SAE TECHNICAL
PAPER SERIES

2008-01-0328

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Reprinted From: Diesel Exhaust Emission Control, 2008
(SP-2154)

ISBN 978-0-7680-1635-2

SAE International™

2008 World Congress
Detroit, Michigan
April 14-17, 2008

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ISSN 0148-7191

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ABSTRACT

Diesel particulate filters are expected to be used on most passenger car applications designed to meet coming European emission standards, EU5 and EU6. Similar expectations hold for systems designed to meet US Tier 2 Bin 5 standards. Among the various products oxide filter materials, such as cordierite and aluminum titanate, are gaining growing interest due to their unique properties. Besides the intrinsic robustness of the filter products a well designed operating strategy is required for the successful use of filters. The operating strategy is comprised of two elements: the soot estimation and the regeneration strategy. In this paper the second element is discussed in detail by means of theoretical considerations as well as dedicated engine bench experiments. The impact the key operating variables, soot load, exhaust mass flow, oxygen content and temperature, have on the conditions inside the filter are discussed. Their practical relevance and the ability to use them for control purposes is analyzed. Guidelines are presented that should be considered when applying oxide diesel particulate filters. The differences between oxides and materials with higher thermal conductivity are discussed with respect to the relationship between regeneration conditions and the achievable regeneration efficiency. Experimental data show benefits for oxide materials vs. SiC, expected to come from their low conductivity. For the regeneration strategy a simple approach is proposed and illustrated by means of examples. The benefits of a staged regeneration approach are discussed, using two temperature levels during the regeneration.

INTRODUCTION

The application of particulate filters to European passenger cars with diesel engines continues growing at a fast rate. For the next level of European emission legislation for passenger cars, EU5, it is expected that most diesel engines will have to be equipped with a diesel particulate filter to meet the further reduced emission standards. While most initial filter installations have been in the underfloor position, a trend can be observed that whenever possible the filter component is installed as close to the turbo outlet as possible (close coupled installation). Although beneficial for the operation due to the reduced heat losses and more passive regeneration, this integration into the engine compartment goes along with significantly tighter packaging constraints. As a result, filters are designed smaller than they have been in the first applications. Since the maximum soot capacity is usually related to the soot mass per volume of filter this may impact the operating strategy. Whereas for current European EU4 passenger car emission legislation the particle filter was not always required to meet the particle emission targets, this may change for the enhanced requirements of coming EU5 and especially EU6 and US Tier 2 Bin 5 regulations. Significantly reduced particulate emissions, mass and, at least in Europe, also number may have to be met in combination with longer lifetime requirements. To meet these requirements robust filter solutions as well as advanced filter operating strategies may be required. For the filter different materials are available today. While first passenger car applications included SiC filters, oxide based filter products, such as aluminum titanate and cordierite receive increasing attention [1]. Aluminum titanate filters (DuraTrap® AT) have been in series production since 2005 with more than 750,000 filters already on the road today [2, 3]. Cordierite filters are a standard solution for heavy duty applications to meet current US 2007 regulations and are expected to be used in some passenger car series applications by 2008 [4, 5].

With respect to the operating strategy two key factors can be identified: (a) the estimation of the soot accumulated on the filter and (b) a robust and reliable regeneration strategy.

Although significant progress has been made [11], the estimation of the soot load by open loop models or closed loop estimation based on a pressure difference across the filter is still subject to uncertainty. This is partly driven by the complexity of this task [6, 7], limited resources to apply and calibrate complex models as well as inaccuracies in sensors (mass flow, temperature, and pressure) used for the estimation. Within this paper we will not discuss these topics but only consider the uncertainty in actual soot mass with respect to the relevance for the regeneration strategy.

The regeneration strategy should allow for a reliable and safe burning of the accumulated soot under all driving conditions. It should also allow for a fast enough regeneration process but, at the same time, manage this burning rate within certain boundaries as it is accompanied by a significant release of heat. Options for this thermal management will be discussed in this paper. We will use theoretical arguments and simulation results as well as results from engine bench experiments with different engines and oxide diesel particulate filters (aluminum titanate and cordierite).

GENERAL ANALYSIS OF THE FILTER REGENERATION PROCESS

Under normal operation of passenger cars the exhaust conditions may not guarantee a continuous oxidation of soot by either oxygen or nitrogen dioxide. Therefore, active regeneration strategies may have to be applied. Today, these are based on increasing the temperature to a level where the oxidation with oxygen occurs at a sufficient rate (usually at T > 550-600°C) [5]. Fuel born catalysts can be used to lower the oxidation temperature [8]. However, many OEMs have chosen not to use this technology.

An effective approach to analyze the regeneration process is to use a simple 0-dimensional model.. Although not capable of exactly describing all the phenomena occurring in a particulate filter it is well suited to understand the general trends, parameters and develop some strategies. The model is well described by a single energy balance and two mass balances, one for oxygen and one for the soot.

$$\frac{dT}{dt} = \frac{\left(-\Delta H_R\right)\cdot R_{C+O_2}}{V_{DPF}\cdot\rho_{DPF}\cdot c_{ps}} - \frac{\dot{m}_G\cdot c_{pG}\cdot\left(T - T_{in}\right)}{V_{DPF}\cdot\rho_{DPF}\cdot c_{ps}} \qquad (1)$$

$$\frac{dm_C}{dt} = \dot{m}_G\cdot\eta_f\cdot w_{C,in} - M_C\cdot\nu_C\cdot R_{C+O_2} \qquad (2)$$

$$\frac{dw_{O2}}{dt} = \frac{\dot{m}_G\cdot\left(w_{O2,in} - w_{O2}\right) - M_{O2}\cdot\nu_{O2}\cdot R_{C+O_2}}{V_{DPF}\cdot(1-\varepsilon_{DPF})\cdot\rho_G} \qquad (3)$$

with

$$\mathrm{R}_{C+O_2} = k_0\cdot\exp\left(-\frac{E_a}{\mathbf{R}\cdot T}\right)\cdot m_C^n\cdot w_{O2}^m \qquad (4)$$

as simplified reaction rate expression for the oxidation of soot by oxygen. In this expression we have replaced the oxygen partial pressure by the mass fraction, as the pressure is assumed to be constant. The soot is represented by its mass, although the surface area would probably the more accurate parameter.

