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Study of Modern Application Strategies for Catalytic Aftertreatment demonstrated on a Production V6 Engine

Rolf Brück, Friedrich-Wilhelm Kaiser, Roman Konieczny
Emitec GmbH

Cynthia C. Webb, Andy Anderson
Southwest Research Institute, Texas

ABSTRACT

A study was performed to develop optimum design strategies for a production V6 engine to maximize catalyst performance at minimum pressure loss and at minimum cost. Test results for an advanced system, designed to meet future emission limits on a production V6 vehicle, are presented based on FTP testing. The on-line pressure loss and temperature data serves to explain the functioning of the catalyst.

1. INTRODUCTION

To meet the demands of the recent and future emission legislation limits, advanced catalyst technology is necessary in combination with optimized engine management systems. One important trend in catalyst design technology is the use of close-coupled catalysts which show a faster light-off due to reduced temperature losses from engine exhaust to catalyst inlet [1]. Close-coupled catalysts can either be used as start-up catalysts in combination with an additional underbody catalyst or as close-coupled main catalysts or cascade systems, often in combination with high cell densities and reduced volume to meet packaging demands in the engine compartment [2]. In addition to the stringent emission limits, further cost reductions and high engine performance are the development goals. To adjust the catalyst system to a specific application, all design parameters have to be taken into account to ensure a high performance design with lowest possible system costs.

2. CATALYST EFFICIENCY

Different factors influence the catalytic conversion efficiency, depending largely on the catalyst temperature. A differentiation has to be made between cold start phase and operation phase after light-off. The limiting factors in these different stages are shown in figure 1.

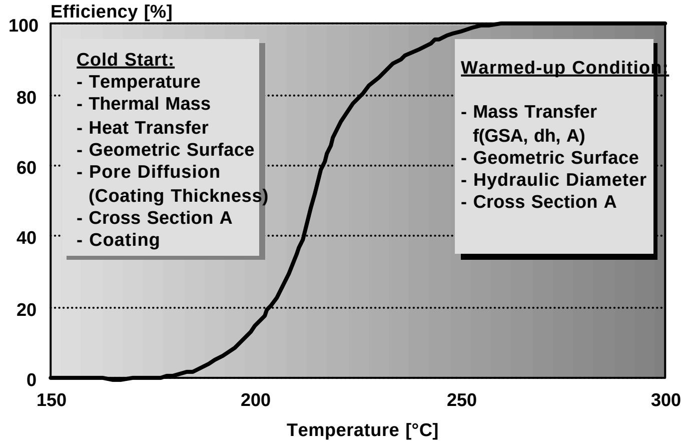


Figure 1 : Parameters influencing catalyst efficiency during cold start and at operation temperature

Parameters like thermal mass (cp), geometric surface area (GSA), washcoat thickness and precious metal loading and their influence on cold start behaviour of a catalyst system were already discussed in numerous publications [3],[4],[5],[6]. Therefore only a short review will be given in this section.

During cold start the catalyst works as a heat exchanger, which means that the mass of the converter is heated up by the exhaust gas. The heat transfer between the exhaust gas and the catalyst is described by the heat transfer factor which is determined by the geometric surface area, the cell size (hydraulic diameter) and the velocity of the gas flow. Using smaller catalyst diameters increases the flow velocity and therefore the heat

transfer and also the specific energy applied to a given cross section area.
The thermal mass which is directly related to the wall thickness of the catalyst substrate has to be as low as possible in order to achieve a short heating-up time.

As shown in figure 1 the efficiency at operation temperature depends mainly on the mass transfer which describes the transfer of the pollutant from the gas phase in the channel to the catalytically active wall. The better efficiency of higher cell densities [5],[7] can be explained by an improved mass transfer factor ß (equation 1) and an increased geometric surface area (GSA) as an exchange area for diffusion .

$$\text{Beta} = D_{12} \times Sh / d_h \qquad (1)$$

with

$D_{12} = f(T)$ -binary diffusion coefficient

$Sh = a\, Re^m\, Sc^n$ -Sherwood number

$Re = \rho\ v\, d_h / \eta$ -Reynolds number

Sc -Schmidt number

d_h -hydraulic diameter of channel

Beta is influenced by the hydraulic diameter and the flow velocity, which is related to the catalyst diameter and the open frontal area (OFA) of the catalyst (for a given massflow).
The only way to increase the GSA in a given catalyst volume is to use higher cell densities, which is related to the benefit of smaller hydraulic diameters.

