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Innovative Metallic Substrates for Exhaust Emission Challenges for Gasoline and Diesel Engines

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ABSTRACT

Increasingly stricter emission standards for gasoline and diesel engines accelerated the exhaust aftertreatment industry to develop high efficiency catalysts with innovative substrates. Engineers face thermodynamic and thermal management challenges to achieve system emission, noise and back pressure targets at minimum costs.

This paper describes advanced substrate technology for exhaust after treatment systems for gasoline and diesel engines. The first part focuses on substrate technology solutions including high cell density substrates and advanced metallic substrates with structured and perforated foil material. This new substrate technology offers great potential to optimize the overall system efficiency through exhaust mixing within the catalyst at minimum back pressure.

Transient temperature condition and available packaging space will have remarkable impact on system design and catalyst performance for future advanced combustion engines and hybrid vehicles.

INTRODUCTION

Engine manufactures have made tremendous effort to develop very efficient high power combustion engines. Engineers focus on weight-optimized high power engines to satisfy customer wishes. However, the vehicle mileage accumulation climbed extremely high in the last decade resulting in more exhaust pollutants. The engine out emissions were reduced through improved combustion technology and lower fuel consumption. Additionally more stringent exhaust emission standards were imposed. While the Tier 1standard focused on the reduction of hydrocarbons further reduction of NOx emission is needed for Tier 2 certification.

The exhaust emission industry developed advanced catalyst technologies to overcome the extreme after treatment challenges to ensure the catalyst performance over longer vehicle life.

The technical and commercial challenges include

low cost
compact converter architecture in close coupled position
fast heat up and heat through with quick close loop engine operation
achieve packaging and thermal management goals
feasible for OBD monitoring
target low flow restriction to ensure high power output
long mechanical and thermal durability
achieve NVH requirements
low weight

Engine manufactures were able to develop close coupled converters taking advantage of higher exhaust gas temperature during engine cold start. However, the thermo chemical advantage of moving the catalyst close to the manifold resulted in design restrictions in terms of converter diameter, length influencing the back pressure, and also inlet flow conditions for the catalyst.

Through higher processor speed in the ECU it is possible to control cylinder AFR with fast closed loop control. The aftertreatment industry has developed on one side substrates with higher cell density and extreme thin wall thickness to manage the light-off performance while keeping back pressure on an acceptable level. On the other side cascaded converter systems with small light-off converters are used taking advantage of high thermal energy density to achieve fast heat up and therefore quick catalyst light-off. The 2007 NOx emission targets and the required OBDII monitoring require new catalyst concepts with either mid bed sensor application or integrated lambda sensor solutions. Moreover, thermal management of catalyst in hybrid applications is a new parameter for the catalytic converter layout.

THE TRADITIONAL CATALYST CONSTRUCTION

Conventional substrates are constructed with parallel channels and efficiency is dominated by the mass transfer coefficient in hot operation. This coefficient represents the probability of pollutants to interact with the catalyst surface. At the entrance of a channel the concentration in the gas is uniform and the conversion high. Further downstream of the channel the flow is developed from a turbulent-like flow regime to a laminar flow regime and the mass transfer limits the reaction.

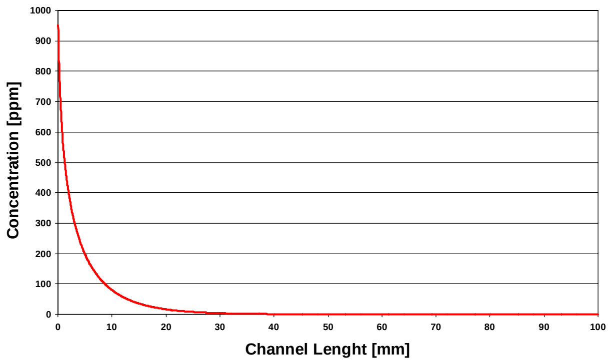

Figure 1: Calculated Conversion as a function of channel length

Also decreasing the channel size by increasing the substrate cell density increase the mass transfer coefficient. The industry takes advantage of higher cell density substrate technology to build more cost effective fast light-off converter systems [1,2,3].

In an experiment the converter volume was reduced from a reference 500cpsi design to a 900cpsi system. The substrates were zone coated with a Pd-only loading on the front half and the rear half applied with a Pt/Rh loading. All parts where aged to simulated 50.000 miles road aging condition and tested on a production V6 engine and installed with the same position of the front face. Table 1 summarizes the physical properties of the tested systems. First 900cpsi system shows 14% less PGM based on volume reduction. For the second 900cpsi system the Palladium loading on the front half was additionally reduced by 50% resulting in an overall absolute PGM reduction of 48%.

