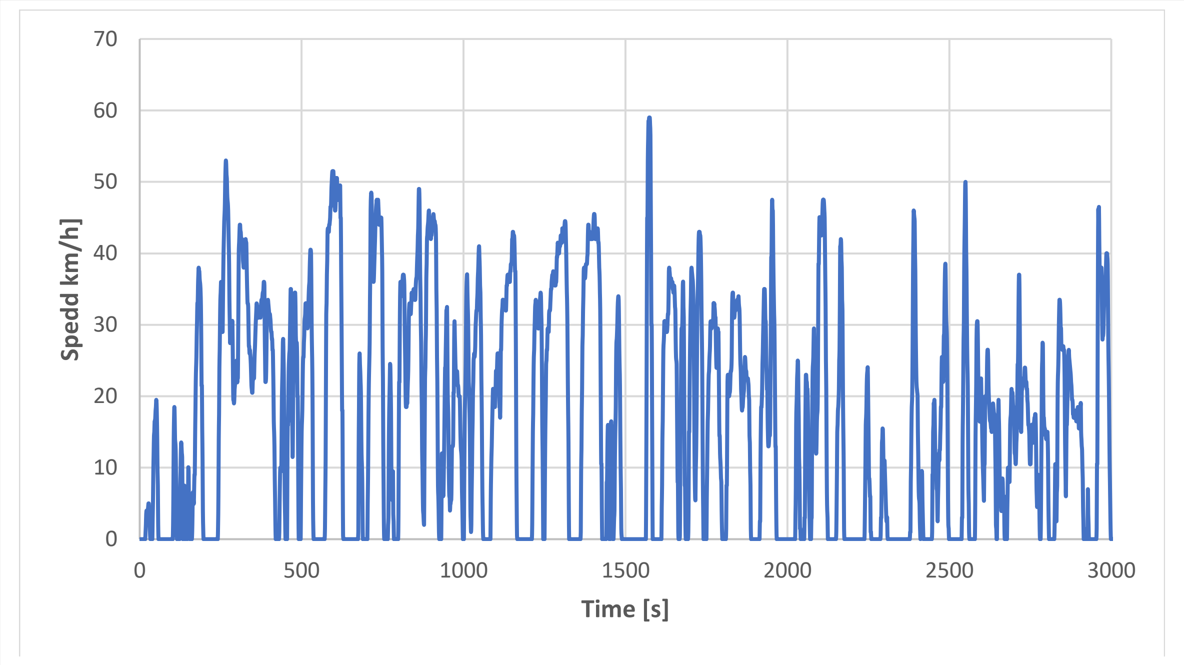


Fig. 15 RDE city cycle

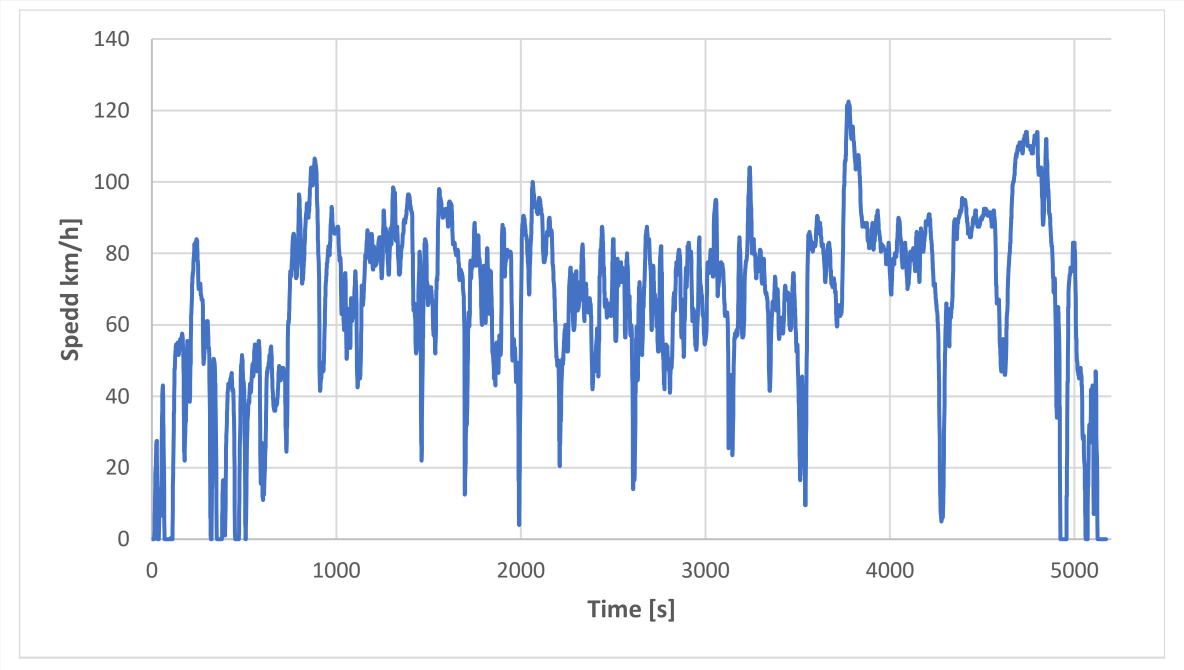


Fig. 16 Falkenstein cycle

Both EU6 and EU7 substrates has been coated with the same coating technology and PGM amount. Both were also hydrothermal aged (10h @ 1050° C in 0,3 m³ air with 10%-vol. steam).