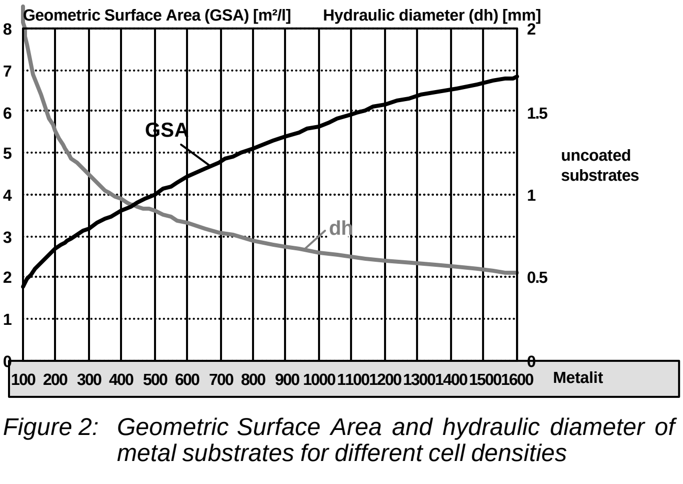


Figure 2: Geometric Surface Area and hydraulic diameter of metal substrates for different cell densities

The influence of the cell density on the efficiency at operating temperature is shown in figure 3. The diagram shows FTP-test Hydrocarbon emission results of different catalyst supports, varying on one hand the cell density of the substrates (at constant volume) and on the other hand catalyst volume (at constant cell density).

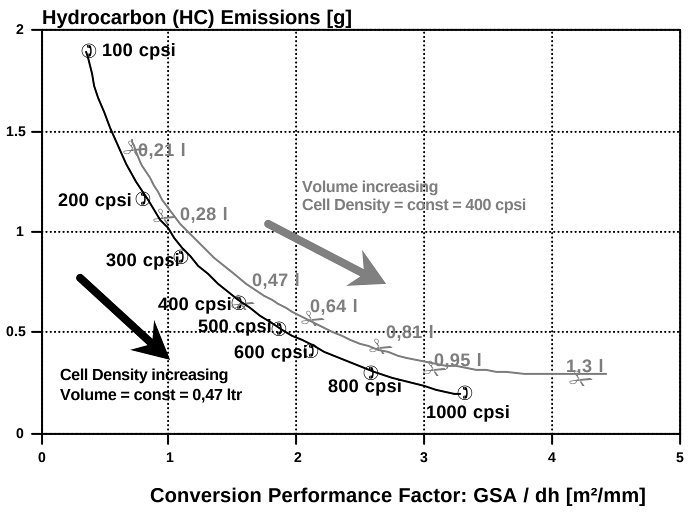


Figure 3: Influence of catalyst volume and cell density on Hydrocarbon emission under warmed-up conditions (FTP bag 1, 126-505s)

Although using higher cell densities has a similar benefit on efficiency as using bigger catalyst volumes, a remarkable difference is apparent from figure 3. It can be seen that improvement in emissions due to increased catalyst volume is limited, whereas increasing cell densities even up to 1000cpsi shows an additional advantage. This is due to the fact that with increased volume, only the GSA is increased, while with increased cell density both GSA and dh are optimized.
Another crucial advantage of increased cell density is, that large cost savings by reduction of the amount of precious metal is possible since a certain efficiency can be obtained using smaller volumes, keeping in mind that precious metal content is a volume specific value.

Besides catalyst diameter and hydraulic diameter of the catalyst channel, the mass transfer factor beta is influenced by the open frontal area (OFA) of the catalyst (for a given massflow). OFA depends on the wall thickness of the substrate and the washcoat thickness. A reduction of OFA caused by thicker walls and/or thicker washcoat layers increases the mass transfer factor and can improve the efficiency at operating temperature .
At the same time pressure loss, which depends mainly on the same parameters (flow velocity and hydraulic diameter) as the mass transfer, is increased. Figure 4 shows calculated mass transfer coefficients as a function of cell density (hydraulic diameter), wall thickness and flow velocity.

