Particulate Filter Made of Cordierite
Design and Regeneration Management

Ceramic filters based on silicon carbide (SiC) are widely used in current diesel particulate filters for passenger car applications. Filters based on cordierite ceramics are produced at lower costs and offer several advantageous technical features. However, a widespread use has been impeded as yet by the lack of a robust regeneration strategy, which provides for a safe soot burning under all operating conditions by the reliable control of high regeneration temperatures. Bosch has developed a complete filter system consisting of a cordierite particulate filter and the regeneration management software "DPF-AC".

1 Introduction

As a result of both future particulate emission limits and a heated public debate about particulate matter, the particulate filter became an inherent part of diesel power engines for passenger cars today and in future. The filter is periodically regenerated every 500 to 1000 km to keep pressure loss and fuel consumption low and to ensure engine protection. The regeneration is carried out by means of engine measures (injection and air supply), by which the temperature inside the filter is increased above 600 °C under almost all operating conditions. At these temperatures, the soot is completely oxidised to CO_2 in the catalytic coated filter. The soot oxidation is a highly exothermic solid-gas reaction with high activation energy. Thus, depending on soot load and operating conditions, soot burning can result in short-term peak temperatures above 1000 °C inside the filter. This necessitates the use of engineering ceramics with good high-temperature stability, e.g. silicon carbide (SiC). However, SiC has some major disadvantages, such as poor thermal shock behaviour as well high material costs and a complex and costly production based on the assembly of segmented honeycomb bodies. As a result, the quest for more cost-efficient DPF material solutions is ongoing. The introduction of De-NO_x reduction methods such as SCR (Selective Catalytic Reduction) NSC (NO_x Storage Catalyst) will further increase the cost pressure on components for exhaust gas treatment. Among the established engineering ceramics Cordierite offers the best balance between cost and function. Despite the excellent thermal shock behaviour, Cordierite-based particulate filters have not found their way to passenger car applications due to the lower melting temperature compared to SiC. An approach to avoid thermally induced damages is the reduction of specific soot load, which in turn would result in shorter intervals between regenerations and higher fuel consumption compared with SiC filters. Hence, a soot load of 8 g/l being a typical value for SiC filter has been a fundamental prerequisite in the development of the presented DPF system. Besides the avoidance of thermally induced damages, the temperature inside the filter has to be limited to minimise potential interactions between the ceramics and accumulated ash. Reactions with ash might occur during long exposition above 1000 °C leading to glazing of the filter surface or to the formation of material phases with unfavourable properties. Nevertheless, Cordierite is capable of withstanding ash reactions during short-term exposition even above 1000 °C. Requirements as well as first approaches to limit peak temperatures have been described elsewhere [1, 2]. A comprehensive concept suitable for series production has been missing as yet. Thus, the main focus of the present work is the development of both, appropriate filters meeting also future particulate matter regulations and an intelligent and predictive regeneration strategy to

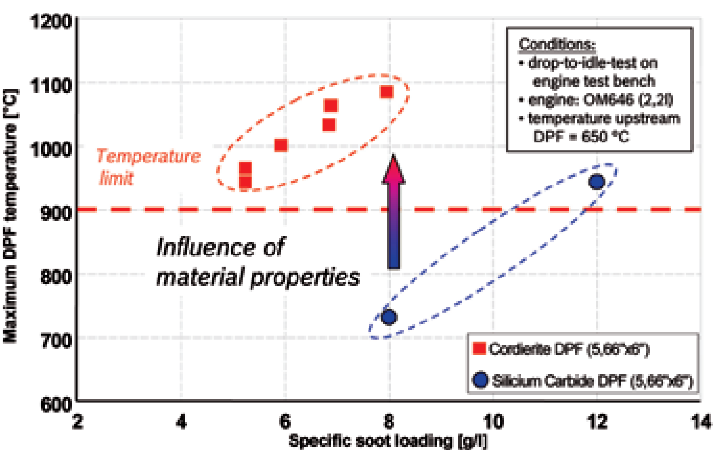

Figure 1: Measured typical maximum temperatures inside DPF as a function of the specific soot loading for cordierite and SiC particulate filters