From equations (1) through (4) we can identify the key operating variables for the active regeneration:

- the soot mass on the filter, m_C
- the oxygen concentration, $w_{O2,in}$
- the temperature, T_{in}
- the mass flow of the exhaust, $\dot{m}_G$

The first two basically determine the amount of oxidation reaction that can take place, $R_{C\text{-}O2}$. As the oxidation reaction is exothermic, they also determine how much heat can be released (first term in eqn. (1)). The soot mass is determined by the target value of the design and strategy, plus the uncertainty from the estimation, e.g. this is where the two key elements of the operating strategy, soot load recognition and regeneration, are linked with each other. The oxygen concentration, $w_{O2,in}$, usually depends on the engine operation (especially the load) but can be manipulated to some extend through the use of EGR or intake air throttling as well as oxidation with additional fuel injected late in the combustion cycle or directly into the exhaust (note, that the latter "converts" the oxygen into temperature, one of the other key variables) [9]. Besides the oxygen concentration the oxygen mass (or mole) flow can be relevant, e.g. the product of oxygen concentration and exhaust mass flow (first term in eqn. (3)). This value represents one limit for the rate $R_{C\text{-}O2}$ at which the oxidation of soot can take place. The rate of the oxidation reaction may be furthermore determined by the temperature in the filter (see eqn. (4), Arrhenius law). As can be seen from eqn. (1), this temperature is a function of the temperature of the exhaust gas that enters and leaves the filter (second term) and the heat released during oxidation (first term). As the reaction is exothermic the rate is self accelerated if eqn. (1) is positive, e.g. the heat released during the oxidation exceeds the heat removed. To achieve a sufficient reaction rate the exhaust gas temperature first may have to be raised to heat the filter. However, care has to be taken that the rate of reaction and heat release does not exceed the rate at which heat can be removed from the system. This requirement leads to the fourth key parameter, the mass flow. As the filter generally can be viewed as adiabatic (especially oxide filters with low thermal conductivity), the dominant mechanism for heat removal is by convection. The amount of convective heat flux is proportional to the mass flow and the filter temperature.

During vehicle and engine operation, out of the four variables the oxygen concentration and mass flow can be influenced only within certain limits [5, 9]. The *mass flow* usually is directly related to the required power. It can be reduced but usually it is quite difficult to increase it. Similar constraints apply to the *oxygen* concentration.

The *soot mass* is determined by the target regeneration distance and the engine out emissions. Therefore, it is a variable that can be set to different targets but it is not a free operating variable during the regeneration. The impact of the soot load on the peak temperature within the filter is quite significant and may follow a roughly linear relationship (within typical ranges of soot loads). Examples for the impact of soot on the peak temperature are given in Figure 1. Shown are data obtained during drop to idle experiments with a EU4 engine and a catalyzed aluminum titanate filter. The typical slope of about 70°C increase in peak temperature per g/dm³ increase in specific soot load can be observed. This relationship will be used later for the design of a suitable strategy.

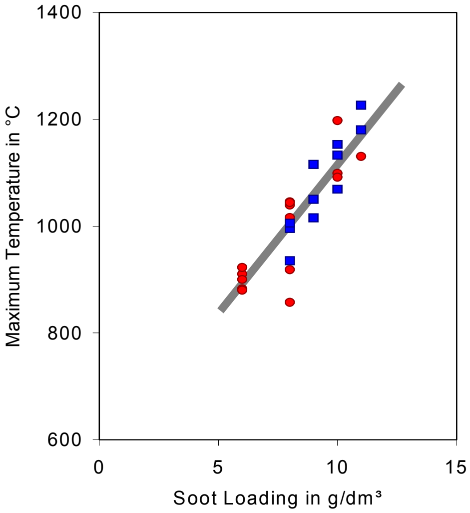

Figure 1. Example for the relationship between peak filter temperature and initial soot load during drop to idle regenerations. Engine: EU4; filter: aluminum titanate. Symbols represent different filters and experiments.

One relatively free variable to work with during the regeneration step is the *exhaust gas* or *filter inlet temperature*. During active regenerations the exhaust gas temperature may be increased anyway by modifying the engine operation.

For this reason, strategies that use the *inlet temperature* as primary control variable are the focus of this paper.

EXPERIMENTAL SETUP AND PROCEDURES

The experimental data used in this paper were generated on the engine bench using different engines, all with modern EU 4/5 common rail fuel injection, cooled EGR, intercooler, intake air throttle etc. Cordierite and aluminum titanate filters in 300cpsi/15mil and 300cpsi/13mil cell density/wall thickness, respectively, were used. The filters had different diameters and lengths, and were installed in close-coupled as well as underfloor type position. The filters were all instrumented with a large number of thermocouples to capture the maximum temperatures, the spatial temperature distribution and the maximum radial and axial temperature gradients. In all cases a DOC was used upstream of the filter.

Only regeneration experiments are considered. The initial soot load was adjusted through a loading step on an engine bench. The actual soot mass was measured by weighing the filter and subtracting the clean weight. The loading was done to achieve the target soot load within roughly ±0.5 g/dm³.

For the regeneration the filter was initially stabilized at 250-300°C for a few minutes. Then the active regeneration step was activated. For steady state regenerations this mode was kept for a desired duration. For severe drop to idle regenerations the engine was switched into idle after a certain criterion was reached, either inlet temperature or time. Then the engine was kept in idle mode for several minutes. At the end of the regeneration the soot mass was measured again to determine the amount of soot burned. Then the filter was fully regenerated prior to the next test cycle.

THEORETICAL ANALYSIS OF STRATEGIES

In this section we will have a closer look at the impact the operating variables have on the thermal conditions within the filter. Modeling and experimental data will be used.

In theory the maximum temperature that can be achieved in an ideal homogeneous system can be described by the adiabatic temperature rise assuming one of the reactants is limiting. At high oxygen concentration and sufficient flow, soot is the limiting reactant and the theoretical maximum temperature rise can be described by the adiabatic temperature rise

$$\Delta T_{ad}^{S} = \frac{m_C \cdot (-\Delta H_R)}{M_C \cdot V_{DPF} \cdot \rho_G \cdot c_{pG}} \qquad (5)$$

based on soot combustion, eqn. (5).

