

Thermal Shock Protection for Diesel Particulate Filters

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ABSTRACT

During a thermal regeneration of a Diesel particulate filter (DPF) the temperature inside the DPF may raise above critical thresholds in an uncontrolled way (thermal shock). Especially driving conditions with a comparable low exhaust gas mass flow and high oxygen content like idle speed may create a thermal shock. This paper presents a concept for an ECU software structure to prevent the DPF from reaching improper temperatures and the methodology in order to calibrate this ECU structure.

The concept deals in general with a closed-loop control of the exhaust gas air-fuel-ratio during the critical engine operation phases. Those critical operation phases are identified at the engine test bench during "Drop-to-Idle" and "Drop-to-Overrun" experiments. The experiments show that those phases are critical having on the one hand a low exhaust gas mass flow and on the other hand a high oxygen percentage in the exhaust gas. Based on the experiments an ECU function is designed in order to detect the critical phases during real world driving conditions. As the DPF temperature and the DPF soot loading are two main criterions for critical operation phases a very accurate knowledge of these values is required. So a calibration method using nonlinear optimization is established which allows an accurate calibration of the ECU's soot combustion model. The DPF temperature itself is determined by using a discrete temperature model of the DPF which is based on the heat transfer between the exhaust gas and the catalyst brick while taking into account the exothermic heat of the soot combustion.

The air-fuel-ratio (AFR) is set to a nearly stoichiometric value during the critical occurrences by raising the exhaust gas recirculation (EGR) rate on the one hand and an exactly dosed fuel injection on the other hand. Using a measurement of the AFR after turbocharger the throttle of the engine is used for a closed-loop control of the AFR. The fuel injection is realized with an external fuel injector which was available on the used truck engine. In order to decrease the AFR the fuel quantity injected by the external injector is converted within in the Diesel oxidation catalyst (DOC). As there is no AFR measurement after DOC a modelled AFR is taken into account downstream DOC. For the calibration of the closed-loop controllers advanced methods were used in order to achieve a fast and accurate control.

By those measures the temperature increase inside the DPF can be reduced or even avoided so that also under critical driving conditions there is no damage on the DPF expected.

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INTRODUCTION

Diesel Particulate Filters (DPF) are essential in order to meet the requirements of the latest emission legislation levels for Diesel engines. Wall-flow DPF-systems filtrate the exhaust gas and oxidise the soot in regeneration phases. In order to achieve the activation energy the temperature within the DPF has to be raised to 600 - 650°C. Under special driving conditions the temperature within the DPF may rise

up to a level significantly beyond this target range which can damage the DPF ("thermal shock").

Table 1 shows different types of damages a DPF may face due to too high temperatures. It has to be ensured that temperatures inside the DPF do not exceed 850°C at any time as this would initiate the deactivation of the catalytic coating of the DPF.

Table 1. Temperature depending damages on DPF [1]

type of damage	temperature inside DPF
deactivation of coating	850-1000 °C
sintering of ash	900-1100 °C
adhesion of ash	1100-1200 °C
corrosion due to ash	1200-1400 °C
crack formation, melting	1400-1700 °C

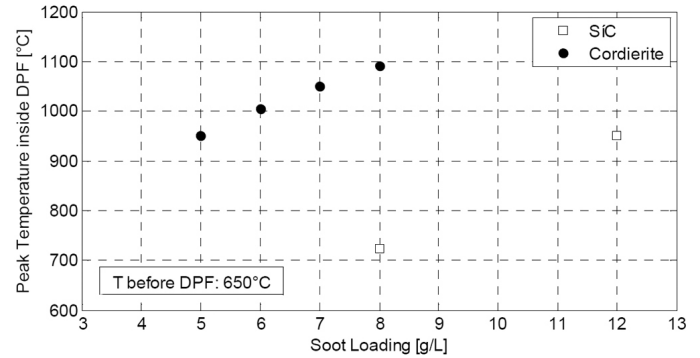
In order to create a strategy to avoid high temperatures first of all the critical driving conditions need to be evaluated. The strategy will be defined by this result. Furthermore, the calibration of the closed-loop controllers used in the strategy will be performed using an advanced controller calibration tool.