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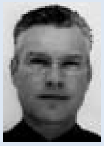
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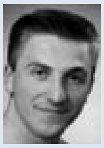
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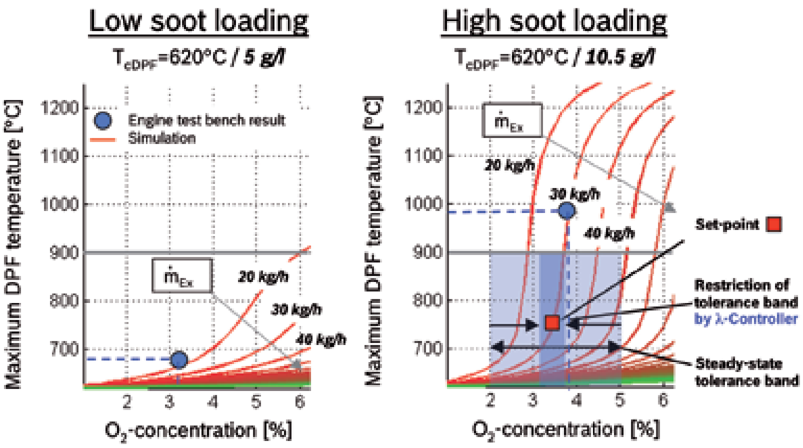

Figure 2: Calculated maximum temperatures inside cordierite DPF for medium (left) and high (right) soot loading

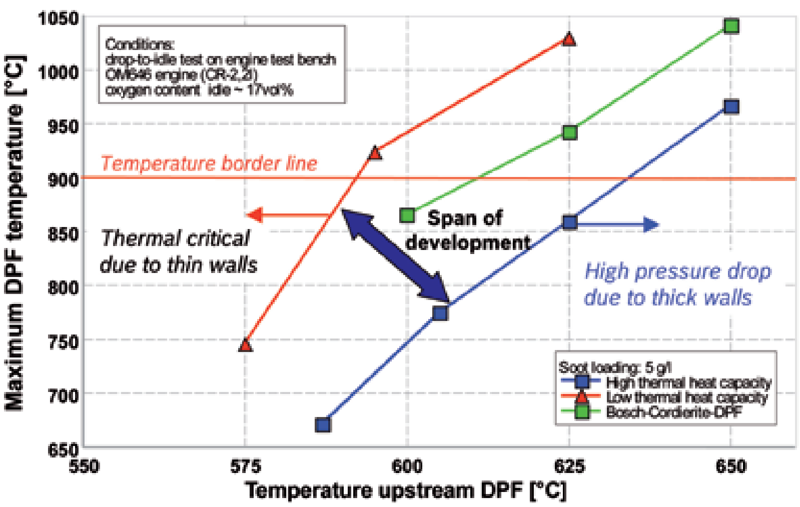

Figure 3: Maximum DPF temperatures measured on the engine test bench during „drop-to-idle test" as a function of DPF inlet temperature for different DPF geometries with low, medium and high heat capacity

prevent uncontrolled regenerations under all operating conditions.