	500cpsi HL	900cpsi HL	900cpsi LL
Dimensions [mm]	Ø98.4 x 130	Ø98.4 x 113	Ø98.4 x 113
Foil Thickness [µm]	40	30	30
Volume [ltr]	1.0	0.86	0.86
GSA [sqm]	3.63	3.69	3.69
Heat capacity [J/K]	528	466	466
PGM Loading [%]	100%	86%	52%

Table 1: Physical Properties of tested Converter Systems (HL = High pgm loading, LL = Low pgm loading).

Figure 1 Figure 2 compares the accumulated HC emissions during 1st phase of the FTP test cycle. The faster light-off of the 900cpsi catalyst shows a significant lower HC accumulation compared to the 500cpsi reference system. When Pd loading was reduced on the front half, light-off is delayed and therefore accumulated HC higher. However, the 900cpsi LL with reduced PGM loading performs better compared to the 500cpsi reference catalyst with HL .

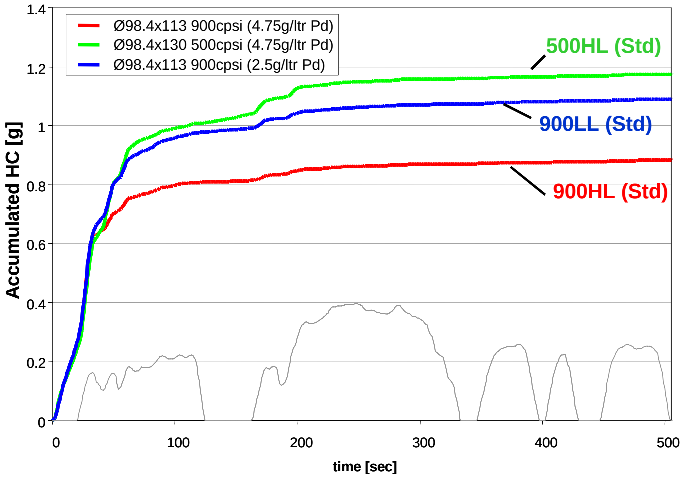

Figure 2: Accumulated HC emissions over the first phase of the FTP75 cycle as a function of cell density and PGM loading.

Overall emissions are shown in Figure 3. The 900cpsi HL (High Loaded) catalyst outperforms the 500HL converter. The 900LL achieves similar values like the 500HL design but a significant NOx advantage even with 12% less catalyst volume and less precious metal content.

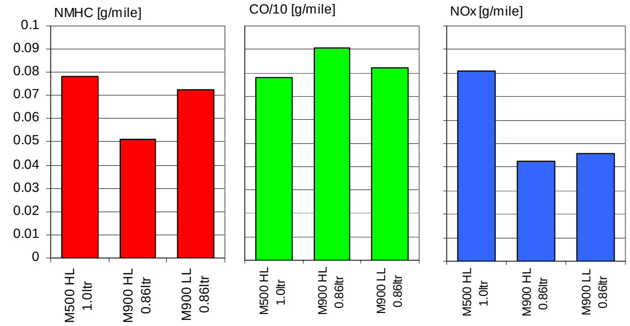

Figure 3: Overall Emission Test Results of 500cpsi catalyst compared to 900cpsi Catalyst with different loadings

THE ADVANCED SUBSTRATE DESIGN

The previously discussed mass transfer coefficient can be increased by smaller hydraulic diameter. Figure 4 demonstrates the improvement where the mass transfer coefficient was calculated as function of exhaust gas flow rate. The mass transfer coefficient is increasing at higher gas velocity/ Reynolds number. The factor for improvement through higher cell density is increased to a significantly higher magnitude at turbulent flow condition. Detailed results of the performance of small catalyst at turbulent flow conditions are reported in [6], [7]. The studies demonstrated a HC and CO emission reduction of more than 40 % with a catalyst volume less than 3% of the engine displacement (0.04ltr). Those applications take advantage of the turbulent flow condition.