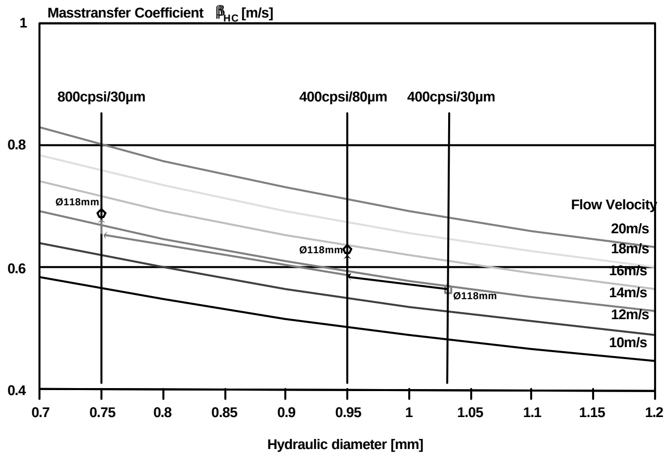


Figure 4 : Mass transfer coefficient as a function of hydraulic diameter, wall thickness and flow velocity

It can be seen that raising the cell density from 400cpsi to 800 cpsi or increasing the wall thickness from 0,03 mm to 0,08 mm increases the mass transfer coefficient by 22 % and 13 % respectively.

In order to show the effect of beta on tailpipe emissions, two catalysts with identical cell density and coating, but different wall thickness were tested on a medium size passenger car in the european driving cycle (Figure 5).

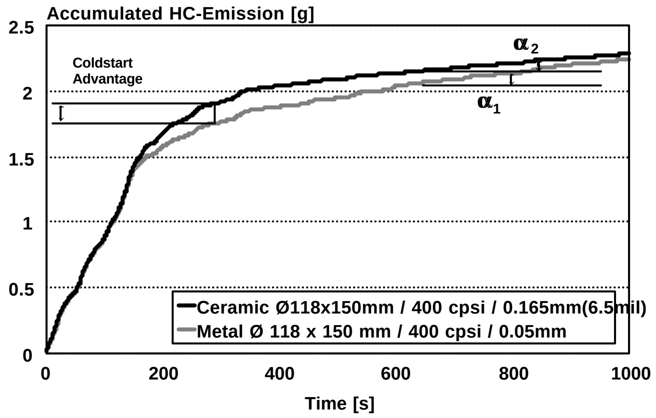


Figure 5: Accumulated HC-tailpipe emissions during the european test cycle

During cold start the lower thermal mass of the substrate with thinner walls shows a clear advantage, but at operating temperature the efficiency of the substrate with thicker walls is higher as can be recognized by the slower increase in emissions after light of $(\alpha_2<\alpha_1)$.

In the past the disadvantage of thin wall substrates during operation temperature was overcompensated by the advantage during cold start. But for ULEV, SULEV and NZEV emission regulations all operation phases have to be optimized.

3. APPLICATION STRATEGY

The trade-off between the different parameters shown in section 2 can be used to tailor the catalyst system to the specific demands of the application. Up to now, metal substrates were often used because of their pressure loss advantage, while emission limits were met owing to their good cold start behaviour.

The goal of this paper is to design a system that is comparable to the production system for overall efficiency and pressure loss, while at the same time reducing system cost with a reduced volume of the system. The evaluation is done on a 3.2l V-6 production car. The production catalyst system consists of 2 ceramic bricks for each cylinder bank, where the first one is mounted in a close-coupled position. Comparing the production catalyst and a metal catalyst with the same cell density, the main difference is the wall thickness. As shown in section 2, this influences the pressure loss, but also the mass transfer of the substrate. Figure 6 shows a comparison of the calculated backpressure of the production catalyst compared to metal substrates with the same cell-density. The comparison is made to a metal system with a) the same geometry, b) the same volume, but decreased diameter and c) decreased diameter and volume, but equivalent GSA.