2 Challenges of Cordierite Application

The temperature increase inside SiC and cordierite particulate filters during so-called „worst-case regenerations" is shown in **Figure 1**. Filters have been loaded with a defined amount of soot on an engine test bench and afterwards been heated up to regeneration start temperature by means of engine measures. After a fixed regeneration period the engine was dropped to idling. Inside the cordierite filter, peak temperatures well above 1000 °C were observed due to high oxygen content in the exhaust in conjunction with a small exhaust mass flow. Owing to the higher volumetric heat capacity and thermal conductivity of SiC, peak temperatures in this filter lie up to 200 K below those in the cordierite filter under comparable conditions. Under low-load engine conditions, the dependence of temperature and oxygen content in the exhaust gas shows a strong sensitivity with increasing soot load. Simulation results of cordierite filters at medium (5 g/l) and high soot load (10.5 g/l) are given in **Figure 2**. At low mass flows oxygen contents below 4 vol. % have to be reached to avoid high peak temperatures. Since oxygen contents around 17 vol. % are observed under low-load engine conditions, the oxygen content needs to be lowered systematically by engine measures. However, due to inherent system tolerances, especially in the air management, a pure engine-based control of the oxygen content is not sufficient. Deviations of ± 1.5 vol. % at the design point of 3.5 vol. % may result in undesired temperature increases inside the filter. Only with a precise lambda control the oxygen content in the exhaust gas can be limited within ± 0.25 vol. %, hence avoiding excess temperatures in low-load engine conditions. Besides the lambda control, attention is turned to an accurate exhaust temperature control upstream the filter, as emphasised in **Figure 3**. Worst-case regenerations have been applied to cordierite filters with different designs by varying the temperature upstream the filter. Filters with high wall thickness (i.e. high heat capacity) show moderate temperature sensitivity. However, the pressure loss especially with catalytic coatings is very high. Vice versa, thin-wall filters show advantageous pressure loss behaviour, however at the expense of high temperature sensitivity due to their low heat capacity. In the latter case, even an overshooting of the temperature set point by less than 25 K results in unacceptably high peak temperatures under worst-case conditions. Hence, a robust system design requires well-balanced pressure loss behaviour and high-temperature stability, as complied with the Bosch particulate filter, **Figure 4**.

3 Characterisation of the Cordierite Particulate Filter

The features of the Bosch particulate filter are the characteristic materials properties, in particular the advantageous pore size distribution, and the innovative asymmetric cell design with different cross-sections and numbers of inlet and outlet channels („hexahex" design), Figure 4. This asymmetric design offers a lower pressure loss and a better soot and ash loading behaviour than symmetric designs. Hence, at a comparable pressure loss level, smaller filters can be applied than with a symmetric design in close-coupled applications. The cell density of the hexahex design is 290 cpsi at a wall thickness of 13 mil. The specific volumetric heat capacity of 550 J/(l K) at 500 °C is comparable with that of the symmetric filter (300 cpsi/ 13 mil). Unlike known asymmetric cell designs [3, 4], the outlet channels of the hexahex design show a higher hydraulic diameter than the inlet channels resulting in low downstream laminar channel losses. Moreover, there are more inlet channels than outlet channels (ratio 2:1). From each inlet channel the exhaust gas flows into three outlet channels, of which each is coordinated by six inlet channels. Engine test bench measurements reveal a pressure loss advantage of about 20 % for the hexahex design, Figure 4.

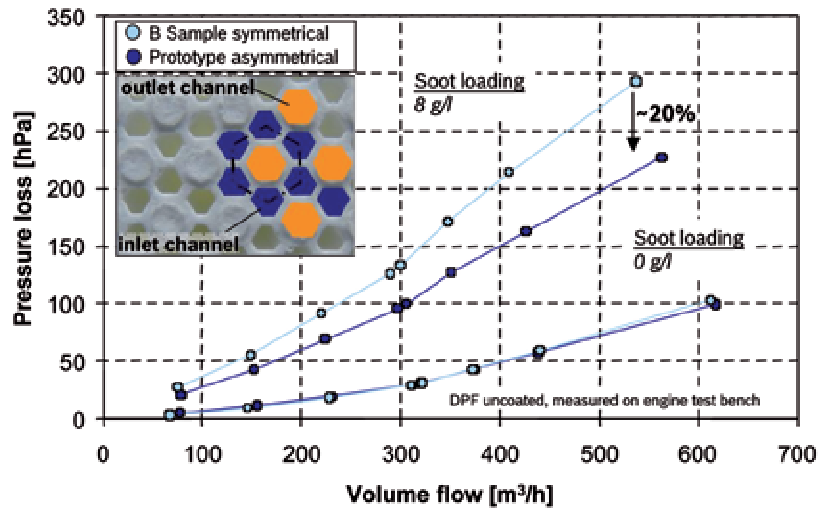

Figure 4: Hexahex BPF design and comparison of the pressure loss with symmetric cell design (300 cpsi/ 13 mil)