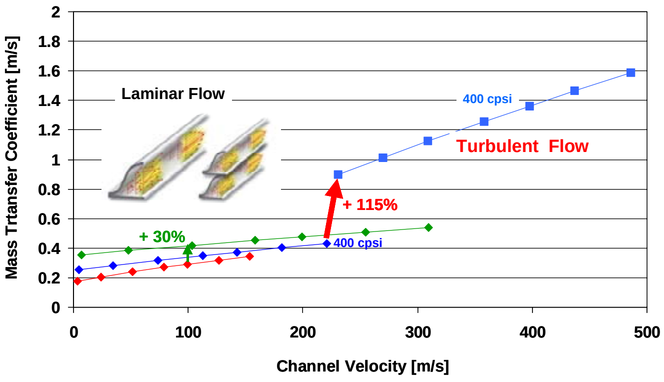

Figure 4: Calculated Mass Transfer Rate as a function of gas velocity

Using the example above, where small catalysts achieved extremely high volumetric efficiency, the objective of new substrate developments focused on the challenge of how to increase the mass transfer coefficient. Metallic substrates consist typically of sinusoidal corrugated and flat foils. By preprocessing the foil material different types of channel structures are possible which directly influence the channel flow. The potential available substrate designs were earlier discussed and presented in [3,4]

TRANSVERSAL STRUCTURE TS

The Transversal Structure (TS) is shown schematically in Figure 5. The structure is applied to the sinusoidal corrugated foil as a secondary corrugation 90 degree to the flow direction.

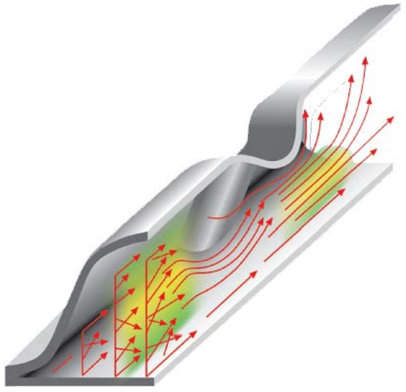

Figure 5: Channel with Transversal Structure

The TS corrugation influences the boundary layer of the laminar flow in the channel. Furthermore the mass transfer is increased compared to a standard channel design. Figure 6 shows the calculated mass transfer coefficient as a function of channel length.

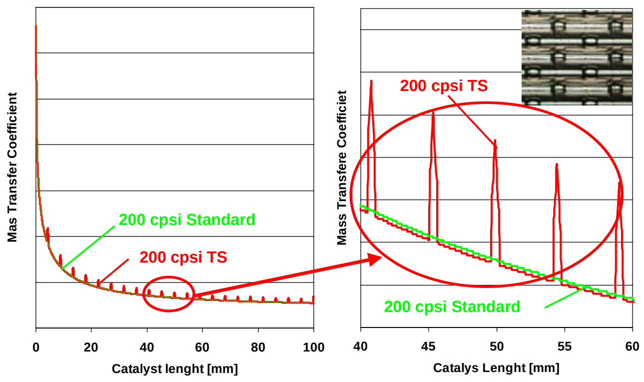

Figure 6: Calculated mass transfer coefficient of a standard channel and an a channel with TS structure

The benefits of the improved heat transfer and mass transfer coefficient through the TS structure were demonstrated in vehicle test programs and successful used in series production due to the advantageous backpressure by avoiding higher cell density [4], [5].

LONGITUDINAL STRUCTURE LS

A significant different magnitude of mass transfer level can be achieved through Longitudinal Structure (LS) as shown in Figure 7. The corrugated foil is cut and the top of the sinusoidal foil pressed into the channel. By this construction the catalyst wall is alternately located in the center stream of the laminar developed flow.

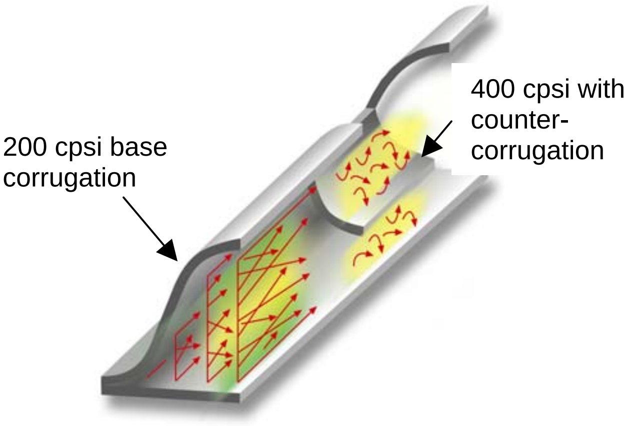

Figure 7: Cannel with LS structure (“=200/400 LS”)

Numerical tools were used to optimize the geometry of the design. A calculated mass transfer coefficient for the 200cpsi and a 200cpsi with LS structure (200/400LS) is compared in Figure 8. The doted line shows the characteristic of a regular 200cpsi channel. A significantly higher mass transfer level can be achieved through the “turbulent “-like flow regime at every LS blade building up a new boundary layer. By optimization of the LS configuration mass transfer coefficient can be optimized.

