Der „Lambdasondenkatalysator"; ein neues Konzept für kompakte Hochleistungs-Katalysatorsysteme

The „Lambda-Sensor-Catalyst"; a New Concept for Compact High-Performance Catalyst System

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Abstract

The exhaust gas treatment of Otto engines has mistakenly been considered to be "completely developed", as the available catalytic converter systems have the necessary effectiveness to fulfill the stringent current standards. However this effectively is purchased with high system costs.

Hence, a new and important development goal in the application of innovative catalytic converter systems is the reduction of the catalytic converter and system costs. Within these goals the functionality of lambda-control and catalytic converter diagnostics must be considered.

The state of the art catalytic converter systems consist of two or sometimes three bricks, which are placed sequentially in one or more housings. A gap between two bricks is used to house the second lambda probe. Additionally the gap facilitates a mixture and equalization of the gas flow.

Using such state of the art systems, which are very effective, in conjunction with open, radial catalytic converter designs can yield substantial function and cost advantages.

Combining this design with another innovation, the 'Lambda-Sensor Catalyst', eliminates the need for the gap between the bricks since this type of catalytic converter allows for the positioning of one or more lambda probes directly in the brick. The radial permeability of the brick (Perforated Design PE) also allows for a diffusional equalization of the pollutant concentration, which increases the control quality of the mixture that is formed.

1. Introduction

The development of future cars and platforms is based on several requirements and interests. For example on the one hand crash safety requires deformation zones, on the other hand a large passenger compartment for improved convenience for the driver and the passengers is requested. In addition to this the driveline itself requires more space, for example because of increased engine displacement and /or number of cylinders. Furthermore, the introduction of all-wheel drive technology increases the need for more space.

This packaging conflict in modern vehicles continues to get more and more complex, especially in the engine compartment and toe-board position. In contribution to this development there is a strong demand for more small and compact components.

For example the exhaust after-treatment system is, because of its properties, a system that is very sensitive to packaging.

Heat from the engine is needed to achieve light-off as soon as possible after engine cranking. Therefore restrictions like how far away from the engine the catalyst installation is needed have to be examined. In addition flow distribution and gas mixing zones which also of great importance for maximizing the catalyst efficiency thus further increasing the complexity. [1]

Legal requirements like On-Board Diagnostics (OBD) with a need for exhaust gas sensors at different positions in the catalyst system also have an influence of the packaging.

Beside space one of the most important factors is system cost. From this point of view smaller compact catalysts also have potential to show benefits, because the coating costs (wash-coat and precious metal) are in principle a direct function of the catalyst volume.

In the case that a single brick catalyst system can be realised also the handling cost can also be reduced. In addition it can be expected that a smaller catalyst has lower weight than a larger one and weight is usually directly transferred to vehicle cost.

All these requirements necessitate a more compact installation so that the overall vehicle properties can be improved.

The goal of this paper is the development and testing of base technologies needed for this task.

2. New Technology for Compact Catalyst Designs

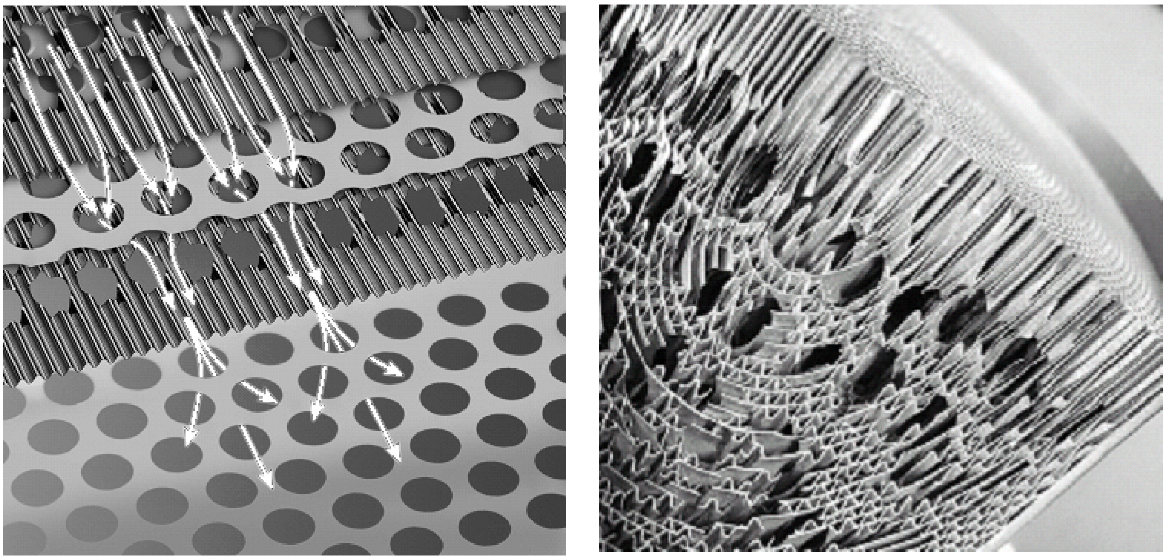
As described above catalyst systems have different space requirements. For catalyst light-off a close-coupled position is preferred. Because of the narrowness in the engine compartment it is often difficult to realise a uniform flow distribution in front of the catalyst. For best catalytic efficiency it is even more necessary that the exhaust flow of each cylinder is distributed over the total cross-section of the catalyst. This is important because tolerance levels of the injection nozzles together with a possible drift over ageing because of poisoning, could lead each cylinder to run with a slightly different lambda value. In such a case with poor flow distribution leading to particular sections of the catalyst being used by individual cylinders then the air/fuel mixture in these sections will be slightly lean or rich and this has a direct influence on catalytic efficiency. A typical solution is to use a two or even a three brick catalyst system where mixing between the individual bricks takes place.