4 Temperature and Lambda Control

4.1 Temperature Control

The temperature controller is designed as a cascade of two PI controllers, **Figure 5**. The inner cascade controls the temperature upstream the diesel oxidation catalyst (DOC) by the attached post injection. Thus, the DOC temperature will be increased up to light-off so that subsequently a release of the late post injection will be effected. The outer cascade acts on the late, torque-ineffective post injection amount, whereas a DOC model combined with operation point data is used to calculate a map-based pilot control quantity. The late post injection amount is completely oxidized in the catalyst resulting in the target temperature upstream DPF. Depending on the application, the ratio of both cascades can be weighted differently. Because of the model-based DOC approach within the ECU, temperature dynamics upstream DPF can be precisely determined and a transition of the operation point can be quickly adapted. Thus, depending on the operational profile, an accuracy of temperature control in a range of ± 25 K can be achieved.

4.2 Lambda Control

The lambda control, **Figure 6**, is based on a lambda sensor, which is in this example placed in front of the DOC. Its measured value is compared with a target map depending on engine speed and

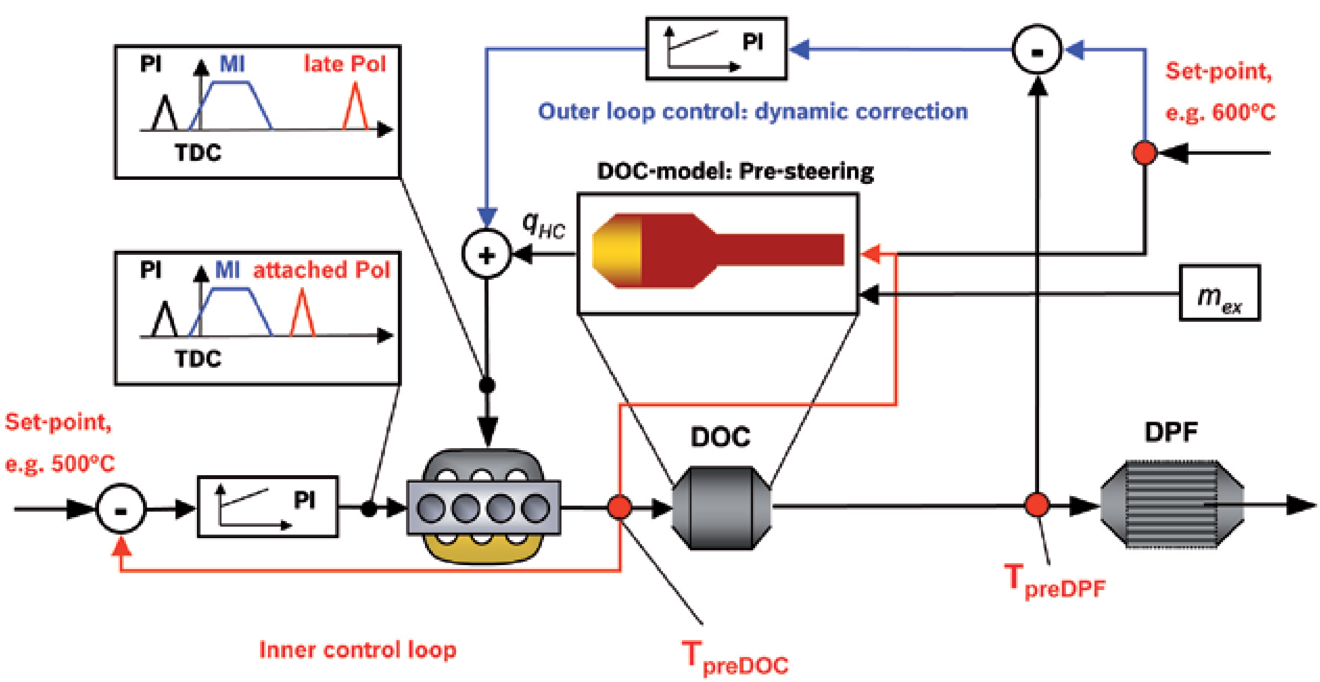

Figure 5: Structure of the cascaded temperature controller

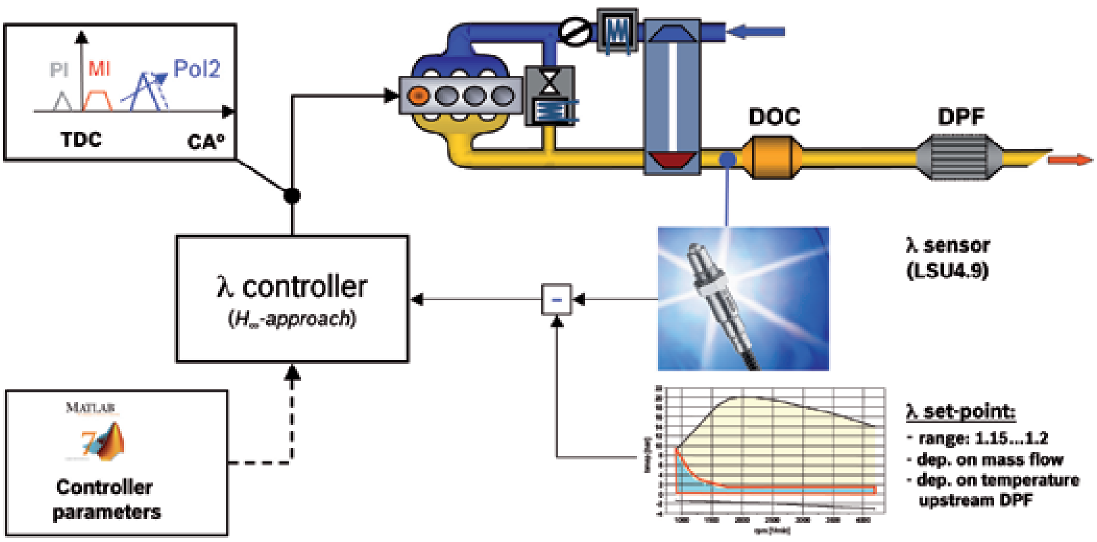

Figure 6: Structure of the lambda controller

load. The lambda controller, which is comparable to that in the three-way-catalyst as well as in the NO_x storage catalyst application, adjusts the deviations. The parameterization of the controller, which is designed by the H_∞-approach, can be done by a Matlab-based calculation tool. The control variable is the post injection closely attached to the main injection.

4.3 Temperature Management

At high soot loadings (> 6-8 g/l) the risk of an uncontrolled temperature increase inside the DPF is most likely in case of an unfavourable transition of operation point during the beginning of the regeneration phase. Therefore, the regeneration is started at a comparably low temperature upstream DPF, which is gradually increased with proceeding soot oxidation. The information of the soot oxidation progress is given by an ECU-integrated DPF regeneration model. This model delivers the actual temperatures in addition to the summarized average soot loading to determine the next value for the desired regeneration temperature. With increasing soot mass, the combustion of the particulates is accelerated and therefore the required time for regeneration is reduced. **Figure 7** shows a step-wise temperature profile during a regeneration phase under city driving conditions. The exhaust gas temperature upstream DPF can be controlled at the desired high level with high precision, even though a low average speed of 18 km/h and a high fraction of idle conditions in a range of 40 % are applied. This approach offers advantages at low engine load, where the generation of high exhaust gas temperatures required for DPF regeneration is difficult.