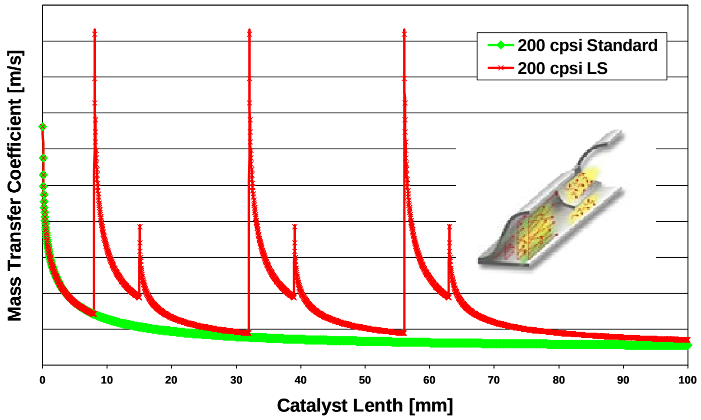

Figure 8: Mass Transfer Coefficient of 200cpsi substrate with and w/o LS structure

The conversion efficiency of a standard 200cpsi and a 200/400 cpsi LS catalyst is compared in Figure 9. The converters were loaded with the same washcoat technology and the same amount of precious metal. Converters were installed in a closed coupled position on a 1.8ltr turbo charged engine and tested in the FTP test cycle. The converters were sized to Ø118x74.5mm (0.45 x Engine Displacement) to emphasize the difference during the heat-up phase as well during hot transient condition. Figure 9 shows HC accumulation during the 1st and 2nd phase of FTP cycle. The 200/400LS catalyst shows a faster light-off performance and even more a higher efficiency during the transient phase.

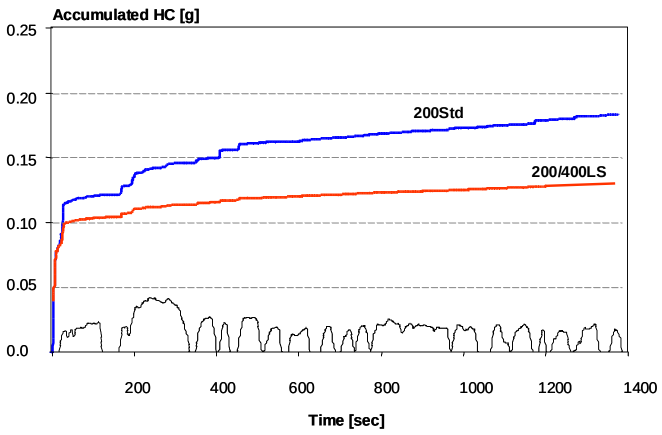

Figure 9: Accumulated HC Emissions of a standard 200cpsi and a 200/400LS catalyst during the first and second Phase of the FTP Test

PERFROATED SUBSTRATE TECHNOLOGY

All previously discussed substrate foil structures influence not only the heat capacity but even more the flow condition within a catalyst channel. However, flow pattern given by exhaust system architecture are only influenced to a minor degree. The optimization of the flow condition for close coupled catalyst are often restricted by the limited degree of freedom through the envelope in the engine compartment. The performance of a converter is notably influenced by the inlet conditions, characterized by flow maldistribution and pressure, mass flow, and composition fluctuations. Even if the overall flow uniformity index is good, deviations between cylinders are possible. The flow pattern across a close coupled catalyst of a 4 into 1 design is shown in Figure 10. The flow was measured at a Re number of 60.000 with a HFM sensor behind the substrate. Cylinder one and three flow is better distributed than flow from cylinder 2 (4 o'clock) and cylinder 4 (9 o'clock) while the overall uniformity index is acceptable.

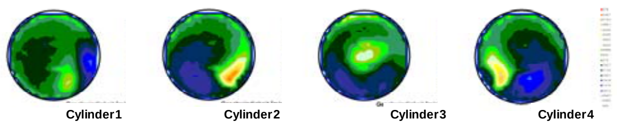

Figure 10: Flow pattern in a close coupled catalyst for a 4 into 1 manifold design

The cross flow within the catalytic converter can only be achieved when gas exchange between channels are possible. This can be achieved with a substrate made out of perforated foil material. Figure 11 shows a cut of a PE Metalit® showing the mixing chambers.