This value is independent of the mass flow as it assumes instantaneous oxidation of all soot (infinite rate, enough O_2). The value is, however, related to the ratio of the soot mass and the heat capacity of the filter.

If the oxygen concentration is low the rate of combustion is determined by the rate at which oxygen is supplied to the system and the rate with which the heat is removed by convection. Both are proportional to the mass flow, and the adiabatic temperature rise based on oxygen consumption is independent of the flow rate, eqn. (6).

$$\Delta T_{ad}^{G} = \frac{X_{O2} \cdot w_{O2} \cdot (-\Delta H_R)}{M_{O2} \cdot c_{pG}} \qquad (6)$$

With X_{O2} being the conversion of oxygen. The maximum adiabatic temperature rise is obtained at full conversion, e.g. X_{O2}= 1.

Both values represent limiting values for an ideal mixed (0D) system. In real filters the spatial effects leading to the propagation of a combustion front can lead to temperatures that exceed the adiabatic temperature rise. Using eqn. (5) and (6) to determine conditions under which the maximum temperature rise is limited by the soot available or the oxygen supplied to the system (assuming X_{O2}= 1) can be a valuable exercise. Although the theoretical approach is limited by lack of spatial effects and information about the actual oxygen conversion (which is determined by kinetics) it should give directionally useful results. The soot and oxygen concentration at which the limit in adiabatic temperature rise is transitioning from the soot into the oxygen limited regime can be obtained from the combination of eqn. (5) and (6). We obtain a linear correlation in which the density of the filter is the only variable, as the heat capacity of the exhaust gas and most materials is assumed roughly constant. A plot of the transition conditions for different filter densities is shown in Figure 2. The filter densities used, cover the range of typical products used today (note: the bulk density of the filter matrix only is assumed). For the conditions above the lines the maximum temperature rise is theoretically determined by the amount of soot present. Below the lines the oxygen concentration is limiting. Although the lines suggest a hard transition from one regime to the other, it has to be kept in mind that under practical conditions this transition will be more gradual. Nevertheless, the simplified analysis can help to obtain an indication of the generic regimes.

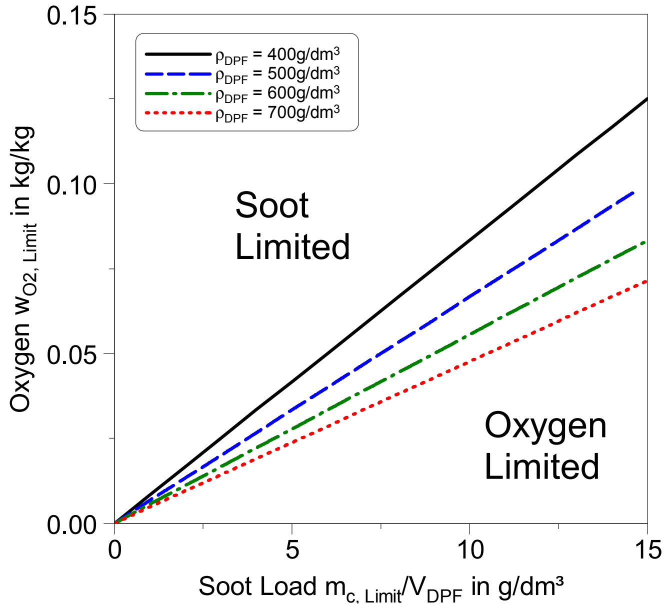

Figure 2. Transition from soot to oxygen limitation in maximum adiabatic temperature rise (X_{O2}= 1).

From Figure 2 we can see that for typical soot loads and complete oxygen conversion one has to reduce the oxygen well below 10% to become limited in oxygen. Assuming a more realistic oxygen conversion of 50% shifts the limits to two times higher oxygen levels. Still oxygen levels well below 10% are needed. This result is in agreement with experimental results from engine bench and laboratory setups. Achieving such low oxygen concentrations is manageable during normal engine operation with some load applied to the engine. In idle and motoring, however, this is very challenging and can often not be warranted.

In Figure 3 results obtained with the 0D model for steady state regenerations at a high initial soot load of 10g/dm³ are plotted, showing the effect of the inlet temperature and the oxygen concentration. Results are given for three typical mass flow rates of 50kg/h, 100kg/h and 200kg/h representing slow urban, extra urban and highway driving (4 cylinder engines). Parameters used are given in Table 1. As the 0D model can not capture the axial accumulation of heat along the filter length the results should be considered as qualitative only (this will be discussed in more detail later).

From Figure 3 we can see the effect of oxygen discussed before. At high inlet temperatures (e.g. 700°C) the reaction rate is fast. We can see that only below 5% oxygen a significant effect can be observed. Above the available soot limits the temperature increase. For lower temperatures this transition is similar but shifted to higher oxygen concentrations as the lower reaction rates lead to lower conversions.

The effect of the inlet temperature can also be seen from Figure 3. In general there are two contributions on the maximum temperature. One is trivial and simply the modification of the baseline temperature onto which the temperature rise due to combustion is added. The other one is determined by the impact on the reaction rate and the ratio between heat released to heat removed by convection. From eqn. (1) and (4) one can see that the heat removed from the system is linearly proportional to the filter temperature and mass flow whereas the heat released is exponentially dependent on the filter temperature. Due to the exponential character the transition range is fairly narrow.

Table 1. Basic model parameters used in 0D model.

Parameter	Value	Unit
Filter Volume	3	dm³
Filter Density	680	g/dm³
Filter Heat Capacity	0.8	J/gK
Activation Energy	155	kJ/mol

Comparing the results shown in Figure 3 (a) through (c) shows that the mass flow may also have an effect on the conditions under which the transition takes place. Another example, including some experimental data from steady state regenerations at 10g/dm³ on engine bench is shown in Figure 4. At high flow rates the transition is shifted to higher temperatures and oxygen concentrations. This is due to the increased heat removal, which is linear in mass flow. The qualitative behavior, however, remains the same.

