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950151

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Reprinted from: Diesel Exhaust Aftertreatment 1995 (SP-1073)

The Engineering Society For Advancing Mobility Land Sea Air and Space®
SAE INTERNATIONAL

International Congress and Exposition
Detroit, Michigan
February 27 - March 2, 1995

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ABSTRACT

Silicon Carbide (SiC) has been shown to have a high melting/decomposition temperature, good mechanical strength, and high thermal conductivity, which make it well suited for use as a material for diesel particulate filters. The high thermal conductivity of the material tends to reduce the temperature gradients and maximum temperature which arise during regeneration. The purpose of this paper is to experimentally investigate the thermal loading which arise under regenerations of varying severity.

An experimental study is presented, in which regenerations of varying severity are conducted for uncoated SiC and Cordierite filters. The severity is varied through changes in the particle loading on the filters and by changing the flow conditions during the regeneration process itself. Temperature distributions throughout the filters are measured during these regenerations.

A model for regeneration is presented and used for interpretation of observed temperature-time distribution at different locations in the filters. The model indicates a very broad progressing reaction zone extending to nearly the whole filter length. Results indicate a trade-off between regeneration efficiency, wall thickness, and peak temperature levels.

INTRODUCTION

SiC as an alternative material choice for wall flow diesel particulate filters has been further investigated complementing previous work (1,2,3,4). The present work is focused on SiC´s special thermal characteristics and the influence on regeneration behavior during continuous and severe regeneration conditions. The main differences between SiC filters and filters based on Cordierite are the >20 times higher thermal conductivity and approximately 8 times higher strength of the former material (1). Another important point is the particular choice of filter design in combination with the heat capacity of the material which defines the thermal inertia of the system. Thicker walls and smaller channel dimensions lead to increased thermal storage in the filter itself during uncontrolled regeneration thus minimizing peak temperatures in the filter. This gives an interesting trade-off between thermal integrity and space volume efficiency.

PROCEDURES AND EQUIPMENT

The SiC filter tested in this work was the new generation of NoTox Corporation un-coated filters with 0.8 mm wall thickness and cell pitch of 2.8 mm (NF-760). Compared to the previous filters with the same material integrity factor (5), both the specific filtration area and the strength have been improved considerably (Table 1, Fig. 1). A new patented technique for channel closure, as

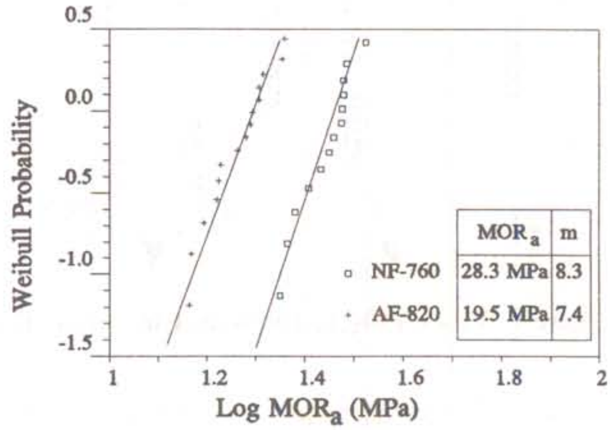

Figure 1. Strength of the SiC filter material.

Property	SiC	Cordierite
Radius - mm	95	95
Length - mm	205	203
Total Volume - liter	5.8	5.8
Active* Volume - liter	5.8	4.3
Filtration Area - m^2	2.9	2.8
Pore Size - μm	6	34
Wall Thickness - mm	0.8	0.43
Cell pitch - mm	2.8	2.53
Specific Area - m^2/liter	0.5	0.48

Table 1. Filter Specifications for the engine regeneration tests. *Total volume minus the wasted volume of the sealed rim (c.10 mm) and the channel plugs (c. 7 mm).

seen in Figure 2 eliminates the waste of filter volume otherwise caused by the conventional plugging method in which 5-10 mm of the channel is blocked in both ends of the filter and thus lost as filter area. With this new technique, the ends of the walls of the channels are made to form a cap on the ends of the appropriate channels before the final processing of the filter body. During the final processing, the connections are made permanent. The end cap has the same physical properties as the remainder of the filter and contributes to the actual filtration area.