The task for a compact catalyst system is to improve the quality of the catalyst internal flow and concentration distribution.

2.1 PE(Perforated)-Catalyst Design

Metal substrates consist of flat and corrugated metal foils. In the case of the Metalit® several flat and corrugated foils are stacked together and then wound in S-Design® to the final shape of the catalyst cross section.

Figure 1: Flat and corrugated foil with PE Holes and view into a PE-Catalyst



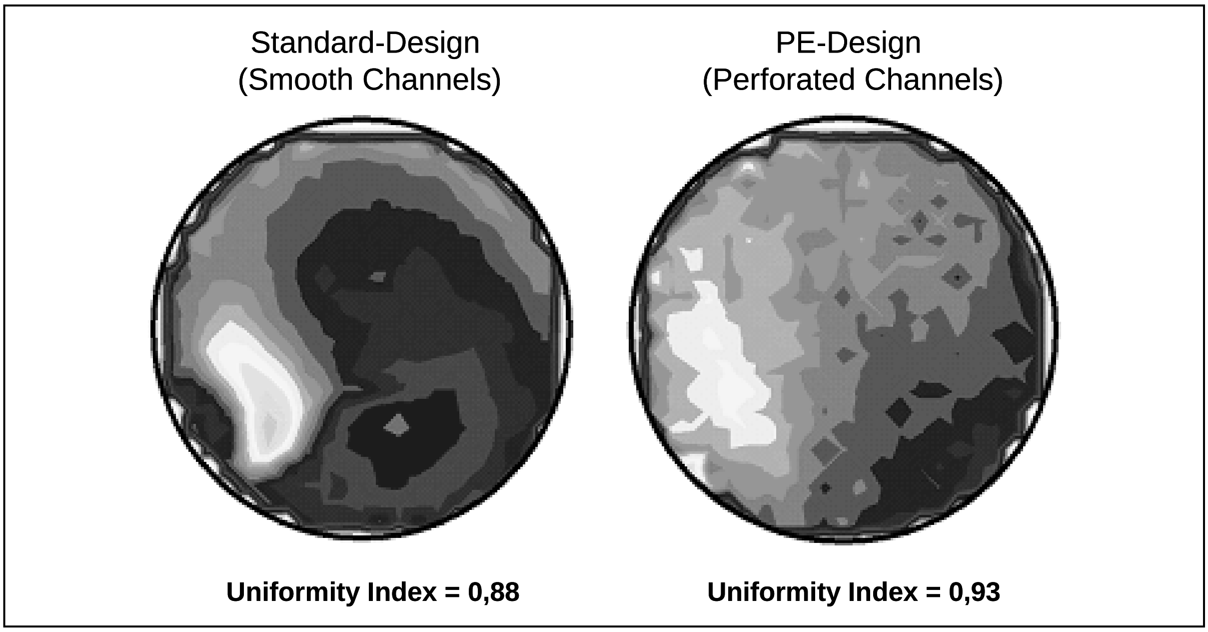
For the PE-Design® [2,3] 8 mm holes are punched into the flat and corrugated foils. During the winding process these holes create cavities. (Figure 1)

During operation the flow exits from the channels into the cavities where the flow and concentration are distributed and then enters the channels again. Along the catalyst length this happens several times improving the total flow and concentration distribution.
The development of metal foils with perforation has promising advantages:

- homogeneous distribution of flow and pollutant concentrations
- compensation of lambda cylinder-to-cylinder variations
- reduction of heat capacity
- back-pressure reduction

Figure 2 shows the improvement of flow distribution in a close-coupled catalyst mounted directly to a prototyp manifold installed on the Volvo in-line 5 Cylinder engine. The catalyst size was Ø 110 x 130mm; 800 cpsi. The measurement was done on a gas flow rig with a Reynold number of 60,000 in the manifold exhaust pipes. As an example cylinder 4 is shown.

Figure 2: Flow distribution in a close-coupled catalyst with and without PE-Design

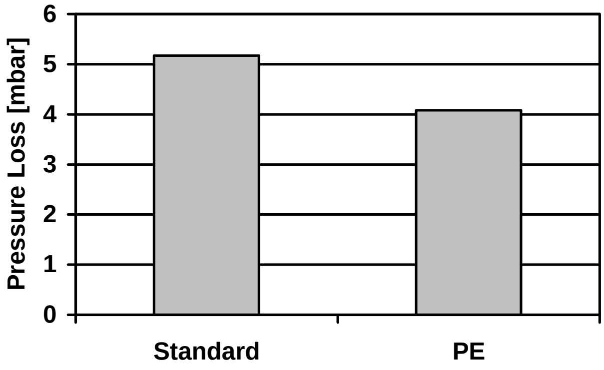


As a result it can be seen that the uniformity index [4] which is an indicator for the flow distribution was improved from UI= 0,88 (for the standard catalyst) to UI= 0,93 (for the PE-Catalyst).