The Tailpipe Emission of the baseline (600PE) has been taken always as 100% in the following figures.

The CS Design has a very high efficiency compared to the baseline, particularly for HC (Figure 17) and NOx (Figure 18) Tailpipe emissions, while both designs have very similar CO Tailpipe Emissions.

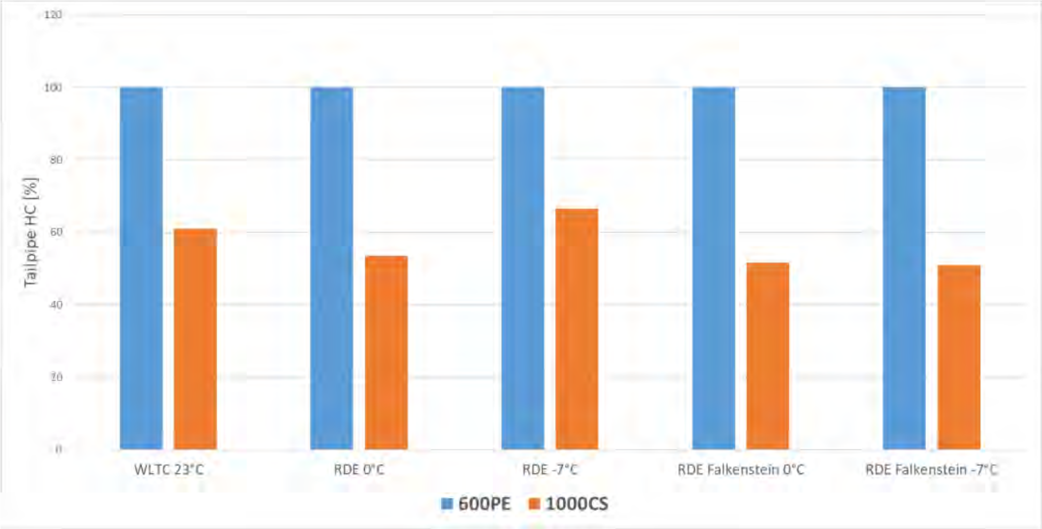


Fig. 17 HC tailpipe emissions

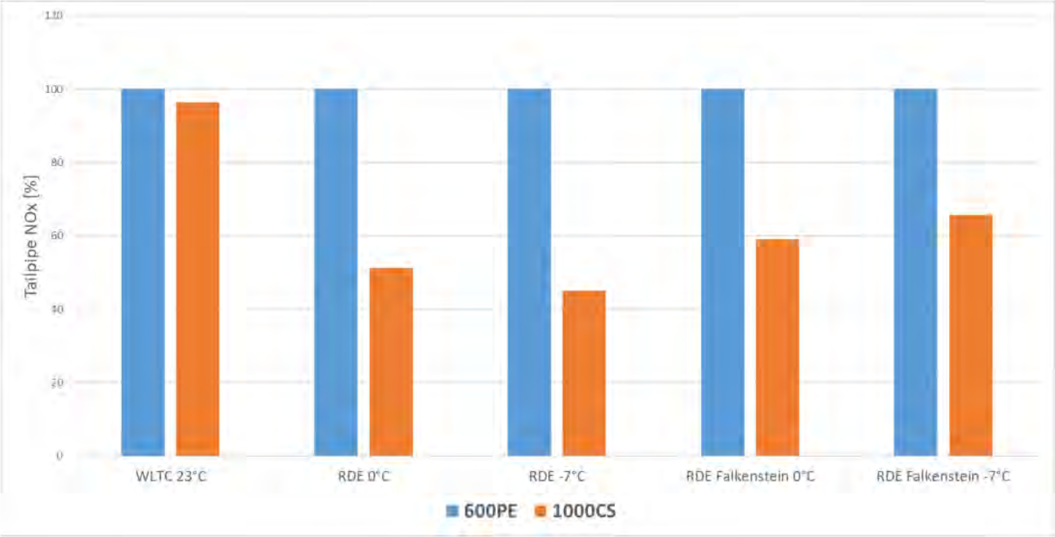


Fig. 18 NOx tailpipe emissions

The faster light-off of the CS1000 design is the reason of the lower HC and $NO_X$ tailpipe emissions (Figure 17, 18). Even if the 1000CS has a slightly higher thermal mass compared to the 600PE (Figure 13), it can reach the full light-off conditions (Figure 19) earlier than the 600PE, confirming not only the positive influence of the GSA on the light-off behavior, but also the benefit of radial flow conditions within the CS structure.