4.4 Application Area

As the temperature and lambda values can not be adjusted independently, the engine map, **Figure 8**, has to be divided

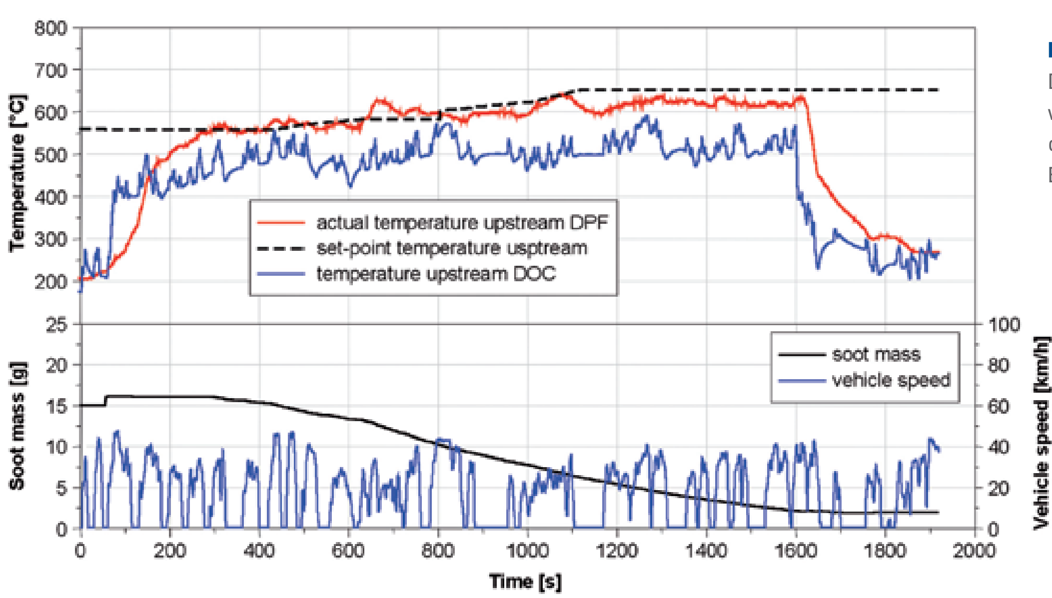

Figure 7: Measured DOC and DPF inlet temperatures in the vehicle under city-driving conditions as well as calculated ECU soot mass

into a temperature controlled and a lambda controlled area.

Whereas the lambda control is principally active at low engine load, the temperature control operates at higher loads.

Thus, the interaction of both controllers becomes clear: while at low engine load an oxygen control is required as a short-term measure, a precise temperature control acts as a predictive measure as the filter temperature changes considerably slow and therefore has to be adapted to the actual soot loading conditions. During lambda control operation, the resulting temperature upstream DPF has to be considered, it is, however, not taken as set point.

Additional measures for overrun conditions are necessary, because fuel injection and therefore lambda control can not be activated. Hence, the intake of further fresh air is shut off by completely closing of the throttle flap.

In parallel, the EGR valve is opened to circulate the exhaust gas in an inner loop of the engine. Thus, the feeding of oxygen-containing exhaust gas and the resulting acceleration of soot oxidation will be avoided.

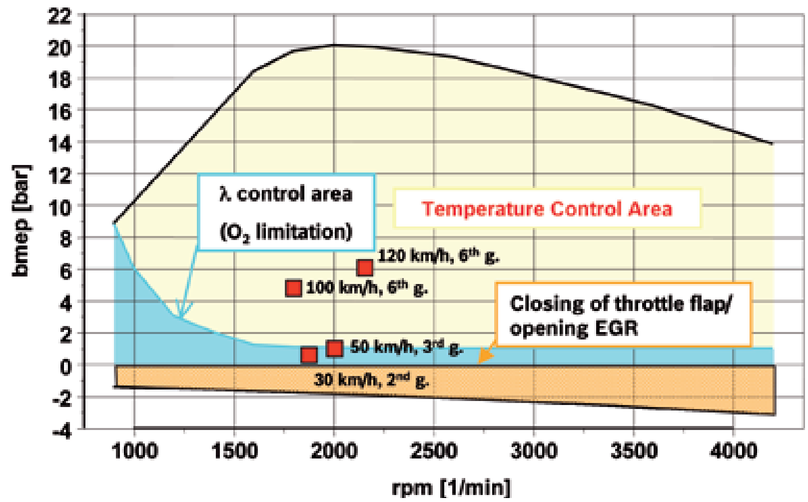

Figure 8: Speed-load engine map of the investigated 2.2 l common rail diesel engine with specific application areas