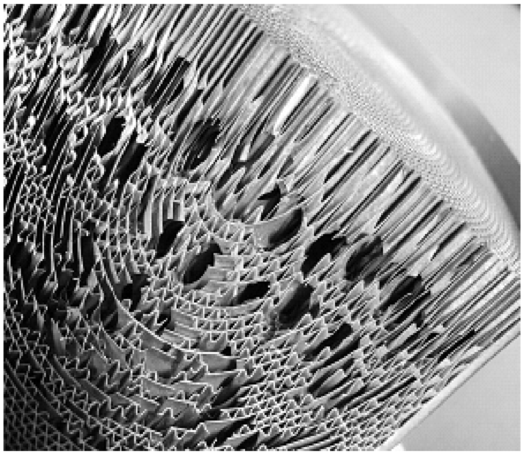

Figure 11: Cut of a PE Metalit®

Catalysts with areas of higher space velocity may result in regions of the catalyst yielding different rates of conversion and rates of aging [4]. Taking the same manifold and replacing the standard substrate by a PE Metalit® results in a more homogeneous flow pattern. The pictures in the top row of Figure 12 are the results with the standard substrate and the measured flow pattern in the second row is the result of a perforated substrate. The utilization of the catalyst volume is improved and mixing of individual cylinder flow within the catalyst is possible. As a result, 15 % back pressure of the converter system is obtained.

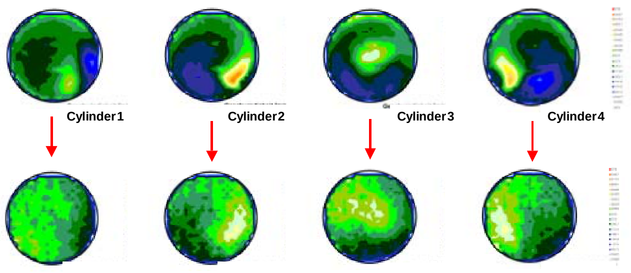

Figure 12: Flow pattern in a close coupled catalyst with a 4 into 1 manifold design – Standard Catalyst vs PE catalyst.

Cascaded system with a small light-off catalyst followed by a main converter incorporates the benefit to have a high energy density for the fast light-off catalyst. The PE-Metalit benefits from the larger energy density per heat capacity. Therefore, converter diameter can be increased to gain lower system back pressure [12].

A test program was conducted to investigate the emission performance of the PE catalyst. Table 2 summarizes the physical properties of the tested systems. The cell density and foil thickness were kept constant but a perforated foil used for the PE design. Major changes include the reduction in GSA and reduced heat capacity compared to the standard Metalit. The WC mass was adjusted for the 800cpsi PE substrate to ensure proper coating thickness. The parts were coated with a precious metal loading of 25g/ft^3.

	STD Metalit®	PE Metalit®
Cell density [cpsi]	800	800
Dimensions [mm]	Ø98.4 x 110	Ø98.4 x 110
Foil Thickness [µm]	40	40
Volume [ltr]	0.837	0.837
GSA [sqm]	3.33	2.23
Heat capacity [J/K]	518	348
PGM Loading [%]	100%	100%

Table 2: Physical Properties of Standard Metalit and PE Metalit

A 1.1ltr 4cylider engine was equipped with the baseline system and afterwards tested with the 800cpsi PE catalyst. The temperature plot for the first 200 seconds of the European Driving Cycle is shown in Figure 13. The gas inlet temperature for both design are similar and a gas inlet temperature of 500°C recorded at the end of the idling phase. The recoded gas outlet temperature demonstrates a quicker heat up for the PE catalyst. A temperature difference of 150 °C is achieved 40 seconds after engine start.

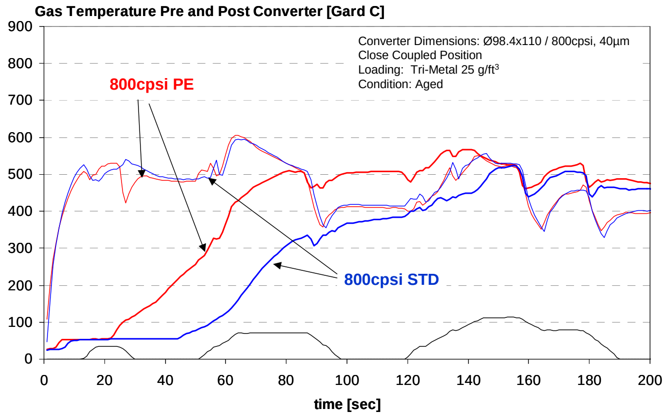

Figure 13: Exhaust Gas Inlet Temperature and Temperature after Catalyst during European Driving Cycle

The difference of the HC-light-off is shown in Figure 14. The PE catalyst shows a quicker light-off and similar conversion rates after 150 seconds. The accumulated HC emissions are 25% lower for the PE catalyst during the first 200seconds and keep the advantage through the test (Figure 15).