Accordingly the PE-Design has an impact on back-pressure because of a more even use of the total catalyst. In addition it has to be mentioned that the back pressure in the cavities is much lower than in the catalyst channels which is overcompansating the inlet back-pressure created by the flow stream out of the cavities back into the channels.

Figure 3 shows a back-pressure comparison, measured at the flow test bench of the standard catalyst compared to the PE-catalyst at the Volvo 5 Cylinder (Cylinder 4). With the PE-Design the back-pressure was reduced by 21%.

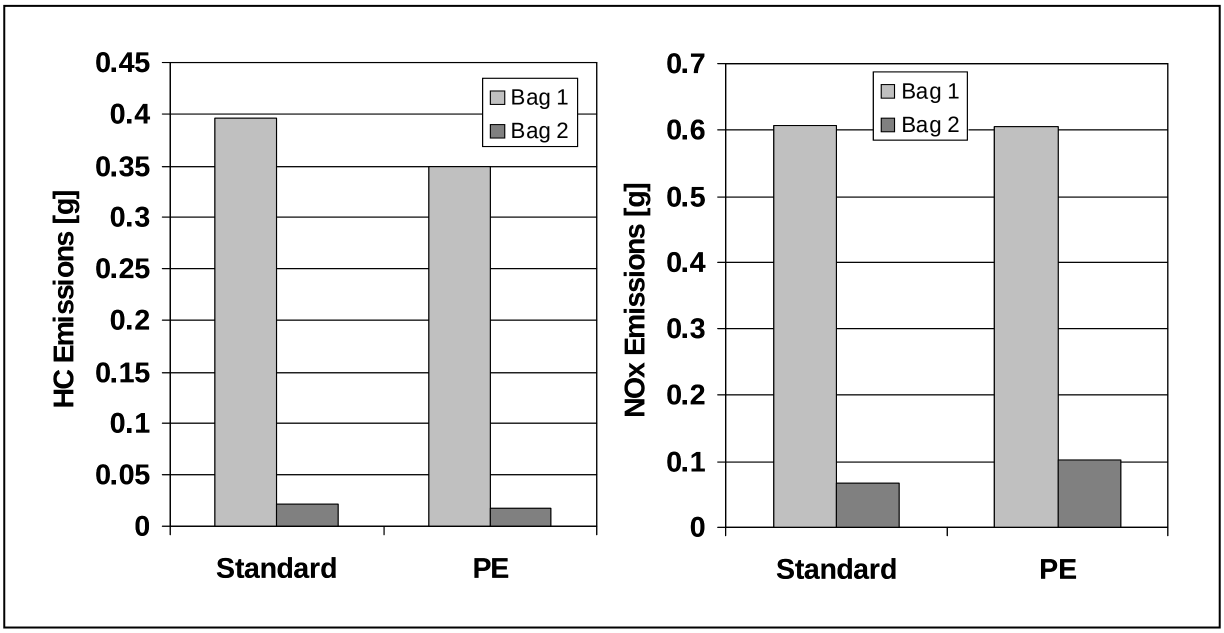
Figure 3: Back-pressure of the close-coupled catalyst with and without PE Design



For catalytic efficiency the loss of catalytic surface area has to be compensated for by improved mass transfer and of course by a better usage of the catalyst because of the more uniform flow distribution. Figure *4* shows emission test results of the PE-design compared to a standard catalyst.

The tests were done on an dynamic engine test-bench. The test engine was a turbocharged 1,8 l; 4 cylinder engine. Because the turbocharger is already doing a good mixing of the single cylinder concentration differences and the flow distribution was already quite good (Uniformity Index: 0,93). The test results of Bag 2 directly represents the influence of mass transfer, showing that the improved mass-transfer of the PE-Design compensates the loss in geometric surface area. In addition it can be recognized that the Bag 1 HC results are positively influenced by the reduced thermal mass of the PE-Design.

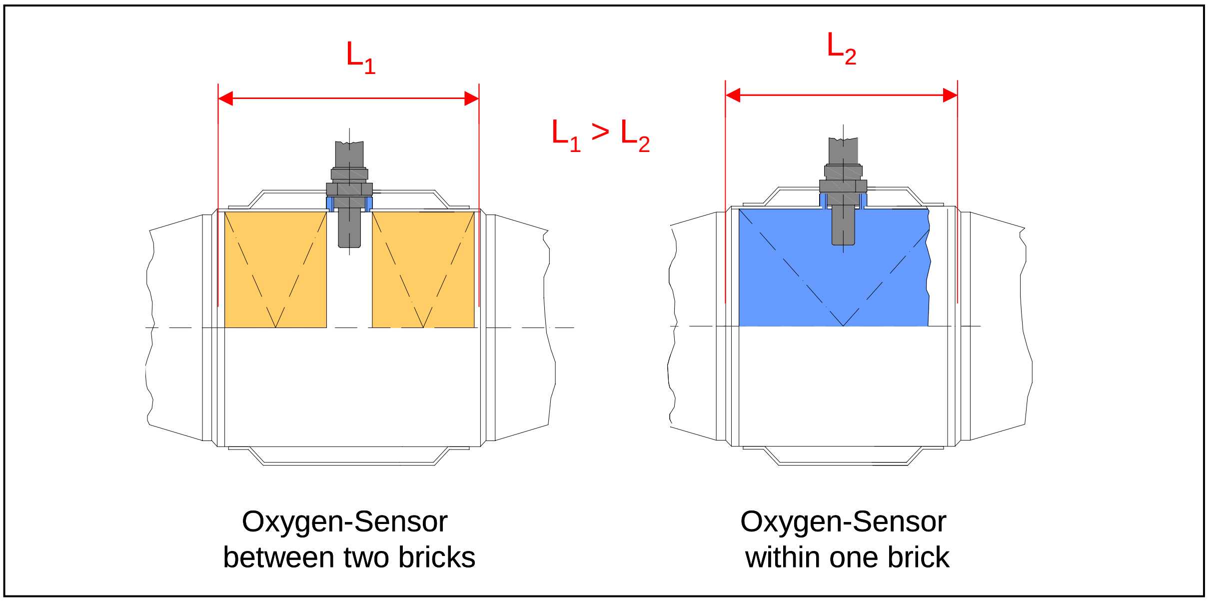
Figure 4: HC and NOx emission results in Bag 1 and Bag 2 of the FTP test