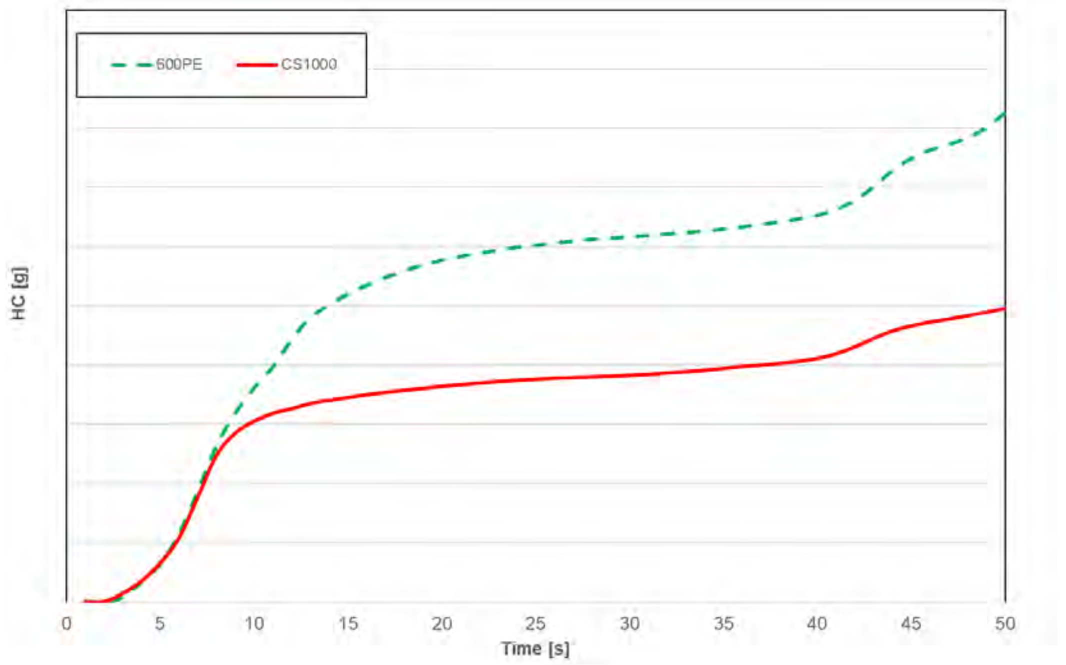


Fig. 19 HC tailpipe emissions during the first 50 sec. of the -7 °C city cycle (arbitrary units)

# 6 EHD Emission Results

## 6.1 Results on Engine

A test program on a 4 Cylinder EU6 Gasoline engine has been carried out to better understand the possible improvement of the exhaust aftertreatment efficiency using the EHD (Figure 20) in combination with a ceramic substrate. The serial production engine with serial calibration has been fitted on a test bench, and the only change that has been made to the stock catalytic converter (600 cpsi / 2,5 mil) is the welding of two flanges to allow the integration of the EHD (Figure 20).

Fig. 20 The close coupled exhaust aftertreatment with (from left to right) the mounted EHD and the original catalytical converter. It is possible to see also the flanges for the EHD mounting.

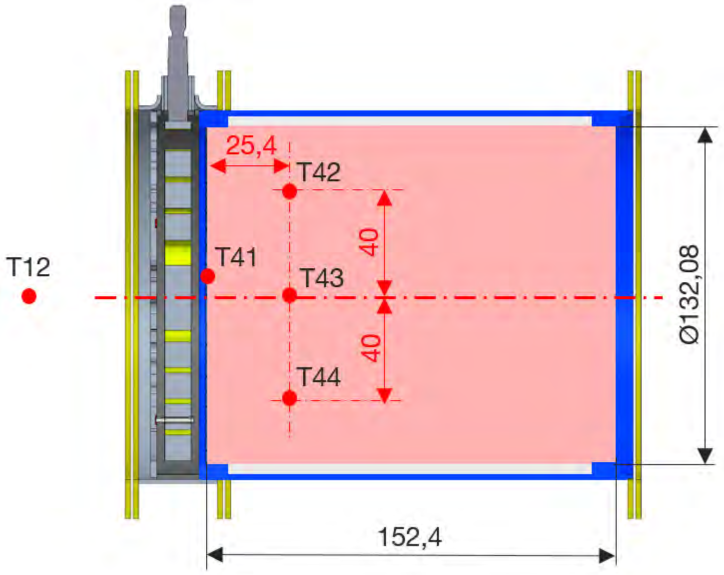


Fig. 21 Position of the Thermocouples in the close couple catalyst

The catalytical converter has been equipped with thermocouples to investigate the effect of the active heating (Figure 21).