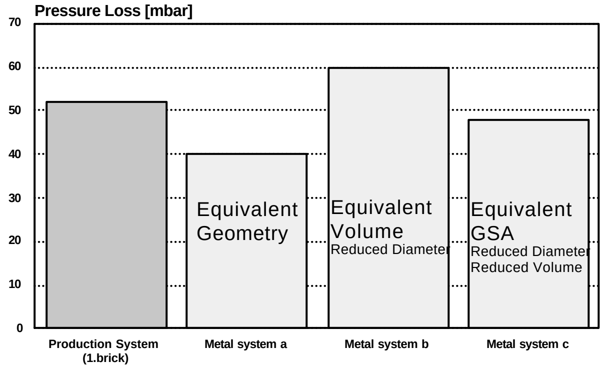


Figure 6: Backpressure of the production catalyst compared to different metal substrates

For metal system a), the higher open frontal area leads to a significant reduction of pressure loss. For system b) with reduced inlet diameter, but increased length (=constant volume), pressure loss is slightly higher. For the substrate with reduced inlet diameter, but same length (=constant GSA) pressure loss is approximately the same as for the production system.

Concerning the mass transfer, similar correlations as for the pressure loss exist. If the production catalyst is compared to a metal catalyst with equivalent cell density and geometry, the higher OFA leads to a reduction of flow velocity and therefore, in spite of a smaller hydraulic diameter, to a reduction of the mass transfer coefficient. By reducing the inlet diameter, this disadvantage can be eliminated. Figure 7 shows the mass transfer coefficient for the production catalyst, the metal catalyst with same geometry and the metal catalyst with reduced inlet diameter.

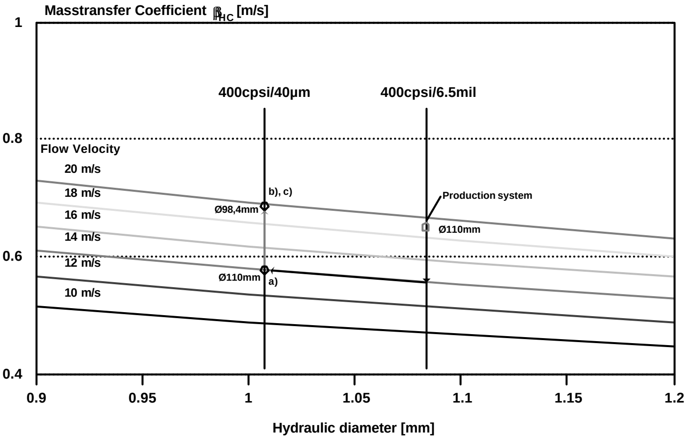


Figure 7 : Mass transfer coefficient of different catalysts

Using this strategy all the goals set in the introduction can be achieved. Due to thinner channel walls and reduced inlet diameter the thermal mass is reduced and therefore the time period to heat up the catalyst is shortened. The reduction of the inlet diameter also increases flow velocity which has a positive effect on mass transfer and therefore on conversion efficiency under operation temperature. While the metal substrate with reduced inlet diameter still has the same GSA as the production system, it is not necessary to increase the length of the converter. This leads to a reduction in catalyst volume, which includes a great cost advantage regarding the amount of precious metal. Table 1 shows the characteristics of the different systems.

To give an indication for possible further improvement, a high cell density substrate is also included into this comparison, showing the possibility to improve overall efficiency without necessarily increasing volume and herefore system costs.

System	GSA (Coated) [m²]	Volume 1 bank [l]	Thermal mass [J/K]	Pressure loss calculated [mbar]	Precious Metal Cost [%]
95.3cm²x115mm, 400cpsi/6.5mil + 95.3cm²x85mm, 400cpsi/6.5mil (Production sys.)	2.79 + 2.06	1.9	1032	90.64	100
Ø98.4x145mm, 400cpsi/40µm (System b)	3.57	1.1	468	59.64	58
Ø98.4x115mm, 400cpsi/40µm (System c)	2.83	0.87	371	47.68	46
Ø98.4x150mm, 800cpsi/25µm	4.93	1.14	474	110.87	60