As a result it can be stated that the PE technology forms the basis for a single brick catalyst solution.

As mentioned before other requirements like OBD also have to be fulfilled. For OBD reasons it is common that only a small catalyst volume is diagnosed and for this reason it is necessary to spread the required total catalyst volume over two substrates. This results in both an increase in canning costs and also in the need for additional construction space in order to fit the lambda sensor in the gap between the two catalyst substrates. (figure 5)
When using a single brick it is necessary to insert the lambda sensor into the substrate.

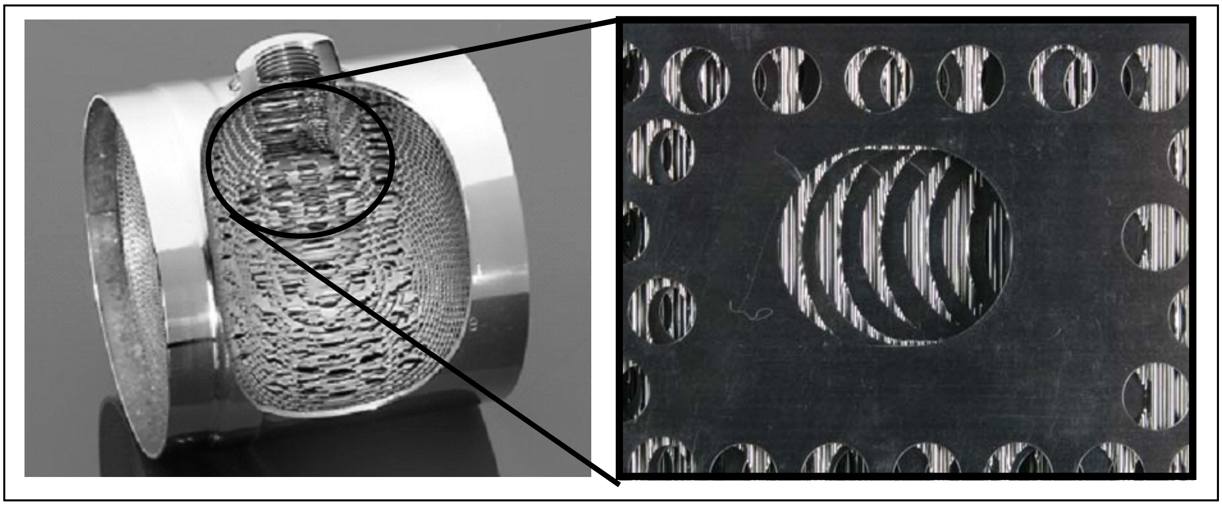
Figure 5: Comparison in Space requirement for a two brick compared to a single brick catalyst



2.2 Lambda Sensor Catalyst

To improve the compactness of the two brick systems in particular, it is an oppportunity to fit the lambda sensor directly on or into the substrate. The lambda sensor catalyst offers one way of doing this, by integrating one or more lambda sensors in the substrate in any axial position. The required clearance and the lambda sensor boss are applied directly during production of the metal substrate. The clearance for the lambda sensor is made by pre-stamping the flat and corrugated foils. By using an S-shape winding, the required clearance is formed during the winding process. Figure 6 shows pre-punched flat and corrugated foils before the winding process and the lambda sensor clearance after winding. The lambda sensor boss is welded directly onto the catalyst mantle. [6]

Figure 6: Pre-punched flat and corrugated foils and the lambda sensor clearance after the winding process



The PE-Design in combination with the integrated oxygen sensor builds the basis for future compact catalyst designs.