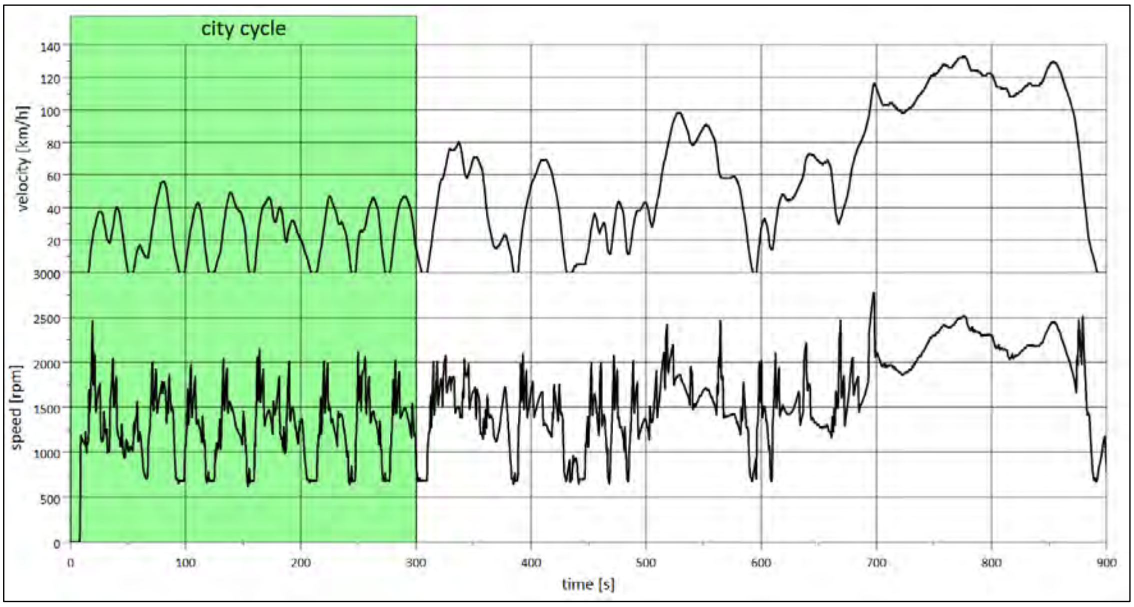


Fig. 22 Test cycle RDE city cycle

The first thermocouple (T12) is directly mounted in front of the EHD, behind the turbocharger. The second thermocouple (T41) is mounted directly behind the EHD following the gas flow. This thermocouple will be also used to control the active heating. One inch in the catalytical converter three thermocouples have been placed, one (T43) in the middle axis of the converter, two (T42, T43) at a radius of 40 mm.

Considering the very quick increase of exhaust gas temperature during cols start on a modern gasoline engine, the use of EHD can bring some improvement only during low load phases. For this reason, the first 300 seconds of a RDE City Cycle has been considered for the emission measurement (Figure 22).

Following test has been measured:

1. Serial system without the EHD (Baseline).

2. Serial system with EHD, heating strategy: 6 kW from engine cranking, turn off the EHD when one of the T42, T43, T44 thermocouples has reached 400°C. (Same strategy also for test 3).

3. Serial system with EHD, heating strategy: 6 kW starting 5 seconds before engine cranking until the temperature has reached the limits described in test 2.

4. Serial system with EHD, heating strategy: 6 kW starting 8 seconds before engine cranking until the temperature has reached the limits described in test 2, then keep heating with a reduced power of 3 kW form max. 20 seconds after engine cranking.

During the preheating phases, secondary air has been introduced in the inlet cone to increase the heat transfer from the EHD to the catalytical converter. The mass flow of the secondary air is 35 kg/h. The secondary air introduction is stopped as soon as the engine is started.