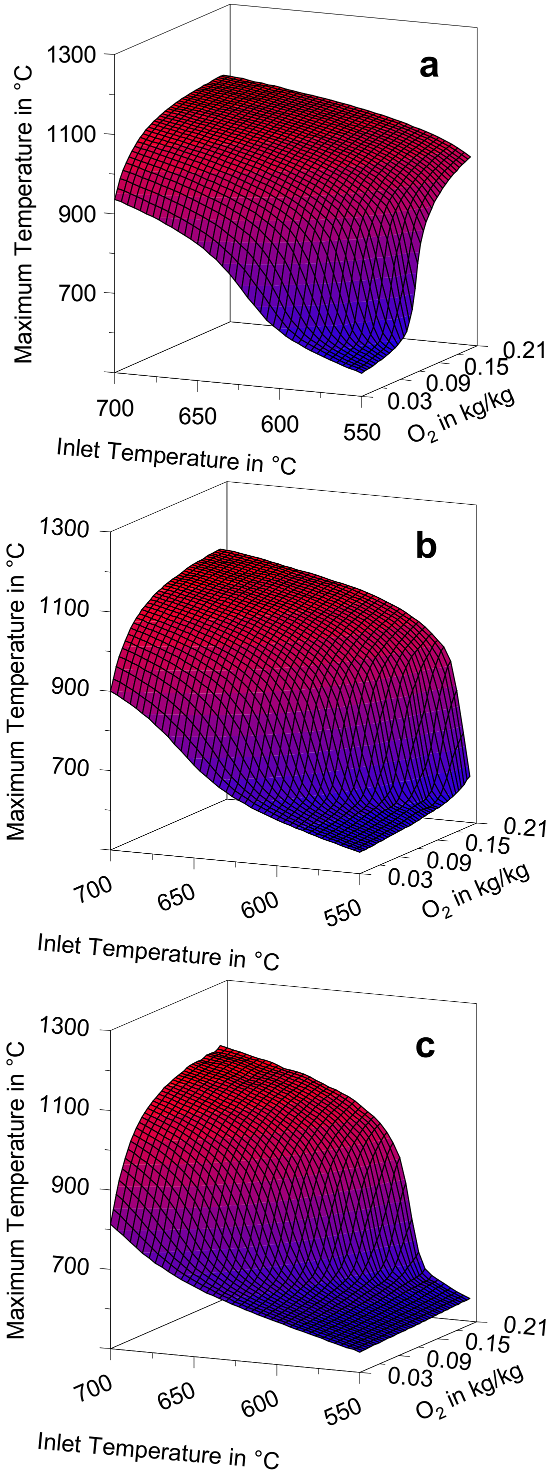

Figure 3. Influence of the inlet temperature on the peak temperature at 10g/dm³ initial soot load. Diagrams show results at different mass flow: (a) 50kg/h, (b) 100kg/h and (c) 200kg/h. 0D model with parameters given in Tab. 1.

The discussion so far has been based on simplified assumptions. As mentioned will the actual temperatures observed in experiments be different. The general conclusions, however, can still be used. With respect to the development of a strategy we can summarize as follows.

The soot load defines the maximum heat load applied to the filter. We can estimate the maximum temperature rise through eqn. (5). The maximum temperature observed during real regenerations can be higher due to the effects of the propagation of the combustion and temperature front and the accumulation of heat, leading to temperatures in excess of the adiabatic temperature rise. The objective of the regeneration strategy is to provide maximum temperature below the limits of the filter material.

For the oxygen we have seen that levels below 7-10% may achieve a reasonable effect. These levels can be achieved during normal operation but are very challenging for the low flow rate conditions at idle and overrun. Most methods to reduce oxygen (throttling, EGR use) also lead to a decrease in the exhaust mass flow. As we have seen that decreasing the mass flow shifts the limiting oxygen concentration to even lower values one may guess that this might not necessarily lead to the desired result. One important parameter to work with is the filter inlet temperature. Through the control of the inlet temperature we may influence the rate at which the soot is burned and heat is released. This can be done independent of the flow rate and oxygen level, although different temperatures may be applied depending on the actual mass flow, oxygen concentration and soot load.

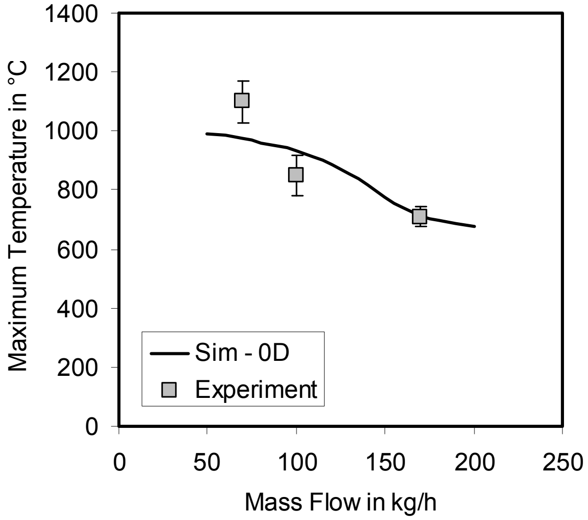

Figure 4. Example of influence of the mass flow on the maximum temperature during steady state regenerations. Experiments from engine bench with a 3dm³ aluminum titanate filter. Soot load was 10±2 g/dm³, inlet temperature: 630°C, oxygen: 7-8%.

EXPERIMENTAL EVALUATION OF THE IMPACT OF THE REGENERATION TEMPERATURE

In the previous section we have discussed the influence of the operating variables based on theoretical considerations. In this section we will try to further explore the use of the inlet temperature to manage the regeneration and to quantify the results based on dedicated engine bench experiments in which the findings discussed in the previous section have been implemented and tested. From the previous section it was indicated that especially low flow rate conditions are noteworthy, especially when high oxygen concentrations are available at the same time. In practical operation such conditions frequently occur when the engine is switched to idle or into overrun or motoring, e.g. approaching a traffic light, a traffic jam or a highway exit. These events represent aggressive operating conditions and are used to test the system behavior for different strategies on engine bench. An example of the temperature readings inside a filter during such a drop to idle (DTI) experiment is shown in Figure 5. The lower line shows the engine speed and the event when the engine is switched to idle speed (no load) at the normalized time 0s. Prior to the DTI event we can see the heat up of the filter with all thermocouples increasing within a short timeframe. After the DTI the temperature in the front of the filter decreases as the exhaust temperature in idle is lower (post injection off). The temperature at the other locations first increases as the soot present is oxidized and heat is released. The downward portion of the temperature transients, e.g. the cool down, represents the tail end of the thermal wave propagating through the filter. The larger separation between the lines compared to the heat up demonstrates the slow velocity of the thermal wave due to the low flow rate.