95.3cm² is equivalent to Ø110mm

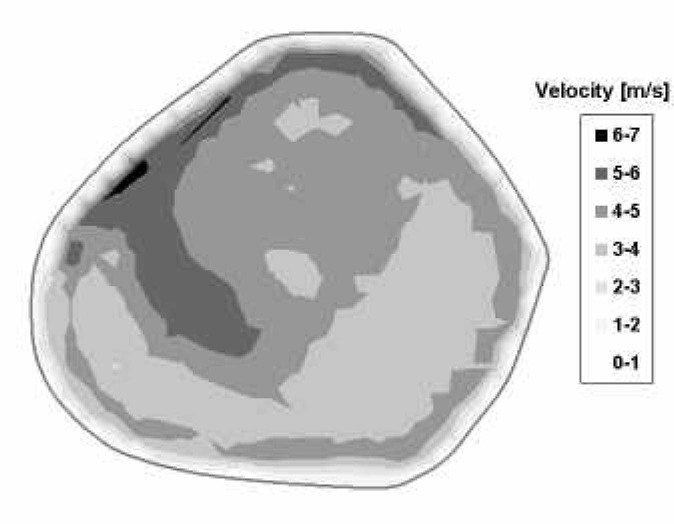
Table 1 : Physical data and relative cost comparison of the different systems

4. TEST CONDITIONS

The different systems discussed in section 3 were tested in a production car application on a chassis dynamometer at Southwest Research Institute (Texas) during the FTP-test-cycle, where both bag and modal analysis were performed. Additionally, conversion efficiency under steady state load was tested for different load points. All systems were equipped with several thermocouples both for gas and matrix temperature, fast lambda sensors and pressure loss measurement. Catalytic coating was the same for all systems.

The flow distribution of the production system and the metal system was measured on a flow test bench using a hot wire anemometer. The measured velocity distribution is shown in figure 8.

PRODUCTION



METAL

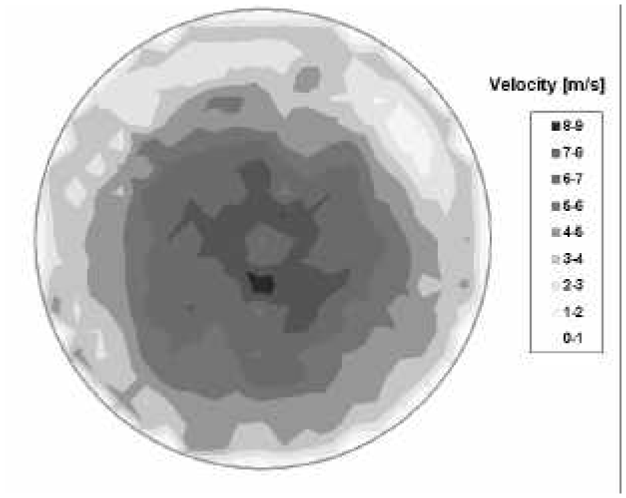


Figure 8: Measured flow distribution of production (1. brick) and metal system b

5. MEASUREMENTS ON THE CHASSIS DYNAMOMETER

Both bag and modal analysis were performed during the FTP-test. Modal analysis was of great importance to be able to detect and explain the differences between the different systems. As the production system is a 2 bank system, modal analysis had to be performed on one bank. At the beginning of the test both sides were tested to find out whether remarkable differences occur concerning raw emissions, temperatures or lambda control.