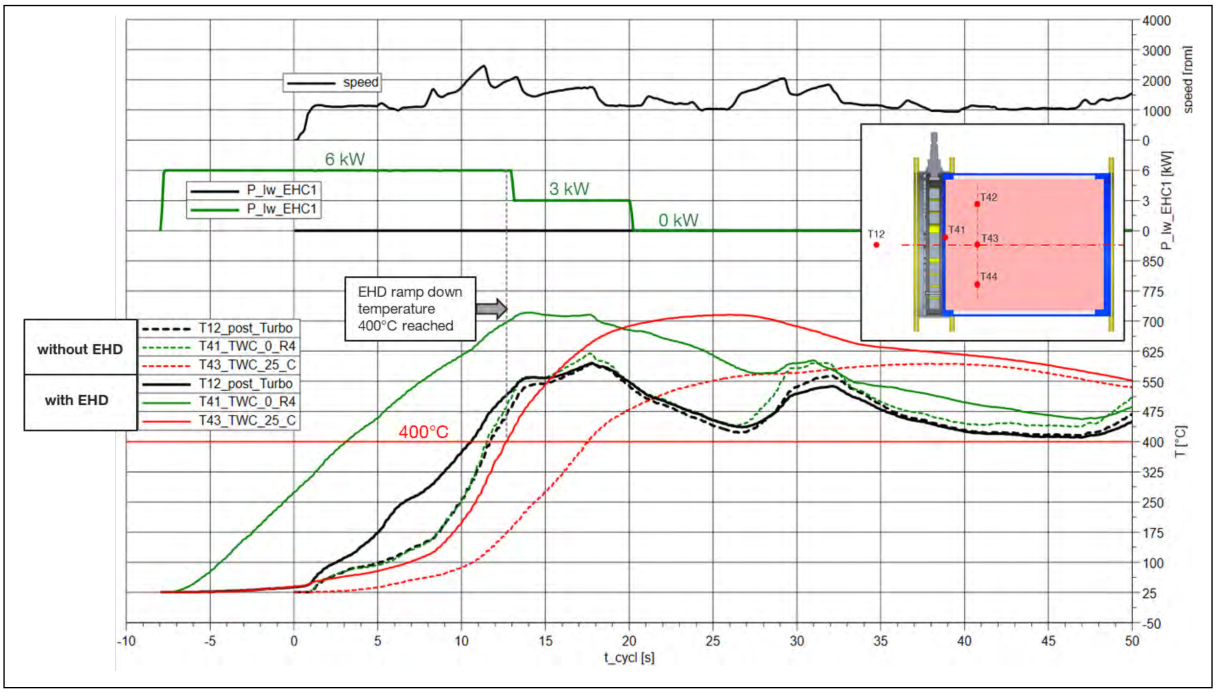


Fig. 23 Test 1 (without EHD) and Test 4 (with EHD), Temperature during the first 50 seconds

The Figure 23 shows a comparison between the temperatures during the test 1 (without EHD) and Test 4 (with EHD; heating strategy reported in the figure). The increase of the T12 temperature is mainly due to heat radiation and should not be considered. More interesting is for sure the increase of the temperatures in position T41: the serial system reaches 400°C 12 seconds after engine start, while the system with EHD reaches the same temperature just 3 seconds after engine start. The same comparison for T43 shows 5 seconds quicker heating to 400°C for the system with EHD. It is also interesting to see how the use of the EHD has a positive influence on the temperature distribution: T42, T43 and T44 are very close in case of Test 4 while more "dispersed" in Test 1.

The emission results are showed in the following figures. The system with EHD can reach an improvement in $NO_X$ of 49% (Figure 24) and 31% of HC (Figure 25) during Test 4 compared with the baseline (Test 1).