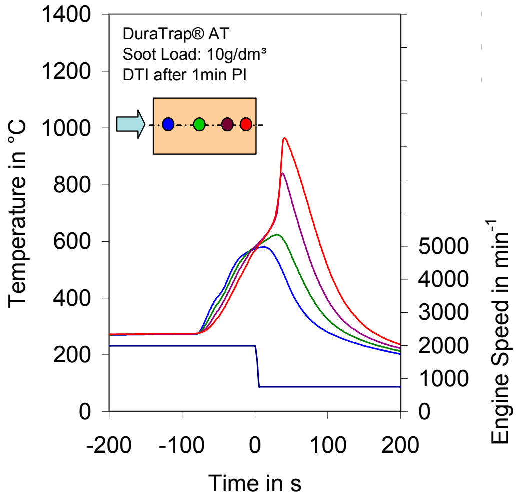

Figure 5. Example of the temperature readings during a drop to idle regeneration.

INFLUENCE ON THE MAXIMUM FILTER TEMPERATURE

In the previous section we have already seen how the regeneration temperature affects the peak temperature based on the 0D model. In Figure 6 results are shown from experiments similar to the one shown in Figure 5 but in which the regeneration temperature was varied over a wide range. To achieve the different regeneration temperatures different engine calibrations were used, mainly through variation of the late post injection. Results are shown for different initial soot loads. In all cases we can see a roughly linear trend, usually having a slope of increase in peak temperature per increase in inlet temperature of 2 - 4 °C/°C.

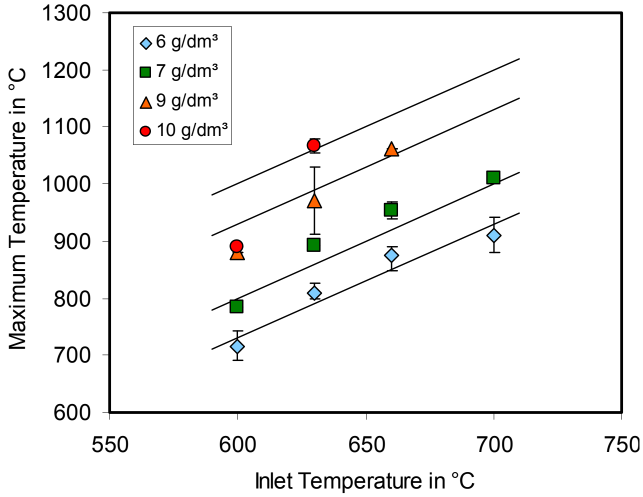

Figure 6. Influence of the inlet temperature on the maximum temperature during a drop to idle regeneration. Filter: cordierite, 5.66” x 6”.

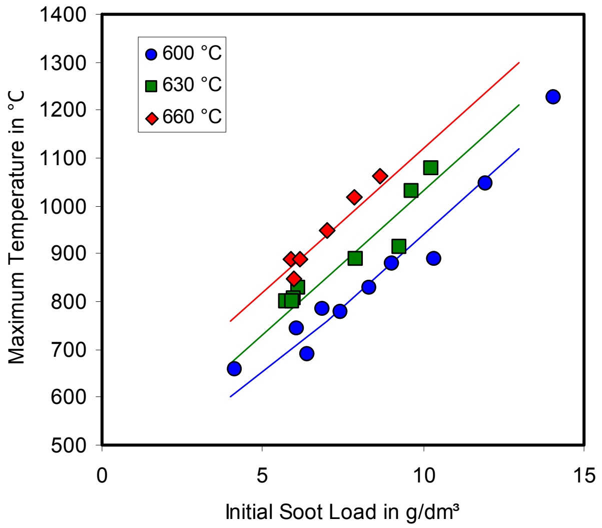

Figure 7. Influence of the soot load on the maximum filter temperature at different regeneration temperatures. Data from drop to idle experiments. Filter: cordierite, 5.66” x 6”.

Figure 7 shows similar data, this time the peak temperature measured within the filter is plotted versus the initial soot load at different regeneration temperatures (or strategies). From Figure 6 and 7 we can already see that using a “mild” strategy with lower inlet temperatures may allow for operation at higher soot load. Indication that at lower temperatures the speed of regeneration, e.g. the soot burning rate, may also be lower will be addressed later.

During highly transient vehicle operation we also have to consider that the temperature control is very difficult and the actual inlet temperature can be higher than desired. An experiment in which we have tried to simulate these conditions is shown in Figure 8.

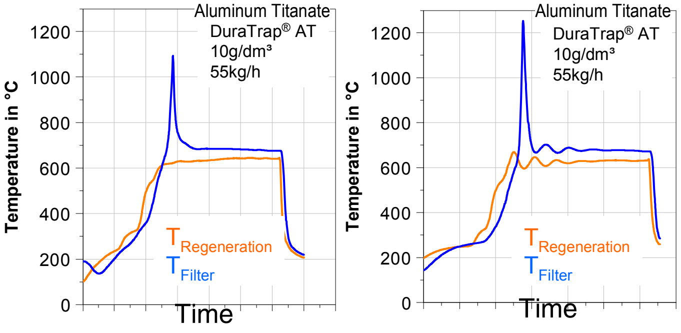

Figure 8. Examples of steady state regeneration at a low mass flow rate and high soot load. Left: smooth temperature increase. Right: temperature increase with oscillations around target temperature.