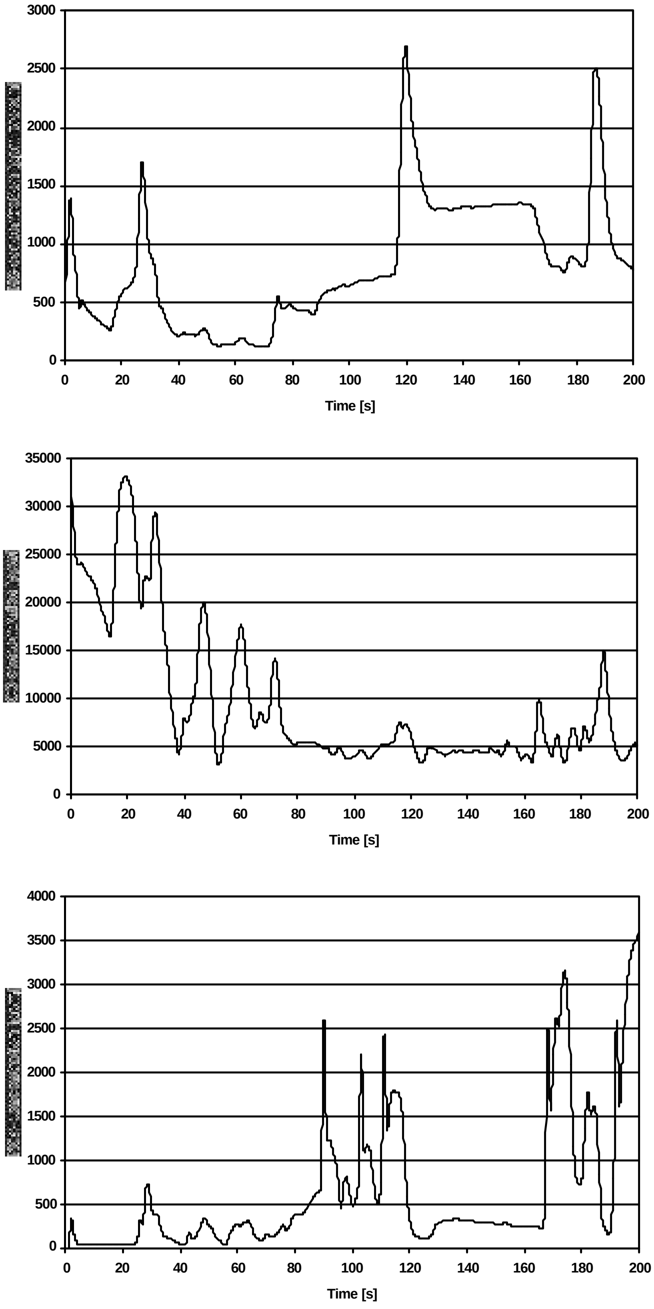


Figure 9 : Engine out data (HC-, CO- and NOx-concentrations)

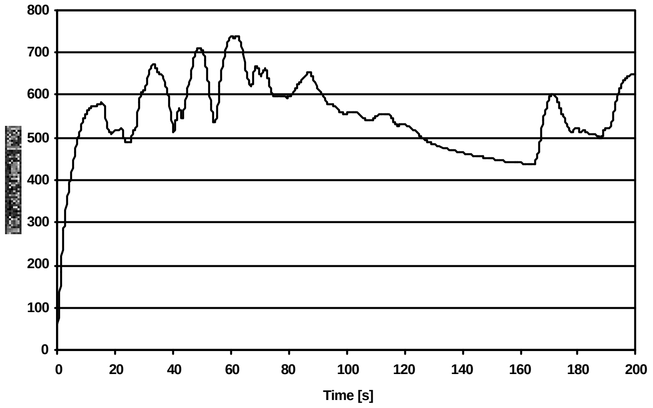


Figure 10 : Inlet Temperature

While raw emissions and temperatures were about the same, differences were detected with secondary air and lambda strategy. The most obvious difference was seen during fuel cut-off in deceleration. While on one bank fuel cut-off was performed for 7-8 seconds, duration on the other bank was only about 2 seconds. While this had no big influence on HC-emission-peaks, NOx-conversion in the following acceleration phase was significantly decreased due to the high amount of oxygen stored in the catalyst. For further testing the bank with the shorter fuel cut-off was chosen to prevent masking of substrate behaviour by the high oxygen amount.