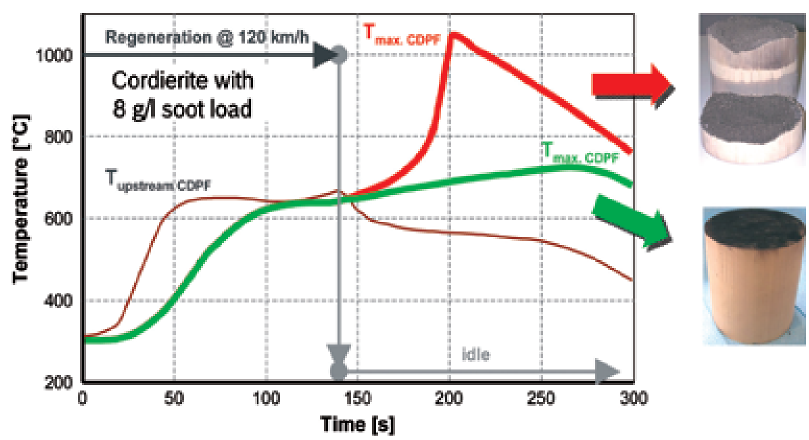

Figure 9: Measured maximum temperatures inside a cordierite DPF (5.66“x6“) with 8 g/l soot loading with and without lambda control during „drop-to-idle test“

5 Engine and Vehicle Results

5.1 Engine Results

Before initial operation of the application in the vehicle, the effectiveness of the DPF-AC functionality was tested on the engine test bench. Cordierite DPFs were instrumented with up to 48 thermocouples with the main focus in the rear part of the DPF body, where the peak temperatures during a worst case regeneration are observed. **Figure 9** shows a comparison of a cordierite DPF with a specific soot loading of 8 g/l with and without lambda control during a drop-to-idle test. Whereas temperatures above 1000 °C inside the DPF can occur without lambda control, the maximum temperature can be limited below 700 °C by the lambda control of the exothermal reaction.

5.2 Vehicle Results

The vehicle testing of the application was performed with Mercedes-Benz E-class vehicles with 2.2 l common rail diesel engine. First investigations were done with a series engine on EDC16 engine management basis and an Ascet bypass interface. In the next step, the compression ratio was decreased from 18 to 16 and the solenoid injection system CRS 2.1 was replaced by a piezo system CRS 3.0 and EDC17 engine managment. In both cases, the series throttle flap was replaced by a flap having a higher tightness with a leakage flow of 2-3 % under totally closed conditions. All functions of the DPF-AC control strategy were integrated into the EDC17 software. The exhaust gas system consisted of a series canning with a 5.66"x6" close-coupled DOC as well as a close-coupled DPF of same size. The series SiC-DPF was replaced by a catalytic coated Bosch cordierite DPF, which was instrumented with eight thermocouples. For most precise information of the soot loading state, the filters were loaded to 8 g/l and 12 g/l (exactness ± 0.5 g/l) on the engine test bench and afterwards mounted to the vehicle. For verification of the functionality, about 80 regenerations were conducted under well-defined city-driving conditions with low average speed and long idle as well as long overrun phases. Here, the peak temperatures inside filter did not exceed 900 °C at any time.