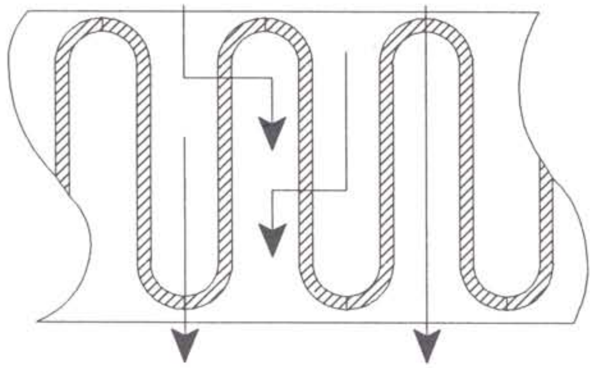

Figure 2. New capping technique used for the SiC filters.

In order to investigate the effects of thermal properties of the filter materials on temperature excursions during regenerations, comparisons were made under engine regeneration tests. SiC and Cordierite filters of approximately the same size and filtering capacity were chosen in order to make this comparison. The properties of the filters tested are shown in Table 1.

The filters used in the regeneration tests were uncoated, and no additive was used in the fuel or sprayed onto the filter to promote regeneration. These methods would reduce the regeneration temperature, and thereby normally give lower thermal loading than the tests with uncoated filters. With the latter, high temperatures are required to initiate a regeneration, resulting in high thermal loading. All tests were performed on low sulfur Shell City Diesel with less than 50 ppm Sulfur.

Engine Displacement liter	2.4
Bore - mm	90.9
Stroke - mm	92.4
Cylinders	4
Combustion System	Pre-Chamber
Intake System	Normally Aspirated
Maximum Power - kW	45
Rated Speed - rpm	3600

Table 2. Specifications of the engine used for the regeneration tests.

The engine regeneration tests were conducted on a Mercedes OM 616 4-stroke diesel engine mounted on a Super Flow SF-901 dynamometer. Engine specifications are given in Table 2. The dynamometer was equipped

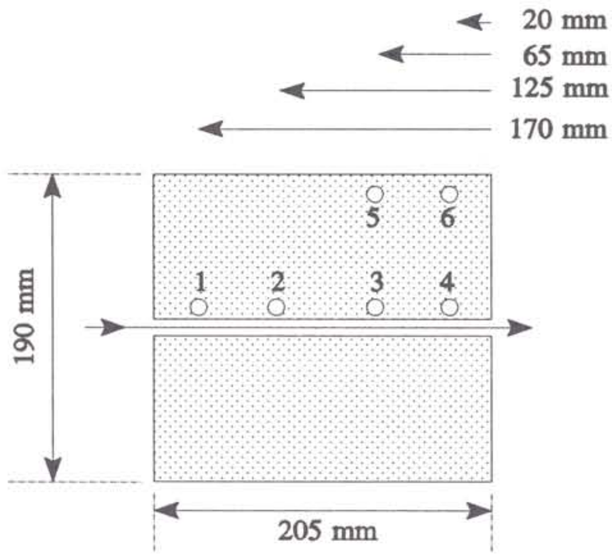

Figure 3. Thermocouple positions and filter dimension

with external data acquisition for monitoring pressure drop and temperatures in exhaust and various places in the filter, as shown in Figure 3. Data was collected each 5 sec. and temperatures were measured with type K thermocouples (Ø 1.0 mm) introduced in the filter channels from the outlet side after soot accumulation. The filter compartment was provided with a simple diffuser to even out the soot and thermal load. The filter canning was open to the atmosphere at the outlet end. The monoliths were wrapped in an expandable insulation mat of the type Interam, XD, 4200 g/m^2. Filter specifications are given in Table 1, the SiC filter is composed of four quadrants (1). The Cordierite filter was a one-piece Celcor EX-66.