In the left diagram an “ideal” regeneration, as typical in steady state engine bench experiments is shown. The soot load was quite high and a challenging low speed, low load operating point with low exhaust mass flow was chosen. In the right diagram results from an experiment on the same test setup and soot load is shown during which the inlet temperature ($T_{Regeneration}$) was calibrated to the same steady state value of 630°C, but initially oscillated during ramp up. The peak inlet temperature was about 40°C higher and reached for a short moment roughly 670°C. The effect of this higher temperature, even if reached only for a short time can be seen from the filter temperature (representing the maximum temperature in the filter, measured in the rear for the filter). An almost 150°C higher temperature was observed. In Figure 9 this and the results from other experiments in which the oscillations reached other maximum inlet temperatures are shown.

Similar to Figure 7 we can see a roughly linear relationship. Considering typical dispersion in actual inlet temperatures during vehicle operation, target temperatures of 600-630°C are suggested, if a regeneration strategy with a single and fixed target temperature is applied (aluminum titanate at the higher end, cordierite at the lower end). This temperature level usually allows for an acceptable regeneration rate at not too aggressive conditions.

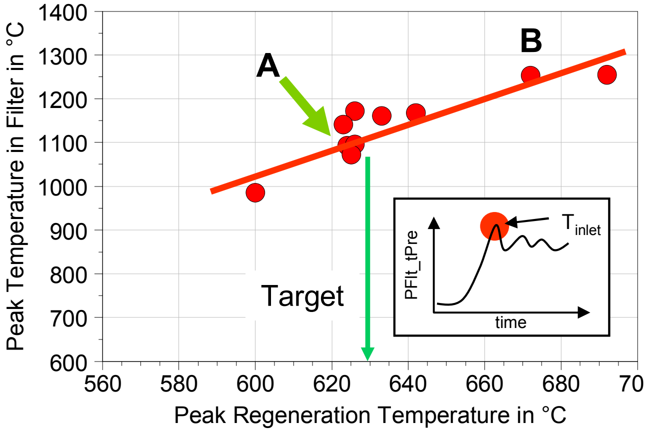

Figure 9. Influence of the maximum inlet temperature during regenerations with oscillating inlet temperature. Data point “A” represents the experiment shown in the left diagram of Fig. 8, “B” represents the right diagram. Soot load: 10g/dm³.

INFLUENCE ON THE REGENERATION EFFICIENCY

As mentioned before the regeneration temperature may also determine the soot burning rate and regeneration progress during active regenerations. To avoid excessive fuel penalties and problems with oil dilution (in case of late in-cylinder injection) short regeneration times may be desired. Typically, durations of 10min to 15min are found in light duty systems and may be viewed as acceptable.

The influence of the regeneration time and temperature is shown for an example system in Figure 10. Shown is the regeneration efficiency as a function of time as well as the soot burning rate, obtained from the results at a regeneration time of 5 minutes. All data were generated in dedicated engine bench experiments. The soot mass was determined gravimetrically and not by using the change in pressure drop. The latter was found to be not very accurate during regeneration events. In the experiments we also tried to minimize the additional soot burning that usually occurs when the regeneration is stopped but the filter remains hot. To minimize this effect the filter was “quenched” by rapidly increasing the mass flow and decreasing the exhaust temperature (e.g. high engine speed and low load).

Also included in Figure 10 are calculated data (lines), which were obtained by using a isothermal model, eqn. (2), with a rate expression like eqn. (4) with first order in soot and oxygen ($m=n=1$, note oxygen was kept roughly constant in the experiments).. For the activation energy a typical value of 165kJ/mole was used.

From Figure 10 the effect of the temperature and the time in this example system can be seen. At low temperatures, such as 550-570°C, already some soot oxidation occurs but at a relatively low rate. Around 600°C the burning rate starts to increase exponentially.

For the given system regeneration temperatures in the range of 600 to 630°C seem to provide the desired regeneration time and efficiency. With other systems and engines we have observed somewhat higher soot burning rates allowing for higher regeneration efficiencies at the given temperatures and shorter times.

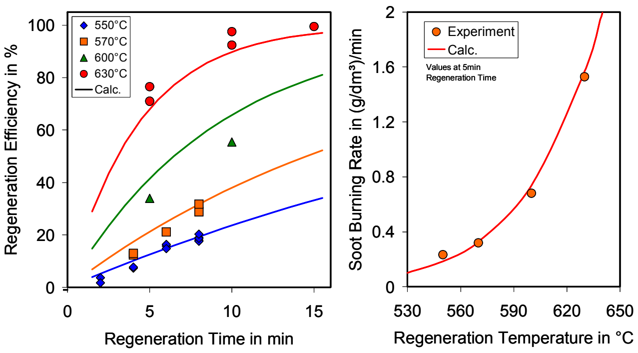

Figure 10. Influence of the regeneration time on the regeneration efficiency and soot burning rate. Controlled regeneration (steady state) at medium engine speed and load; catalyzed aluminum titanate filter.

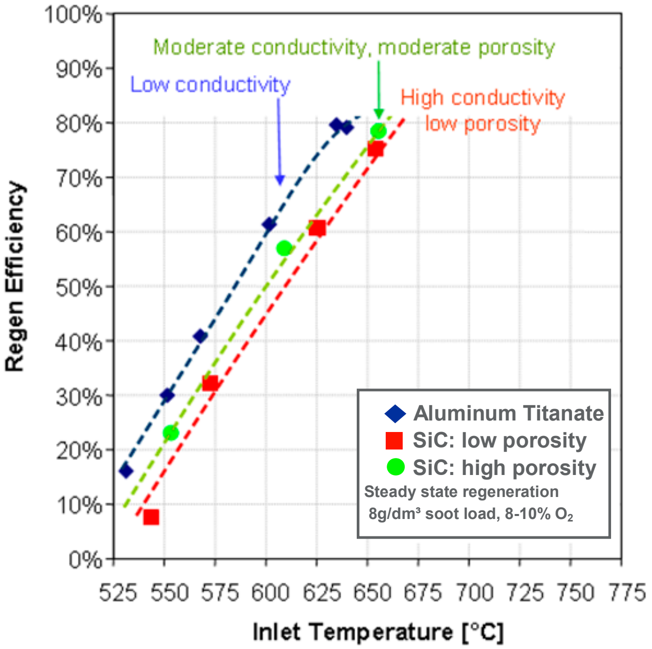

Figure 11. Influence of the regeneration temperature on the regeneration efficiency during steady state regeneration experiments. Comparison of filter with different thermal conductivity.