3. Advantage of Integrated Sensors; Test Results

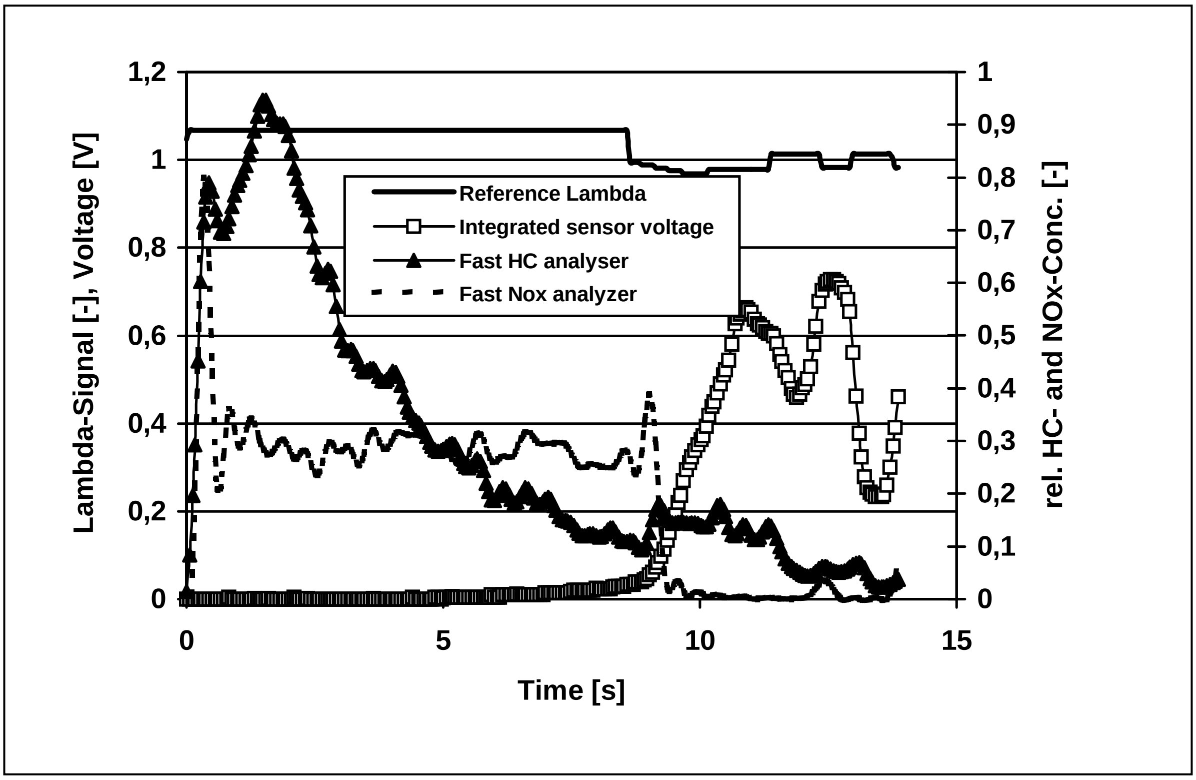
An integrated lambda sensor is a technology that contributes to the introduction of compact catalysts. Previously this technology has been presented as emission reduction technology. This of course also means that catalyst volume and/or cost can be taken out from the system whilst keeping the emission performance neutral. Both from control reasons and On Board Diagnosis (OBD) reasons there is a desire to locate the sensor at a certain position [5]. With a normal catalyst this leads to a divided multi-brick catalyst system (as mentioned above) whereas the integrated sensor brings the freedom to position the sensor at each position regardless of substrate configurations.

As an advantage of integrated oxygen sensors, it was shown that it becomes possible to increase the speed at which the lambda sensor is heated. Water drops no longer collide directly with the lambda sensor during cold start and are adsorbed instead by the catalyst substrate and/or the wash-coat. The water then evaporates from the coating when the catalyst is heated and passes the lambda sensor in a gaseous state.

Because the waiting time before activating the heating of the lambda control sensor can be reduced (removed) the activation time of the lambda control sensor is minimized. This improvement leads to the possibilty for activation the lambda control feedback from the catalyst control after 8 - 10 seconds (if a fast light-off sensor is used), thus giving a much better control and reproducibility of cold start emissions. [6]

Figure 7 shows Hydrocarbon (HC) and Nitrogen-Oxyde (NOx) emissions during cold start behind a catalyst with integrated oxygen sensor. The test vehicle was a modified (the system is discribed in chapter 3) MY05 Volvo S40 with a 5 cylinder SULEV engine. The emissions were measured with Cambustion Ltd fast response analyzers, HFR500 fast FID for HC and CLD500 for NOx.

Figure 7: Cold start HC and NOx emissions behind a catalyst with integrated oxygen sensor