Soot was accumulated under accelerated loading conditions with throttled intake, 37 % of rated speed and 50 % of max. power giving exhaust temperatures in the range of 400 to 450°C. Before each regeneration, the filters were dismantled from the engine, released from both the canning and the insulation mat and weighed to an accuracy of 0.1 gram. After remounting the filter to the engine, the engine was run at accumulation conditions without throttled intake for another 5 minutes in order to reach reproducible temperature conditions from test to test. The additional soot accumulation during this 5 min. period was negligible.

Step	Continuous Regeneration	Severe Regeneration
1	1300 rpm 65 Nm 5 min	1300 rpm 65 Nm 5 min
2	3000 rpm 110 Nm 15 min	3000 rpm 105 Nm 300 - 500 s
3	1000 rpm 8 Nm Continuing	3500 rpm 115 Nm 100 - 200 s
4	-	1000 rpm 8 Nm Continuing

Table 3. Regeneration modes for continuous and severe regeneration.

Two types of regeneration were selected for study, a continuous regeneration and a severe regeneration. The regeneration conditions are given in Table 3. The former is an example of a moderate severity, because there is adequate flow to remove the energy released from the regeneration. The latter corresponds to the case where the regeneration is started and then the flow substantially reduced and oxygen content increased. In this situation particularly, the thermal inertia of the filter is expected to be a significant factor in determining temperatures.

THEORETICAL CONSIDERATIONS

In order to evaluate the soot distribution in the 4-quadrant design, a partly loaded filter was dismantled after a certain period of accumulation and two of the four segments were replaced by clean segments. The filter was then loaded for a similar period of time and it was found that the soot load of the four segment had become identical to within less than 2%. It is concluded that the soot load is evenly distributed partly due to the diffuser and partly due to the self regulating relation between soot layer thickness, pressure drop and volumetric flow rate. Thus, filter temperatures were only measured in one segment.

THERMAL INERTIA - The term thermal inertia is defined as the inverse of the adiabatic temperature increase of the filter material possible for a certain soot load. Though disregarding the heat loss due to gas flow through walls and channels, the thermal inertia expresses the possibility of obtaining sharp exothermic peaks during uncontrolled regeneration:

$$TI = \frac{c_p M_{sp}}{m_s H_u} \quad (1)$$

where: m_s is the soot load in mass per area, H_u is the heat of combustion of the soot, c_p is the specific heat of the filter material. M_{sp} is the specific mass which is dependent on the design of the filter. One unit length of a channel has the mass of filter material given by:

$$M_{sp} = t\rho\left(\frac{t}{2w}+1\right)(1 - P) \quad (2)$$

where: t is the wall thickness and w is the channel width, as shown in Figure 4, P is the pore fraction and ρ the material density.

Since Q is not known Q exactly, it is useful to form the ratio of thermal inertia between SiC and Cordierite presupposed that the soot loads are identical:

$$\frac{TI_{SiC}}{TI_{Cor}} = \frac{c_{p,SiC} M_{sp,NoTox}}{c_{p,Cor} M_{sp,Celcor}} \quad (3)$$

Using material properties from References 1 and 6 and the design parameters for the new generation SiC filter, the thermal inertia is 3 times higher for the SiC filter than for the Cordierite filter used in this test. It is