5.3 Vehicle Endurance Test Results

The experiments described in 5.1 and 5.2 have proven the principal feasibility of a robust cordierite application. For a final assessment of the road capability, a fleet test with four Mercedes-Benz E-class

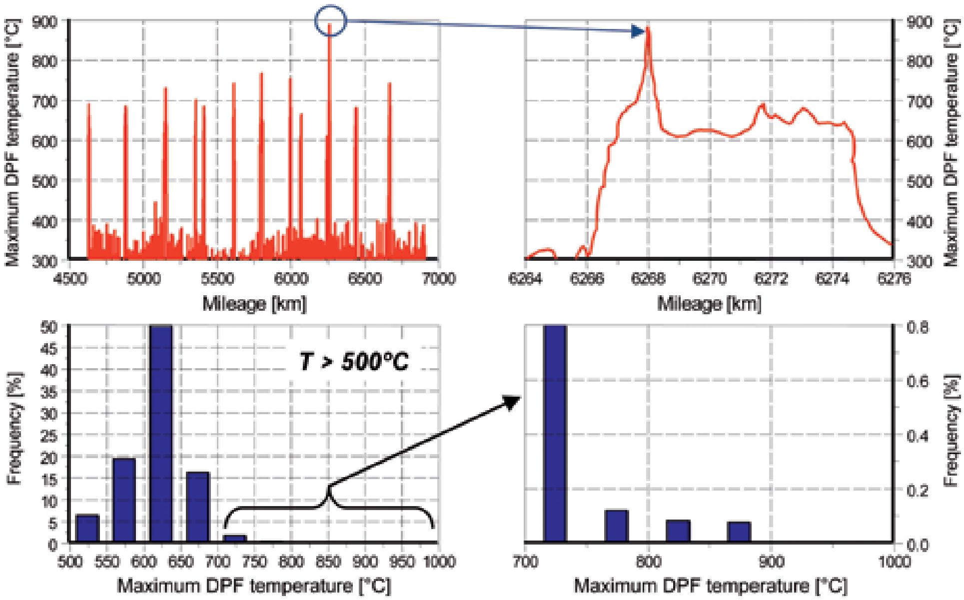

Figure 10: Example of regeneration profiles with focus on maximum temperatures and frequency-distribution of the DPF maximum temperatures measured in city-operated vehicle

vehicles under real-life conditions with a target mileage of 400.000 km has been started. Two vehicles have been operated under city driving conditions while two vehicles have been tested in mixed operation (33 % city, 46 % federal road, 21 % highway). The regeneration is triggered at an ECU value of 6 g/l, but for tolerance reasons of the soot load monitoring also trigger values of 9 g/l are possible. Temperatures in the exhaust line and inside the particulate filter as well as pressure loss over DPF are recorded and stored by a data logging system. The vehicles are periodically checked on the emission roller test bench (HC and NO_x, CO, PM). The filter masses are determined to check for ash and soot loading. Additionally, oil samples are periodically analysed by GC measurement to monitor the oil dilution (portion of diesel fuel in engine oil). The oil dilution for the vehicles in mixed-operation mode was in a range of 8 to 10 % as a forecast for 30.000 km according to the existing results. The temperatures inside DPF have been continuously recorded by eight thermocouples. The analysis of approximately 500 regeneration events of all four vehicles showed that the peak temperature inside DPF during regeneration was always within the target area between 700 °C and 900 °C. The maximum temperature profiles inside filter of a city-operated vehicle as well as the frequency distribution of the regeneration temperature > 500 °C are shown in **Figure 10**. The constantly high filtration efficiency of the cordierite DPFs has been demonstrated for all vehicles on the emission roller test bench and by a soot-free exhaust tailpipe („wipe test“).

6 Summary

Because of the increasing cost pressure on the diesel engine driven by complex and costly $DeNO_x$ exhaust gas treatment systems, all exhaust line components have to be reviewed regarding costs and function. SiC-based ceramic particulate filters have ful-filled the task of particulate limitations very well, but the costs can be significantly reduced at same effectiveness. The Bosch cordierite DPF (BPF) has comparable functionality as SiC-DPFs. As a required measure a new regeneration management has been developed. The Advanced Control regeneration strategy DPF-AC represents a robust element within the complete system, which helps to avoid thermal damage of the cordierite DPF at high soot loadings, so that a safe and reliable regeneration under all operation conditions is possible. DPF-AC makes use of an existing SiC application as a starting point to keep the additional effort for DPF-AC function integration at low level. The numerous engine and vehicle tests as well as the positive endurance test results underline the feasibility of the integrated concept.

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