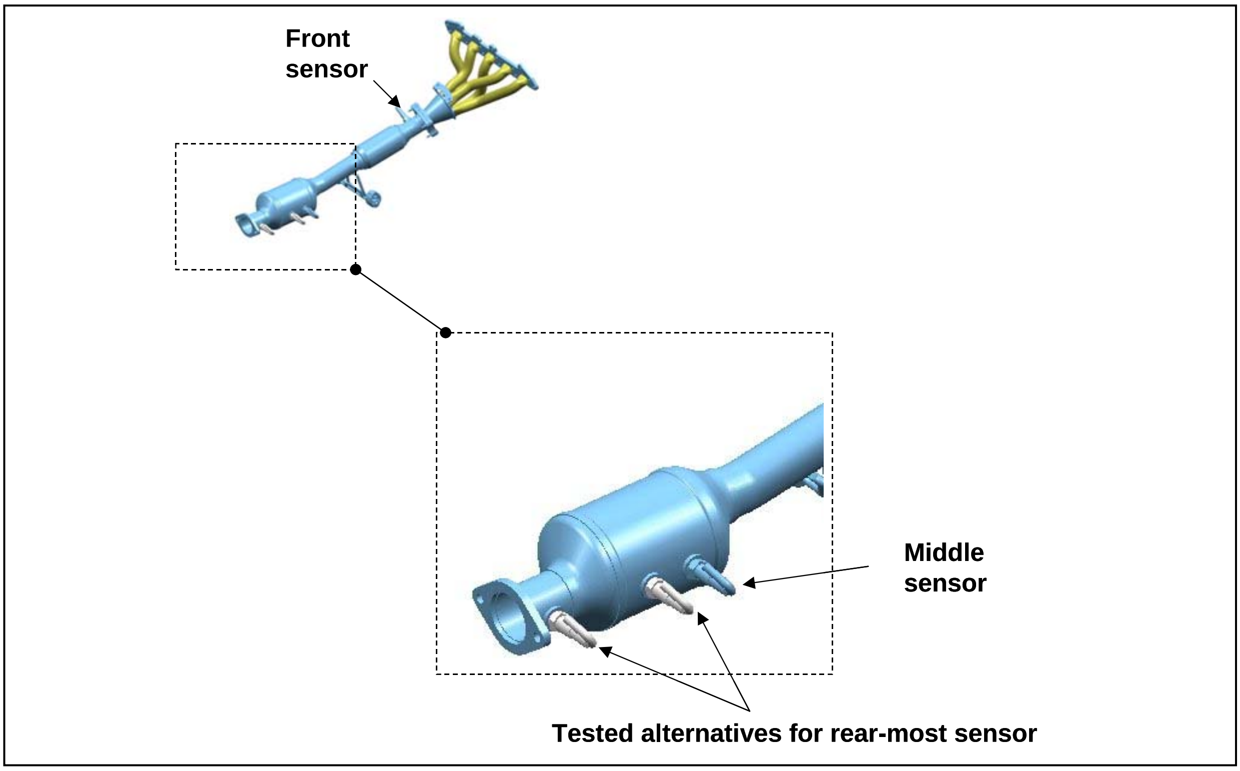


During this measurement lambda control was switched on after 10 seconds. It can be recognized that specially the NOx emissions from the lean cold start are rapidly reduced and also the HC emissions are stable. The possibility of a close-loop control shortly after engine cranking improves the stability and reproducibility of cold start emissions.

3.1 System Overview and its Control for Catalyst Systems

The first lambda sensor is a linear sensor that controls the engine to a calibration setting using the ECU for a continuously delivered target value.
The second lambda sensor monitors the frontal part of the catalyst and serves as an input to the lambda target value calculation with relatively fast and frequent sampling.
The third sensor monitors a larger portion of the catalyst (or the whole catalyst) and performs a similar work as the second sensor. The difference is that it has a slower influence on target lambda except when it reaches certain more extended limits.
Figure 8 shows the system layout of a catalyst system with three sensor layout. The rear sensor was varied between a position behind the catalyst and inside the rear end of the catalyst.

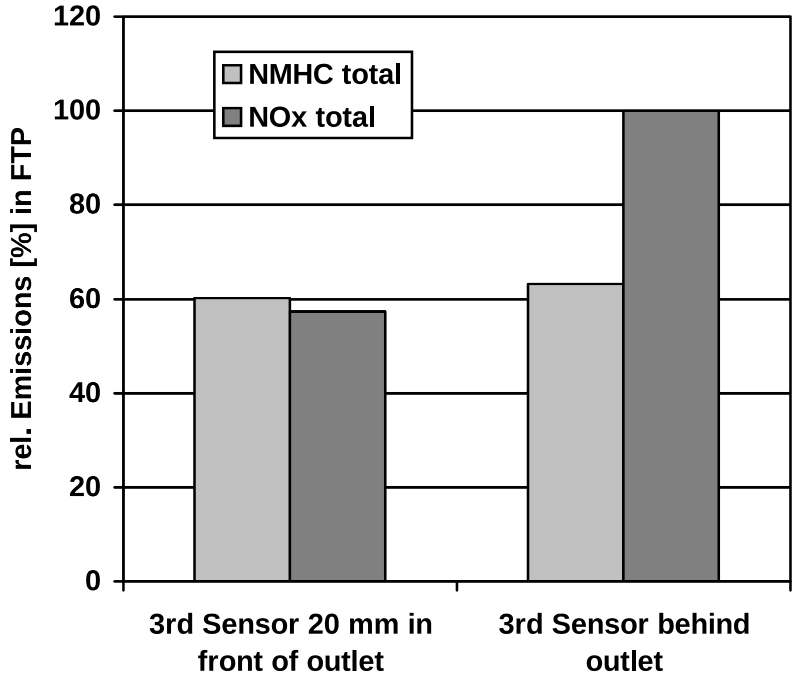
Figure 8: Principle System Layout



3.2 Integration of the Rear-Most Lambda Sensor

In order to minimize break-throughs during lambda control and OBD diagnostic the rear (third) oxygen sensor was varied between a position behind the catalyst and a position integrated into the substrate 20 mm before the outlet face.
In the software functionality as explained previously this sensor serves as a safeguard. This means that when "excessive" emissions pass it and it is positioned behind the catalyst those "excessive" emissions will go through to the tailpipe . Then they will be observed by the emission measurement equipment (slip) Not surprisingly as a result higher bag emissions were measured when the sensor was positioned behind the catalyst compared to the integrated sensor (figure 9). This shows the benefit of having the rear-most sensor integrated.

Figure 9: HC and NOx tailpipe emissions during FTP test with the third sensor behind the catalyst system and integrated 20 mm before the outlet face.