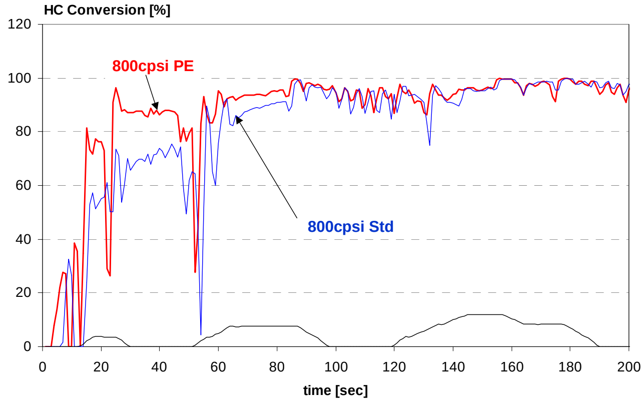

Figure 14: HC-Light-Off during EUDC with Std and PE Catalyst

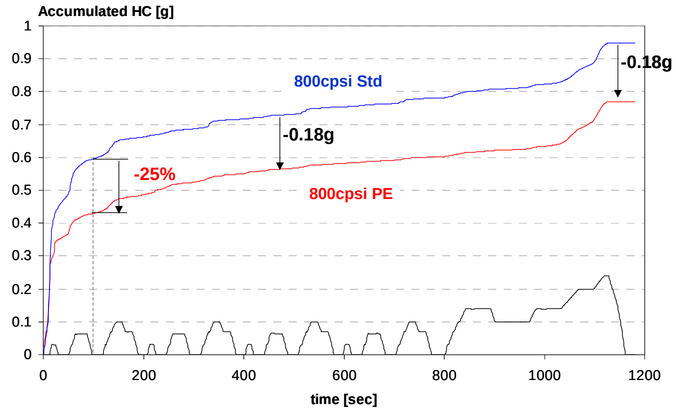

Figure 15: Accumulated HC during the EUDC driving cycle

The overall weighted emission test results are compared in Figure 16. The emissions are more than 25% lower with for the PE catalyst.

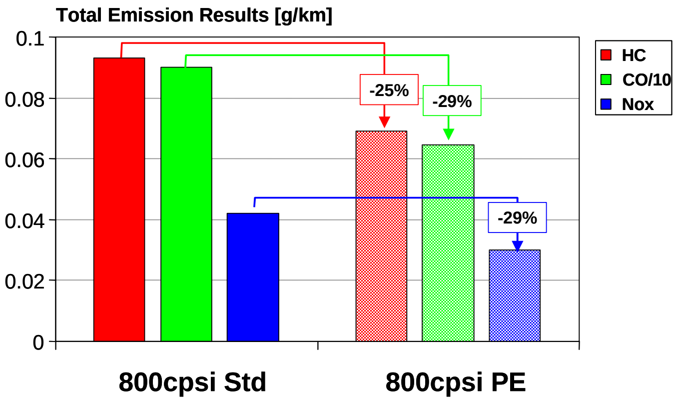

Figure 16: HC, CO and NOx Emission results of 800cpsi Std and 800 PE catalysts

The performance of the PE catalyst demonstrates feasibility that it can be used in place of cascaded systems, saving both weight and cost.

CONCLUSION

The innovative new metallic substrate technologies introduce new possibilities for catalyst designs to manage future challenges for lower HC, CO and NOx emissions. The presented results across different applications can be summarized as follows:

- high cell density substrate technology demonstrate higher specific efficiency
- flow distribution and malsdistribution within the catalyst can be improved through perforated foil technology
- back pressure penalty through use of higher cpsi product can be reduced through PE technology
- “turbulent”-like flow achieved through the LS construction increase the conversion efficiency to a new level
- decoupling of the thermal mass and efficiency is possible with LS and PE technology

For overall optimization of the system performance a close cooperation between engine manufacturer and the exhaust aftertreatment industry is needed to achieve a cost-effective solution.

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