In Figure 11 data obtained with a different engine, aftertreatment setup and different filter materials are shown. All regeneration experiments were performed under identical conditions (soot load, oxygen, mass flow, time, filter size). The comparison between the results with the different materials shows that higher efficiencies may be obtained with the low conductivity oxide filter material, aluminum titanate. Even between the two SiC materials the trend holds with the less conductive SiC indicating somewhat higher efficiencies. For the practical application this difference can be used to calibrate for lower target regeneration temperatures when oxide filter materials are employed. As a rough guideline, typically 20-30°C lower temperatures are suggested.

The results in Figure 10 and 11 have been obtained under steady state regeneration conditions. Another important design consideration is the regeneration efficiency under transient conditions, such as they may occur during urban stop and go traffic. In Figure 12 results are shown from experiments which were designed to evaluate this situation. In this case the regeneration was interrupted by switching the engine into idle mode (active regeneration modes is turned off). The switch to idle and interruption of the regeneration was done after different time periods with the active regeneration on (shown as “regeneration time” in Figure 12). One observation from Figure 12 is that a similar correlation between time and regeneration efficiency is observed as before. Figure 12 also provides a comparison between different filter materials. Two oxide filters, cordierite (AC) and aluminum titanate (AT) and one silicon carbide. All had similar catalyst load and were tested in the same setup and on the same engine.

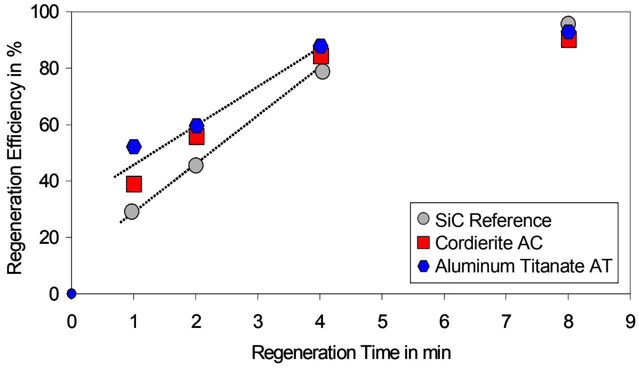

Figure 12. Influence of the time after which the engine is switched to idle on the regeneration efficiency during drop to idle regenerations. Data for cordierite (AC), aluminum titanate (AT) and SiC filter.

For long periods with active regeneration on, all filters behave similarly. For short periods after which the regeneration is interrupted, the two oxide filter products cordierite (AC) and aluminum titanate (AT) may deliver higher regeneration efficiencies compared to SiC. This is quite useful information for the application as it enables better regeneration during highly transient city driving. The basis for this difference is that the lower thermal conductivity of the oxide filters helps to keep the heat within the filter and minimizes dissipation of it.

EXAMPLE OF A STAGED REGENERATION

In the previous sections we have discussed the relationship between the initial soot load and regeneration temperature as initial and boundary conditions for the regeneration and the maximum filter temperature as one key resulting variable characterizing the thermal stress applied to the filter material. Generally high soot load and regeneration temperatures can lead to high peak temperatures, if non-optimal conditions with respect to flow and oxygen occur. The soot load is typically defined by the target regeneration interval and the engine emissions and not a free variable. Therefore, to always maintain suitable conditions the regeneration temperature may have to be adjusted according to the actual soot load. Initially, when the soot load is high a low temperature (mild strategy) may be applied whereas a higher temperature (aggressive clean out strategy) can be used at the end of the regeneration, when most soot is burned. This is shown schematically in Figure 13 and was conceptually also discussed in [10, 11]. One practical difficulty is that estimating the actual soot mass during the regeneration process is even more difficult than during the normal operation. The pressure drop based estimate is challenging as the burning usually does not occur uniformly. This may lead to a highly non linear and difficult to capture pressure drop response with respect to the soot load [6]. The use of sophisticated soot combustion models is possible but significant calibration effort may be required [11]. Even then the quality of the estimate may not be sufficient during transient operating conditions. For this reason one alternative simple approach may be to use a staged regeneration approach in which the regeneration event is divided into several intervals. The simplest version is the approach with two intervals or steps. For this two step approach we will discuss results for one example system.

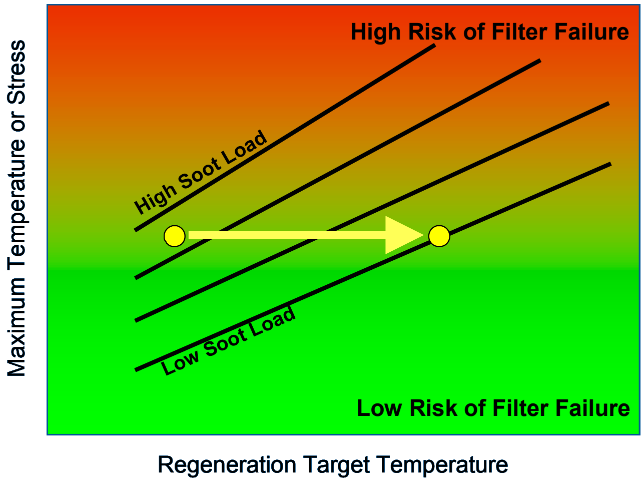

Figure 13. Schematic representation of an ideal regeneration strategy with the regeneration temperature being adjusted to the actual soot load. Lines represent data at different soot loadings.

A schematic of such a two step regeneration process is shown in Figure 14. Variables are the two temperature levels, T_{Reg1} and T_{Reg2}, and the duration in each phase, t_{Reg1} and t_{Reg2}. The total regeneration time should not exceed the typical durations, at least not significantly.