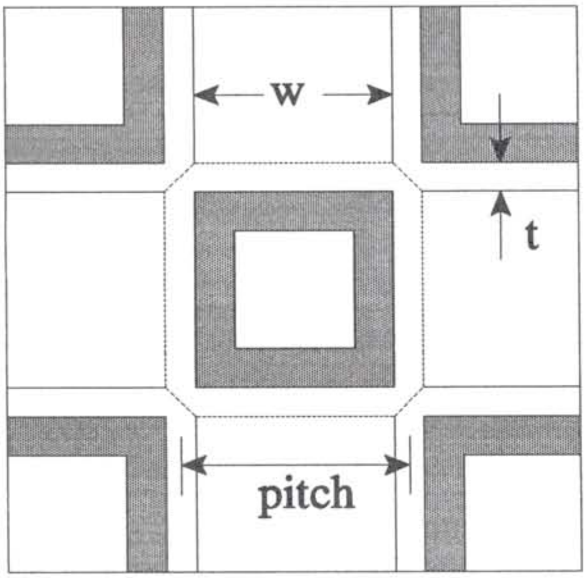

Figure 4. Geometry of the loaded channel in a wall flow filter.

thus expected that temperature peaks during regeneration will be more modest for the SiC filter.

DYNAMIC THERMAL MODEL - In order to study the effects of dispersion of the generated heat by thermal conduction in the filter material and thermal convection due to exhaust gas passing through the filter walls, a simplified one-dimensional thermal model was used as shown in Figure 5.

The model is similar to that used in Reference (1). In this study, the model was modified in the following manner. The convection model was modified to include the effects of the variation in the local flow velocity through the filter wall on the heat transfer. It was assumed that the heat transfer could be described in a similar manner to that for flow past cylinders. The Reynolds number inside the porous structure was estimated on the basis of the equivalent diameter of the particles as determined from the permeability of the filter material (2). In this case, the heat transfer can be described by a function of the form given in Equation 4 for the range of Reynolds numbers encountered (7).

$$Nu_d = CRe^b \qquad (4)$$

where: Nu_d is the Nusselt number based on the equivalent diameter of the particle, and C and b are empirical constants.

Due to the low velocities (< 5 cm/s) and small sizes (< 60μm), the Reynolds numbers are small. The value of the power, b, was therefore found be 0.33 (7). While Reference (7) cites a value for the coefficient C in Equation (4), it was not felt appropriate to use this value in the model. This was due to uncertainties in the particle size and the surface area of the porous filter material. Consequently, Equation (4) was used to estimate the relative effects of flow velocity through the filter material by the power b, and the coefficient C was chosen to give correct values for the temporal change in filter and gas temperatures encountered when the exhaust gas temperature was changed without the occurrence of a regeneration.

In order to determine the relative effects of flow velocity on the heat transfer, it is necessary to estimate the flow velocity through a clean filter wall and through a filter wall loaded with particulate matter. The results from Reference (2) were used to do this. Using Darcy's law for the flow through porous media, the flow velocity, V, through a porous media, either the filter or the particle layer, can be written as:

$$V = \frac{\Delta p}{R_{eq}} = \frac{\Delta p}{\frac{\mu t}{\alpha}} \qquad (5)$$

where: R_{eq} = the equivalent flow resistance of the entire filter, μ = the gas viscosity, t is the thickness of the porous material, α is the permeability of the porous material, and Δp is the pressure drop over the porous material.

For the entire filter, it was assumed that one of two conditions was applicable. The first condition is that of a loaded filter. In this case the flow resistance of the particle layer is taken to be the dominant factor, due to the low permeability of the particles (2). The other condition is that of a completely clean surface after a regeneration. The flow resistance of the particle layer is typically one to two orders of magnitude larger than that of the filter wall. The total resistance to the flow is then assumed to be the equivalent resistance for the two resistances taken in parallel, when weighted for the fraction of surface area loaded with particles ξ_p and the clean fraction ξ:

$$R_{eq} = \frac{\mu \frac{t t_p}{\alpha \alpha_p}}{\frac{t}{\alpha}\xi_p + \frac{t_p}{\alpha_p}\xi} \qquad (6)$$

In an engine situation, the flow, $\dot{m}_{exh}$, through the entire filter area, A_f, is taken to be constant, and unaffected by the filter resistance. The pressure drop over the filter is then determined by Equation (7):

$$\Delta p = \frac{\dot{m}_{exh}}{\left[\frac{p_{exh} + \Delta p}{RT_{exh}}\right]} A_f R_{eq} \tag{7}$$

Equation (7) can be readily solved for Δp given T_{exh}. From the value of Δp, the velocities through the clean and loaded areas of the filter can then be determined by application of Equation (5). These velocities are then used to estimate the relative convective heat transfers in the loaded and clean regions of the filter. The boundary between the two conditions was taken to be the middle of the combustion wave traveling along the filter.