CRITICAL CONDITIONS FOR THERMAL SHOCKS

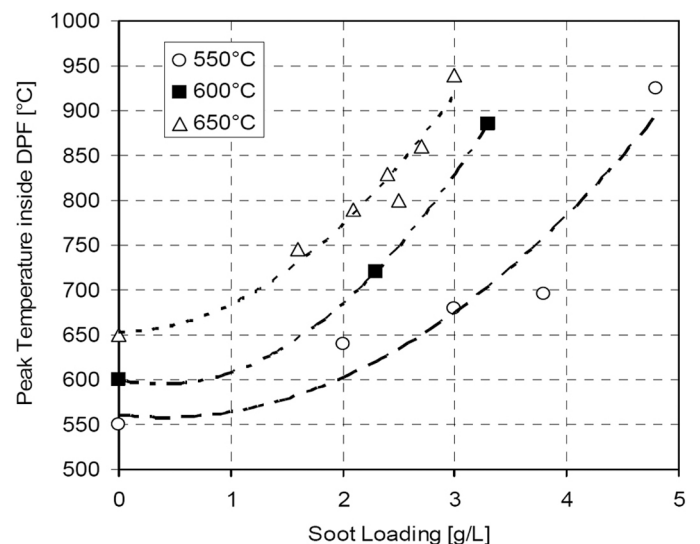
Thermal shocks occur when the thermal equilibrium of the DPF during a thermal regeneration gets out of balance. Heat is generated inside the DPF by exothermic oxidation of carbon (soot) to carbon dioxide. The heat gets dissipated mainly by the exhaust gas. If the exhaust gas mass flow is too low, the temperature inside DPF will raise as not sufficient heat gets dissipated.

LITERATURE RESEARCH

A literature research has been performed in order to reduce the test bench experiments. Literature shows that the occurrence of thermal shocks depends on several factors. First of all, the peak temperature inside the DPF depends on the soot loading. Higher soot loadings cause higher temperatures. [Figure 1](#) shows the peak temperatures inside the DPF for different soot loadings. A linear behaviour can be assumed for the given soot loadings. [Figure 1](#) also shows the influence of different DPF materials. While the peak temperature inside silicon carbide (SiC) filters is still moderate (720°C) at medium soot loadings, the temperature inside cordierite filters exceeds the critical temperature of 850°C even at lowest soot loadings. This effect is based on the different heat conductivity coefficients of silicon carbide (70-270 W/(mK)) and cordierite (1-3.2 W/(mK)) [2, 3].

**Figure 1. Peak temperature inside DPF depending on soot loading [4]**

Besides the soot loading and the material, the exhaust temperature at the DPF inlet also influences the peak temperature inside the DPF. [Figure 2](#) shows the peak temperatures of different thermal shocks depending on the inlet exhaust gas temperature and soot loading. With rising exhaust gas temperatures the peak temperatures inside the DPF also increases. As a general reduction of the regeneration temperature would lead to an increase of the regeneration duration [5], some manufacturers start regenerations with lower temperatures to reduce the risk of thermal shocks and increase the temperature with the progress of the soot combustion [6]. Another approach is the reduction of the oxygen mass flow [4, 7, 8] as oxygen - besides the temperature which indicates the necessary activation energy for the soot combustion - is the central factor for the intensity of the soot combustion.

**Figure 2. Peak temperature inside DPF depending on DPF inlet temperature [9]**

TEST BENCH EVALUATIONS

A cordierite DPF is equipped with 26 thermo couples to detect temperature peaks and gradients in the entire DPF. To ensure comparability during the test bench evaluations the DPF soot loading is always approximately 5 g/L. The soot loading gets ensured by using a steady-state operation point for the DPF loading and the monitoring of the delta-pressure signal over the DPF.