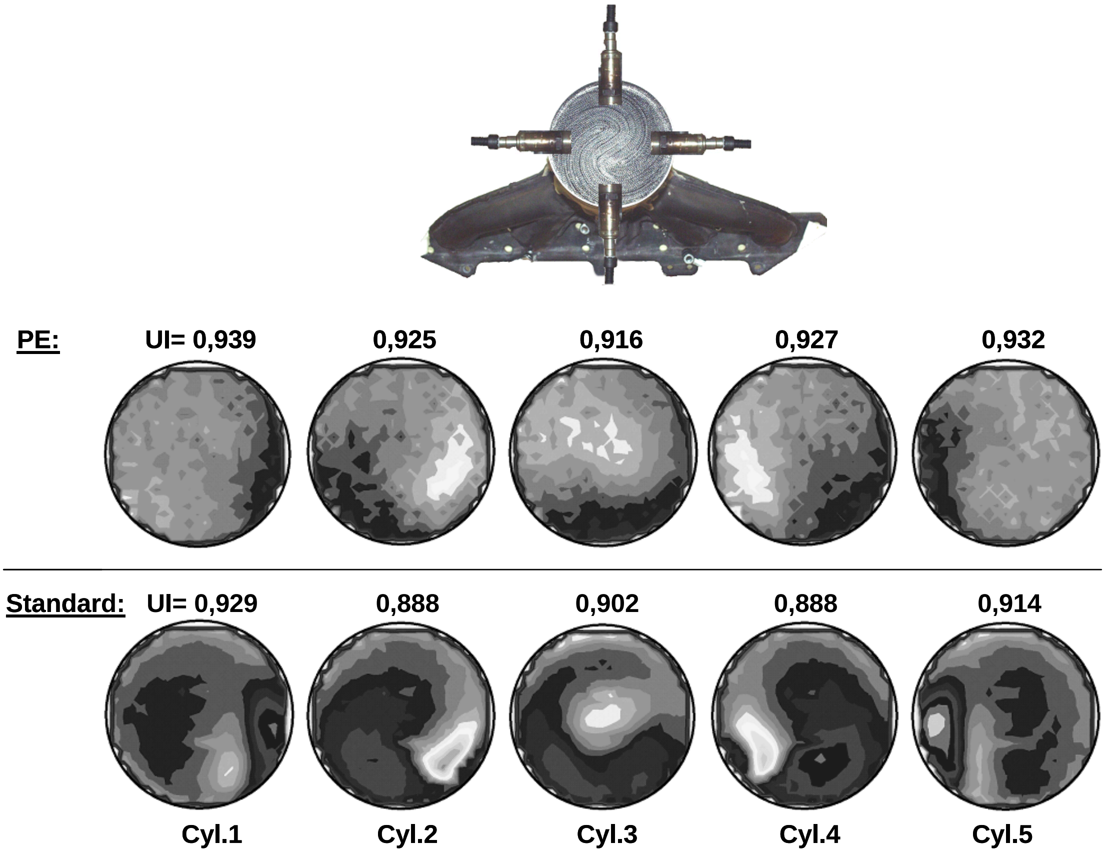


Since the rear-most sensor positioned and integrated into the substrate shows emission benefits it is of interest if the sensor really shows a signal that is representing the complete engine.

3.3 Influence of Radial Sensor Position

Dependend on the space situation in the car the radial position of an integrated sensor is limited. Taking a look to the flow distribution of each cylinder of the close coupled catalyst of the Volvo 5 cylinder (figure 10) it can be seen that for the standard catalyst each cylinder is using a different cross section of the catalyst whereas the PE-Catalyst is able to distribute the flow.