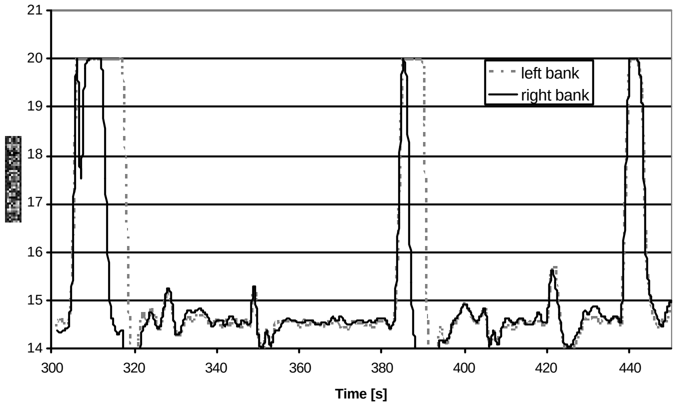


Figure 11 : Air/Fuel-ratio of LHS and RHS during deceleration in Bag 1

Figure 12 shows the cold start behaviour of the different systems related to hydrocarbon-emission. Due to the smaller catalyst diameter and the lower thermal mass, light-off of the metal system is slightly advanced compared to the production system. The behaviour of the two 400cpsi-metal converters with different lengths is more or less identical, they both end up at the same emission level. The metal substrate with 800cpsi has a clear advantage regarding light-off behaviour, which reduces the HC-cold-start emission by another 12%.

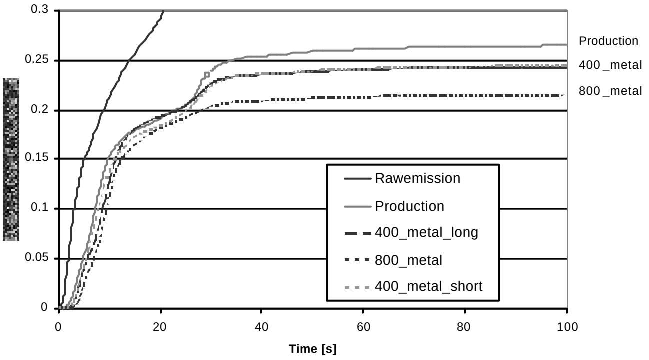


Figure 12: Cold start behaviour of the different test catalysts

The faster heating-up of the metal system is also shown by the temperature curves behind the catalyst. Figure 13 shows the inlet temperature and the temperature behind the first brick of the ceramic system and the long version of the 400cpsi metal converter, which both have the same volume.

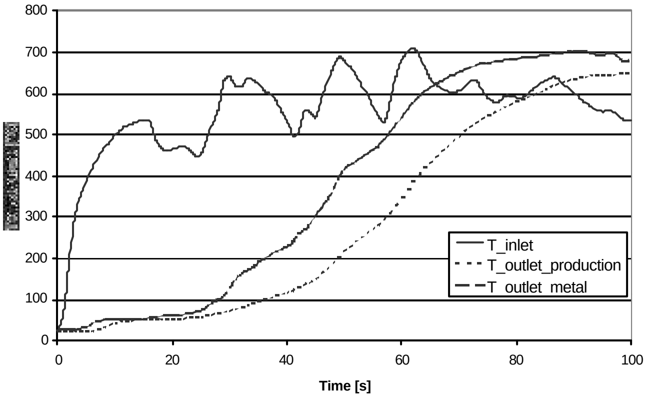


Figure 13: Temperatures behind first brick of production system and long version of 400cpsi metal converter

Taking a look at the weighted FTP-results of all three pollutants, only little differences between the systems occur. As already shown for the coldstart, HC-emissions decrease slightly with lower thermal mass and higher geometric surface area.

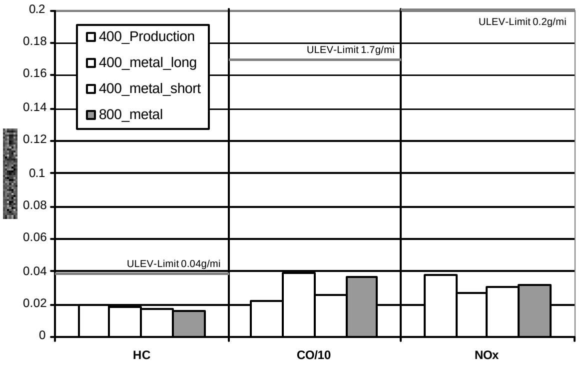


Figure 14: Weighted FTP-results of the different systems (fresh)

This effect is not obvious for the CO-emission, which is probably related to influences of the engine management system and lambda control, which was not seperately adjusted to the different test catalysts. Figure 15 shows the CO-conversion rate and the feedgas- and tailpipe oxygen-concentrations during a 150s-period of phase 2 in FTP-test. It is obvious that the CO-conversion is only limited by the amount of oxygen available in the exhaust gas, while HC-conversion rate for this period is constantly at 99.99 %.