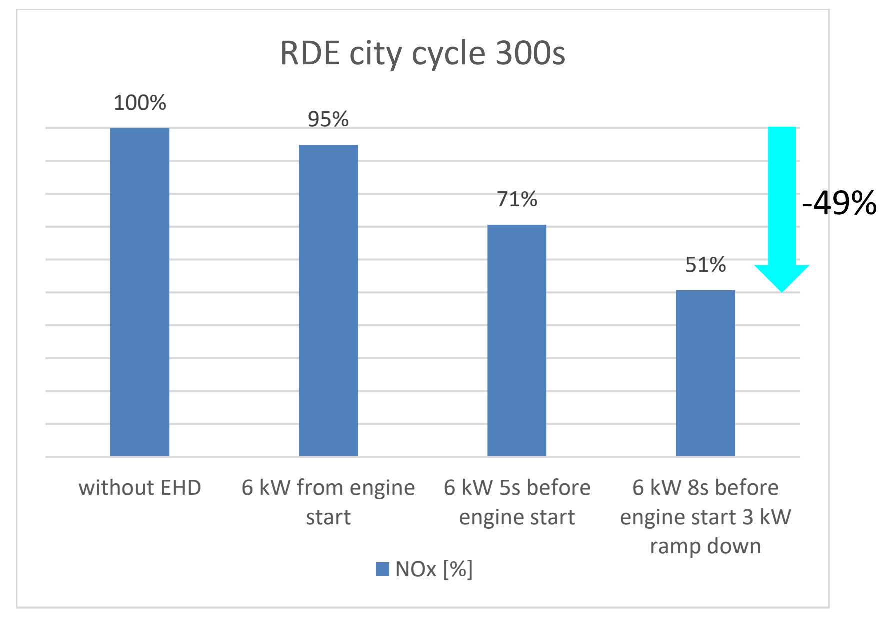


Fig. 24 Measured $NO_X$ -Reduction

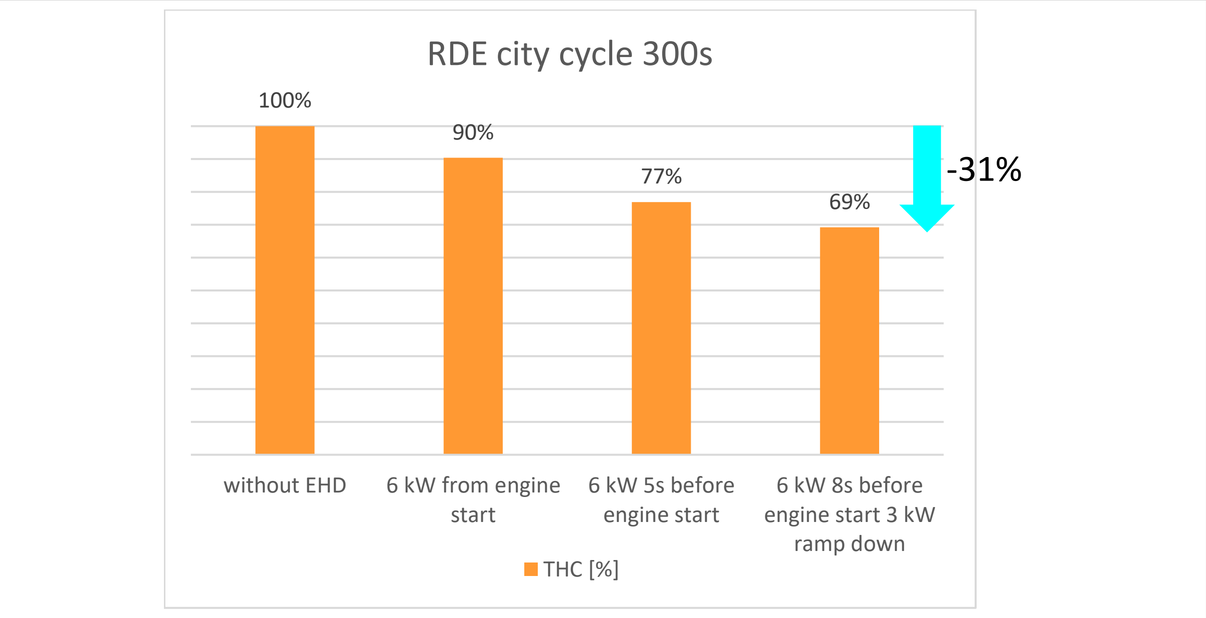


Fig. 25 Measured THC-Reduction

## 6.2 Commercial vehicle applications

To meet future emissions legislations, Commercial Vehicles require more refined thermal management strategies to move the selective catalytic reduction catalyst into the most efficient temperature range while minimizing $CO_2$ impact under cold start conditions as well as in low load operation. Previous studies have investigated possible solutions for heavy-duty engine and aftertreatment systems, and one likely scenario is a Light-Off SCR (LO-SCR) system followed by a primary Aftertreatment System (ATS) which includes a diesel particulate filter (DPF) and main SCR catalysts [1][2].

The primary ATS ideally uses current and proven technologies to take advantage of the extensive experience of engine manufacturers with respect to aging, diagnostics, calibration, and application and to minimize the risks that are normally associated with the addition of new technology. The LO-SCR is placed as close as possible to the turbo outlet to minimize temperature losses. To introduce auxiliary heat into the ATS, a small electrical heater could be placed upstream of the LO-SCR, or a large diameter electrical heater could be placed upstream of the main SCR catalysts, see Figure 26.

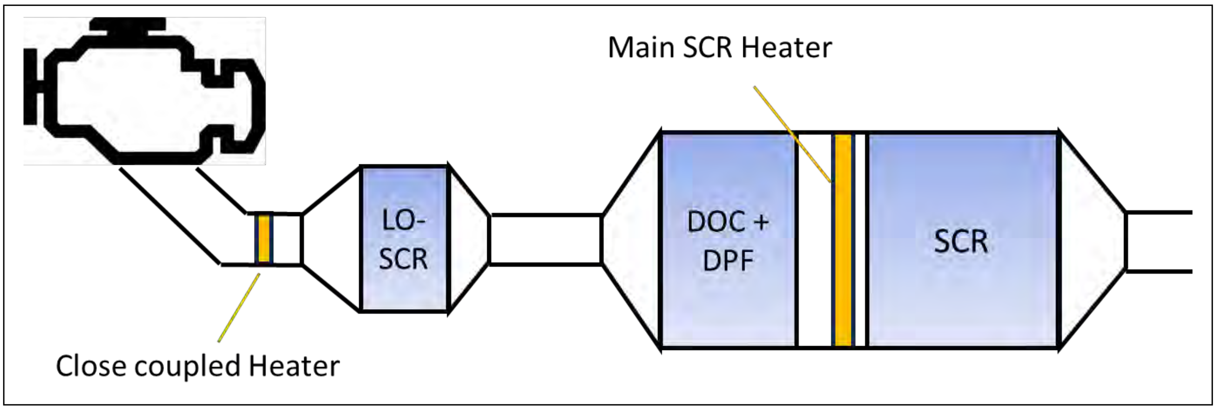


Fig. 26 Possible locations for an electrical heater in a 2027 HD engine ATS

A simulation was carried out to investigate the heat up benefits of either position for an exhaust heater for a particular low load engine start. For this study, a small 6 inch (150 mm) diameter heater was compared with a typical large 13 inch (324mm) diameter heater. The results in Figure 27 show the benefit with a smaller diameter heater - the gas outlet temperature downstream of the heater is increased quicker than with the large diameter heater. For the given conditions used in this simulation, a SCR dosing release as early as 30 seconds after engine start could be considered possible, if a LO-SCR was to be installed directly downstream of the small heater.