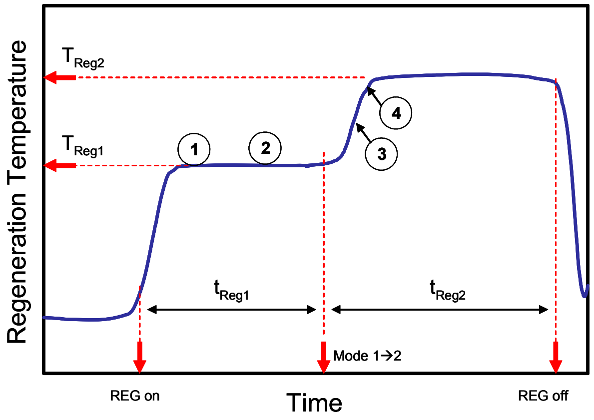

Figure 14. Schematic description of a two stage regeneration strategy.

The objective of the first stage is to burn enough soot to minimize peak temperatures in operation in the more aggressive stage two, even under non-optimal engine conditions.

EXAMPLE 1

For the design example the observations shown in Figure 10 will be used. For this system it has been found that operation at 8g/dm³ provides suitable peak temperatures for the filter under all conditions. However, during soot estimation uncertainties may lead to higher values, probably up to roughly 10g/dm³. The objective of the first regeneration stage is to reduce the soot load at least somewhat, e.g. by ~2g/dm³. From the data in Figure 10 we can estimate that we may need about 5 minutes for this step when a temperature of 550-570°C is used as the target. Then the mode can be changed to the second stage. In this stage we want to oxidize the remaining soot, e.g. 8g/dm³ in the case where we have started at 10g/dm³. To achieve this also within 5 minutes the target regeneration temperature can be set to 630°C, a typical regeneration temperature for aluminum titanate which may allow for good clean out.

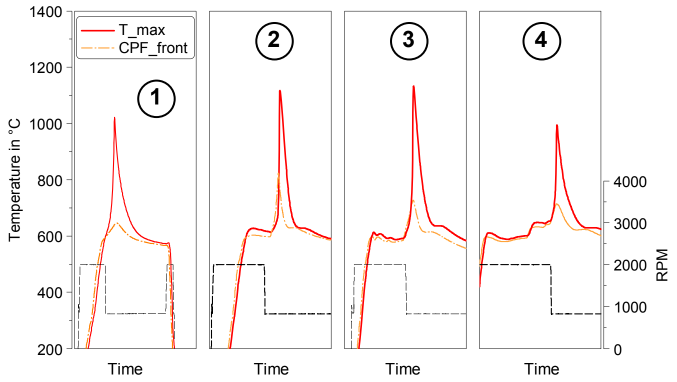

Figure 15. Experimental investigation of a two step strategy. The engine was idled at different times after the active regeneration was activated (see numbers 1 – 4 in Fig. 14).

EXAMPLE 2

Experimental results for a system/strategy tested under drop to idle conditions on the engine bench are shown in Figure 15. The idle event was triggered at different times during the regeneration cycle. Early in the first mode, after 2 minutes in the first mode and when the temperature reached 600°C and 620°C during the transition to the second mode. These conditions can be viewed as non-optimal conditions as later in the regeneration cycle most soot would be burned. For reference, if the engine would be idled with a normal one stage regeneration strategy (630°C target) and the initial soot load used in the experiments the maximum temperatures may have reached values in excess of 1300°C. With the staged approach the peak temperature may be managed well below 1200°C demonstrating its technical benefit (Fig. 15). In separate experiments we have also found that the staged strategy may deliver sufficient regeneration efficiency under steady state regeneration conditions.

CONCLUSIONS

The key factors determining the processes during active regenerations have been discussed based on theoretical as well as experimental considerations. Four main parameters may determine the regeneration process: the soot load, the mass flow, the oxygen concentration and the temperature. Out of these four parameters the mass flow may be the most difficult to influence during normal driving conditions, as the critical conditions are primarily those under which the mass flow is low as the engine is idling. Increasing the idle flow rate in this condition is challenging. The easiest method via an increased idle engine speed is usually limited due to noise concerns, at least in case of passenger car applications. The oxygen content is believed to have a significant effect only if low values are achieved, usually well below 10%. This again is challenging under critical conditions such as idle or over-run conditions. The main struggle is that most methods that would lead to lower oxygen content also decrease the mass flow at the same time. In this case one may want to optimize between the two effects. The soot load is determined by the requirements from the application such as regeneration interval and engine emissions. In addition, one may want to consider for uncertainties during estimation. Therefore, once a filter design is fixed the soot load appears to be only a weak tuning parameter under practical application conditions. An important parameter to work with towards an optimized regeneration strategy is the regeneration temperature. During active regenerations the exhaust temperature has to be modified “artificially” anyway and the level is to some extent adjustable. Generally strategies with a mild regeneration strategy, e.g. low temperatures, at the beginning of the regeneration are suggested. Towards the end of the regeneration more aggressive conditions with higher temperatures can be applied to achieve a good clean out. An example of a simple strategy with two stages has been discussed and demonstrated.

We have also found that oxide based filters may offer better regeneration efficiencies at lower temperatures or shorter times compared to filters made form materials with a higher thermal conductivity, such as SiC. This is based on the reduced dissipation of the heat provided.

The data and results reported in this paper are based on tests conducted using certain apparatus and conditions with specific vehicles, systems, components, coatings, catalysts, and /or controls. Results in other applications may differ based on conditions, apparatus, and other factors, including but not limited to the vehicles, systems, components, coatings, catalysts, and controls used.

NOTATION

c_p	Heat capacity
E_a	Activation energy
ε_{DPF}	Void fraction of diesel particulate filter
η	Collection / filtration efficiency
k_0	Pre exponential factor
m_C	Mass of carbon
m	constant – reaction order oxygen
$\dot{m}$	Exhaust mass flow
M	Molecular weight
ν	Stoichiometric coefficient
n	constant – reaction order soot
ρ	Density
R_{C+O2}	Reaction rate of soot oxidation
$\mathbf{R}$	Gas constant
ΔH_R	Heat of reaction
ΔT_{ad}	Adiabatic temperature rise
t	Time
T	Temperature
w	Mass fraction
V_{DPF}	Filter volume
X	Conversion

Subscripts

G	Gas
S	Solid
DPF	Diesel Particulate Filter
In	Inlet
O_2	Oxygen
C	Carbon or soot

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