As engine operation points with low exhaust gas mass flows seem to be critical, the experiments are performed as “drop-to-idle” and “drop-to-overrun”-experiments. Within those experiments the regeneration is initiated at a medium loadpoint. When soot combustion is detected the engine is set into idle-speed resp. overrun. In these operation areas there is also comparable high oxygen content. Thus, the exothermy of soot oxidation (increased due to higher oxygen content) and the heat dissipation through the exhaust gas do not equal anymore and the temperature inside the DPF rises.

The strategy to avoid thermal shocks shall also be capable to avoid a worst case thermal shock. Therefore all test bench evaluations are performed with the standard regeneration temperature of 600°C. Furthermore the “drop-to-idle” experiment shall be performed directly after the beginning of the soot combustion to ensure that the soot loading is still at the level of 5 g/L.

Table 2. Selected position of temperature sensors inside DPF

#	x_{axial} [%]	y_{radial} [%]	φ [°]
1	8.2	0.0	0
2	36.1	0	0
4	91.8	0.0	0
5	8.2	37.3	-45
6	36.1	37.3	0
9	82.0	37.3	-75
10	85.2	37.3	-85
14	95.1	37.3	-120
16	36.1	63.4	0
17	63.9	63.4	45
20	36.1	89.6	0
22	91.8	89.6	90
26	91.8	97.0	90

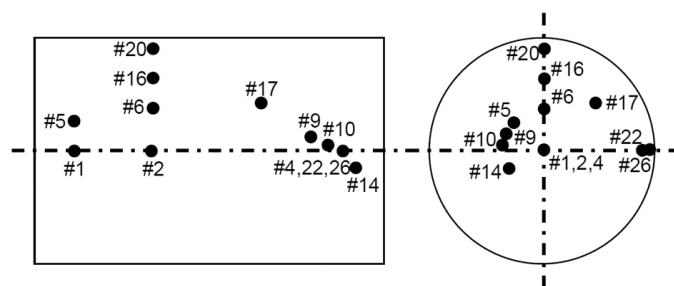


Figure 3. Selected position of temperature sensors inside DPF

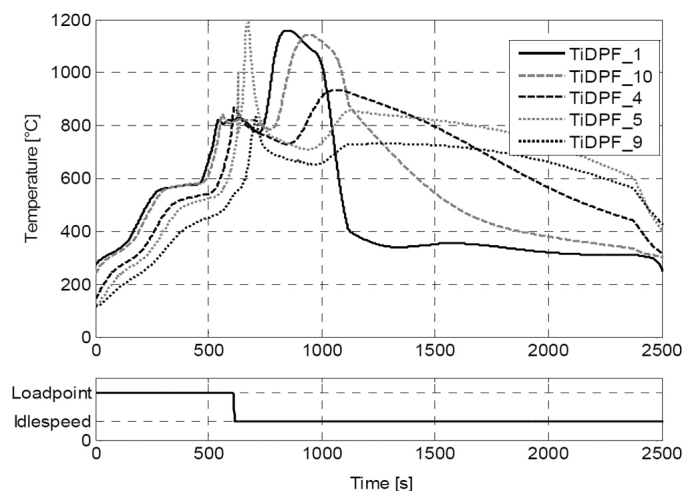


Figure 4. Thermal shock after drop-to-idle

Figure 4 shows the temperature at different positions inside the DPF. The engine is set to idle speed from a load point (2000 min^{-1} , 7.5 bar, medium-duty truck engine) directly after the detection of the combustion of the soot. The temperature rises locally up to 1200°C inside the DPF immediately after the drop-to-idle in the front end of the DPF (see TiDPF_5 in Figure 4). The heat front travels inside the DPF until all soot is burned. Figure 5 shows the temporal temperature gradient at two selected measurement points inside the DPF assuming that the soot is locally burned off completely. In this case, the temperature itself and the temperature gradient increase and decrease very fast. The figure also shows that the behaviour at thermo couple 1 is different as the gradients are lower, however, the absolute temperature is as high as at thermo couple 5. The spatial temperature gradients in Figure 6 even show the local heat release where the gradients in radial direction are significantly higher than in longitudinal direction which can be explained by the exhaust gas flowing against the center of the DPF and the colder DPF canning.