This simulation result is in line with other studies, who have carefully weighed the emissions benefits and the impact on fuel penalty or $CO_2$ emissions, and who concluded that the addition of a small electrical heater in close coupled position, upstream of the LO-SCR, yields better results [3][4].

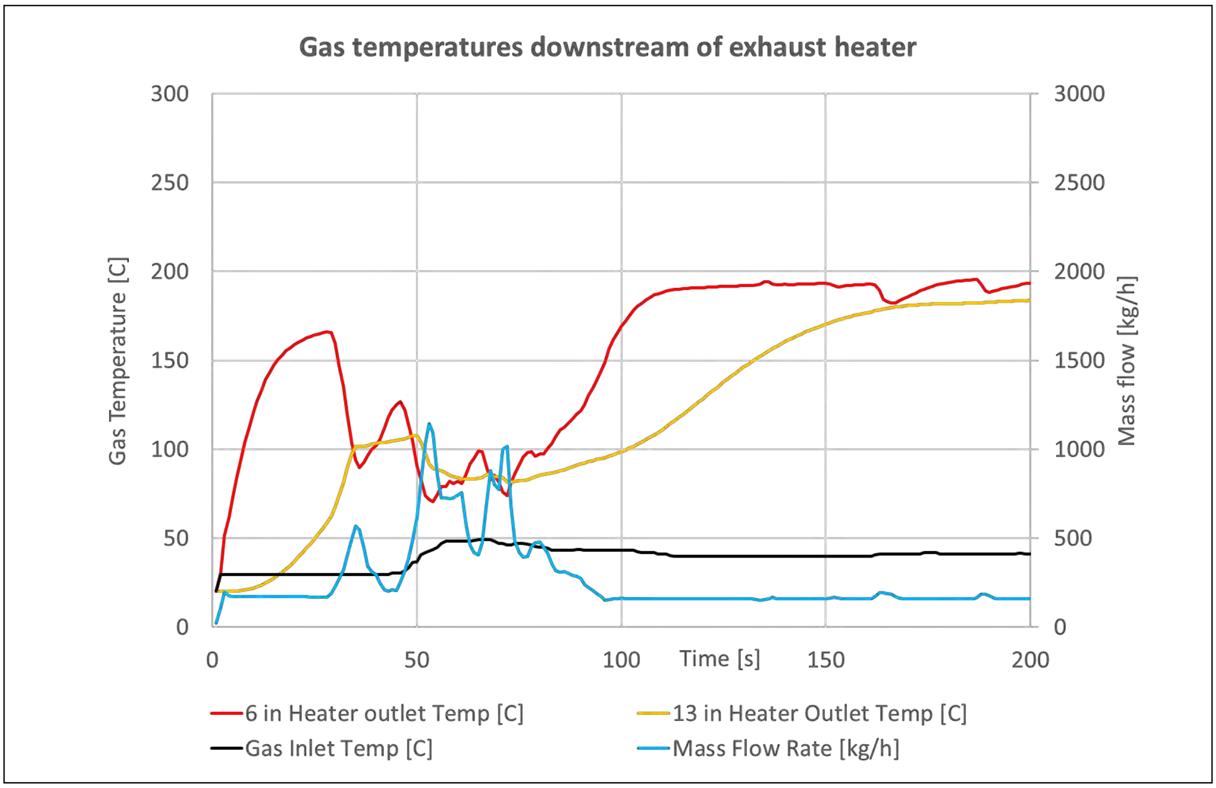


Fig. 27 Heat-up efficiency of a Small vs. Large diameter EHD

In preparation for upcoming engine dynamometer and emissions tests, an electrical heater (EHD) capable of achieving 10 kW at 48V was designed and built. A heater diameter of 6 inch (150mm) was chosen, as it represents the typical exhaust pipe diameter between turbo outlet and main ATS of a current HD diesel engine.

In a typical automotive application, the exhaust heater shall be powered only when the engine is running and exhaust gas flow is present, to prevent overheating. A constant supply of exhaust flow is needed to withdraw the heat generated in the heater matrix, away from the heater surface and into the exhaust gas. Due to its extremely low thermal mass, the EHD is expected to exhibit a very rapid heat up when powered without gas flow or even under low flow conditions.