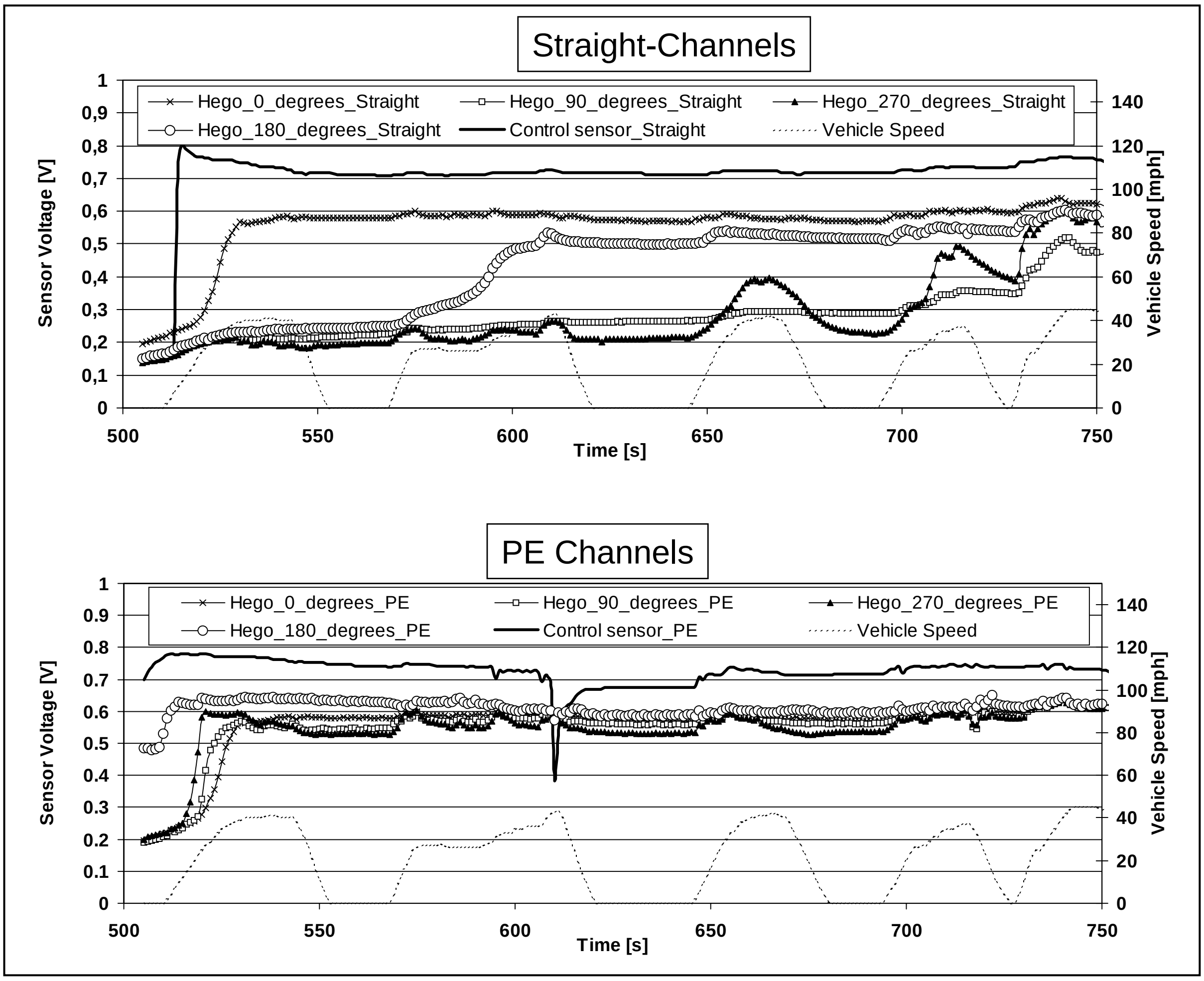
Figure 10: Flow distribution of each cylinder of the Volvo close coupled catalyst measured behind a Standard- and behind a PE-Catalyst



A closely related engine investigation was done using the system described in chapter 3.1.. In the first step 4 oxygen sensors were mounted at 4 radial positions 20 mm behind the substrate. During emission tests two observations can be made from the results.

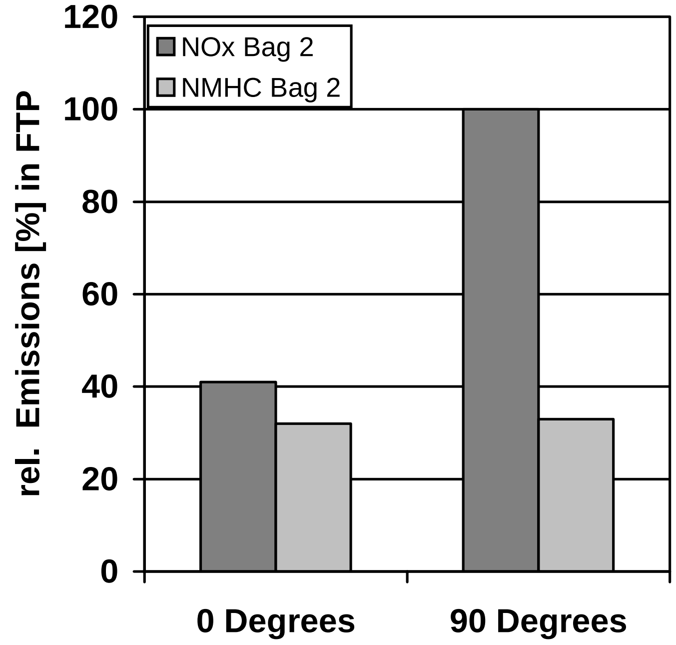
(Figure 11) The four reference sensors are more aligned when a PE substrate is used. Further, the control sensor and the reference sensor are more aligned when a PE substrate is used.

Figure 11: Lambda measurement results of oxygen sensors at different radial positions with a Standard- and a PE-Catalyst



To investigate the influence of the radial sensor position on a vehicle, the sensor was varied between two radial positions with 90° difference. The results in figure 12 show that, the radial position affected the emissions using a standard catalyst with straight channels. This explains the importance of a reliable sensor signal.

Figure 12: Emission test results in the FTP Bag 2 dependend on the rear sensor radial position.



This difference is expected to be even more clear if the gas mixing zone (down-pipe) is shortened which would be the case in a more close-coupled catalyst type of installation or an installation having a worse flow distribution of the single cylinders.

4. Summary and Outlook

The test results shown in the chapters before prove that new substrate technology like the PE-Design® and the integrated Lambda-sensor can be seen as the basis for for improving system complexity, cold start and emissions over the total test.

This contributes to an optimized system potential, cost saving and customer satisfaction
Specially the possibility of internal mixing of the PE-Design® minimize the sensitivity of space dependend locations of catalysts and sensors thus improving the robustness and long term emission stability of catalyst systems.

Future work using only a two sensor control and an integrated sensor which is used as control and in the same time HC OBD sensor is planed to achieve the final goal of a single brick catalyst system for SULEV applications.

5. References

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