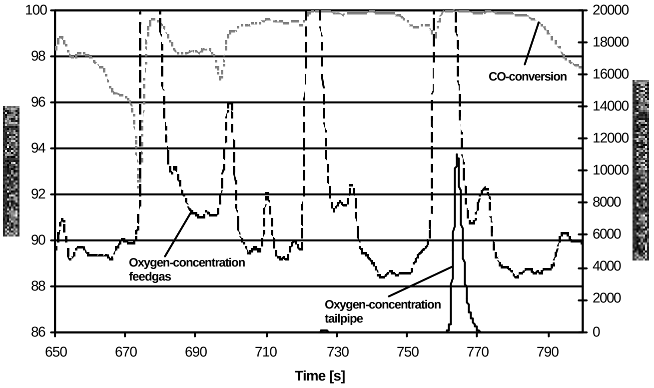


Figure 15 : CO-conversion rate and oxygen concentration in phase 2 of FTP-test

The comparison of the weighted FTP-results showed that all systems are well below the legislation limits of ULEV at fresh condition, even if the system is originally designed for LEV-legislation. What is of great importance is to prove the catalytic durability of the system. Therefore the long version of the 400 cpsi metal substrate and the 800 cpsi metal substrate were aged on an engine bench according to ZDAKW-aging procedure [8], which is comparable to a 50000 mile aging on german autoroutes. The aged systems were again tested in the FTP-test cycle.
The results are shown in Figure 16.

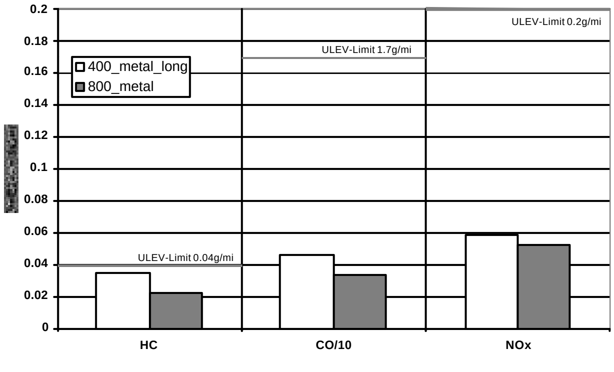


Figure 16 : Weighted FTP-test results of the aged metal systems

The 400cpsi metal system is still significantly below LEV and even ULEV-limits, even with the reduced catalyst volume compared to the production system (metal system has approximately 60% of volume). This leads to a cost saving potential of about 100$ regarding only the precious metal cost for a complete aftertreatment system, calculating that the metal converter has the same precious metal loading as the first brick of the production system.

A greater safety margin can be obtained with the same catalyst volume, but an increased cell density. Under aged conditions, the advantage of the higher mass transfer and higher GSA of the 800cpsi-converter is obvious, which leads to an HC-value of about 50% ULEV even after aging, while simultaneously reducing the other pollutants CO and NO_x. The NOx-value is just about the ULEV LEV II limit (0.05g/mi at 50,000 miles), which should be obtainable by more closely integrating the engine management system calibrations with the emission system.

5. SUMMARY

To design a catalyst system for a certain application and specific requirements regarding catalyst efficiency, system cost and pressure loss, several parameters can be adjusted.

- For cold-start thermal mass and heat transfer is of great importance
- Thermal mass is mainly influenced by the wall thickness of the substrate
- Heat transfer is depending on hydraulic diameter and geometric surface area (cell density)
- Under warmed-up conditions, mass transfer is the determining factor
- Mass transfer is a function of catalyst diameter, cell density and wall thickness

Using these parameters, a catalyst system with optimized volume and therefore system cost can be designed, keeping efficiency and pressure loss at the required level.

- Measurements on the chassis dynamometer showed equivalent efficiency for the volume reduced metal system compared to the production system under fresh conditions
- Even after catalyst aging, ULEV-standard is still achieved
- By using higher cell density, the efficiency under aged conditions can be increased
- Due to volume reduction, a significant cost saving can be obtained regarding precious metal cost and therefore total system cost

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