A first functional test was developed to demonstrate the functionality and confirm the fast heat up behaviour of this heater. The EHD was placed on concrete ground and powered by a large battery pack with 48V. Power to the heater was cut off manually as soon as the matrix was visibly glowing. Figure 28 shows the test result - as expected, the EHD exhibited a rapid heat up and was found to be glowing red hot within 4 seconds, at which power was shut off.

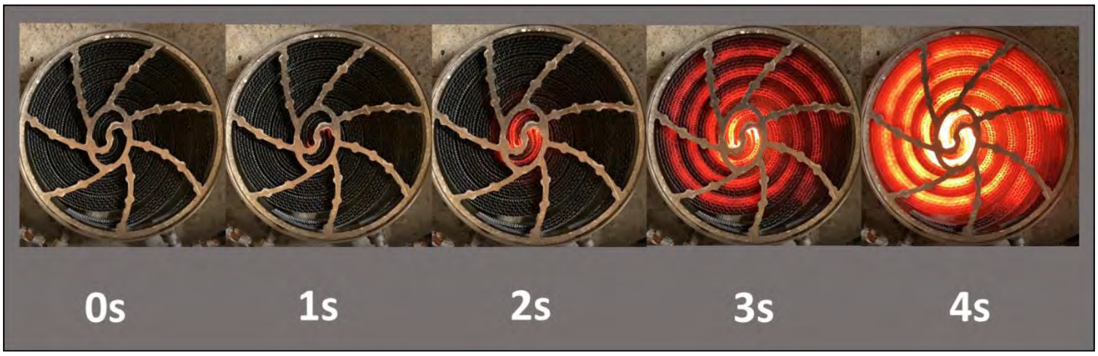


Fig. 28  Heat-up test of a 6 inch EHD

While this test may not be representative for an EHD installed in an exhaust pipe, it still demonstrates the ultra-fast heat up behaviour of this device. This fast thermal management can enable the ATS to reach sufficient catalyst temperatures or an early Urea dosing release threshold in the shortest possible time, while reducing the amount of fuel and electrical power needed.

Further tests on an engine dynamometer and the effect on emissions reduction are scheduled in the coming months.

## 7 Conclusion

It is well accepted that ICE powertrains will continue to serve both individual and commercial mobility for decades. The expected boundary conditions of the EU7 package will have a focus on RDE and cold start operating phase, consequently posing a significant challenge on operating efficiency of the EATS. The commonly accepted technological path consists of active thermal management by means of local electrical heating elements.

This paper introduces for the first time Emitec’s innovative EHD as a valid alternative to the well known EHC.

In particular, the EHD can play an important role in applications with critical layout conditions and in all cases where any change of the vehicle architecture or its EATS package have to be avoided for cost and timing reasons.

It has been shown that the development of the EHD significantly benefits of the long year experience gained with decades of application of the EHC. Furthermore, the extremely rapid thermal heating of the EHD has been demonstrated by means of experimental testing both on component test bench as well as chassis dyno bench.

Additionally, emission tests performed on a gasoline passenger car vehicle have proven the superior performance of Emitec’s metallic substrate with CS-Design.

## 8 References

[1] C. Webb, P. Stephenson, M. Meijer, A. Coumans, R. Brueck, J. Kramer
Future Regulatory Technology Options to Reduce Risk in Application for Heavy-Duty Diesel Engines
30th Aachen Colloquium Sustainable Mobility 2021

[2] B. Zavala, J. McCarthy Jr., A. Matheaus, C. Sharp
Fast Diesel Aftertreatment Heat-Up Using CDA and an Electrical Heater between 1.2 and 5.0kW
Frontiers in Mechanical Engineering, July 25, 2022

[3] P. Meruva, A. Matheaus, C. Sharp, J. McCarthy Jr, T. Collins, A. Joshi
Meeting future $NO_X$ emissions using an electric heater in an advanced aftertreatment system
Frontiers in Mechanical Engineering, September 6, 2022

[4] J. McCarthy
Pathways to Heavy Duty Zero-Emissions
Vehicle Efficiency, Electrification and Emissions conference, May 3, 2023

[5] Holz, O., Presti, M.; Mosch, T.; Dachsel, J.; Rodatz, P.; Fink, F.; Nienhoff, M.: Heavy Duty Exhaust Systems for Low NOx Application: Thermal Management and Control, ATZ Live Heavy-Duty-, On- und Off-Highway-Motoren 2020

[6] Presti, M., Pace, L., Mattei, M., 2019.: Innovative motornahe Platzierung eines DOC mit Metallsubstrat in CS Design: Integration in die SDF-FARMotion-Motoren der Stufe V. In: Emission Control. Dresden, 2019.

[7] Brück, R.; Presti, M.; Keck, M.; Dengler, J.; Faiß, M.: Thermal Management on Demand; the Exhaust Aftertreatment Solution for Future Heavy Duty Application, ATZ Live international 8th engine congress 2021