When the filter is loaded with particles before regeneration, $\xi = 0$, $\xi_p = 1$, and the flow resistance is determined solely by the particulate layer. Early in the regeneration, the pressure drop falls significantly, since the flow resistance of the clean wall is much lower than that of the loaded wall. A consequence of this is that the flow rate through the remaining loaded area of the filter decreases, and the convective heat transfer here drops correspondingly. This results in higher temperatures in the last regions of the filter to regenerate. Typically, these areas are near the exit of the filter, and part of the reason for the higher temperatures in this region during regeneration is due to this effect.

As in Reference (1), a combustion wave was assumed to travel from the inlet to the outlet of the filter with a constant velocity, c and a width δ. The combustion rate was assumed to have a sinusoidal distribution across the width of the reaction zone. The resulting partial differential equation for the filter temperature of the filter material is given in Equation (8).

$$\frac{\partial^2 T}{\partial x^2} + \frac{\pi}{2\lambda}\rho_p \frac{t_p}{t} H_u \frac{c}{\delta}\sin\left[\pi\left(\frac{x-ct}{\delta}\right)\right] = \frac{\rho c^p}{\lambda}\frac{\partial T}{\partial \tau} + a\left(\frac{\rho_g V d_p}{\mu}\right)^b \frac{\lambda_g}{\lambda}\frac{f_c}{d_p^4}(T - T_g) \tag{8}$$

where: the subscript p denotes properties of the particles and the subscript g denotes properties of the exhaust gas, T is the temperature, ρ is density, H_u is the heating value of the particulate matter, x is the distance along the filter (x=0 is the inlet), λ is the thermal conductivity, t is the thickness, τ is the time, d_p is the equivalent particle diameter, and f_c is the surface area per unit volume of the filter material.

The boundary conditions are such that there is no conductive heat transfer out of the ends of the filter. The filter is assumed to be at a uniform initial temperature,

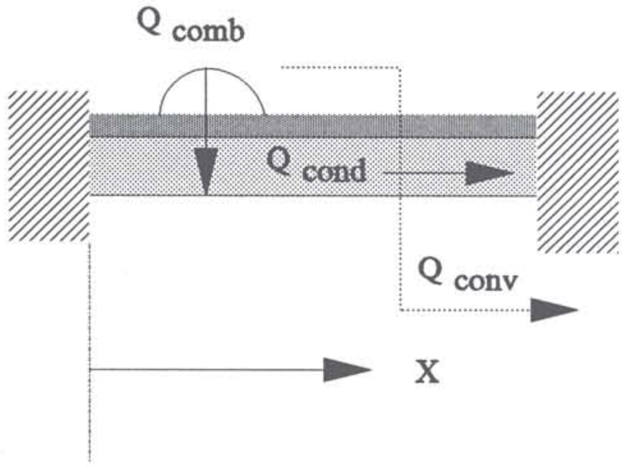

Figure 5. Schematic representation of the one-dimensional thermal filter model.

and the exhaust gas temperature is held constant, at an arbitrary value. The model is shown schematically in Figure 5, which shows the boundary conditions at the ends, as well as the energy transport processes.

RESULTS AND DISCUSSION

SEVERE/UNCONTROLLED REGENERATION - The second step in the cycle raises the temperature in the whole filter starting a slow but continuous oxidation. When the temperature is stabilized, the rpm and load are increased in order to raise the filter temperature another ~100°C, then the engine is put into idle in order to initiate an uncontrolled regeneration. The severity of this cycle is controlled by the initial soot load on the filter and the length of the second and third steps during which the soot load is slightly diminished.

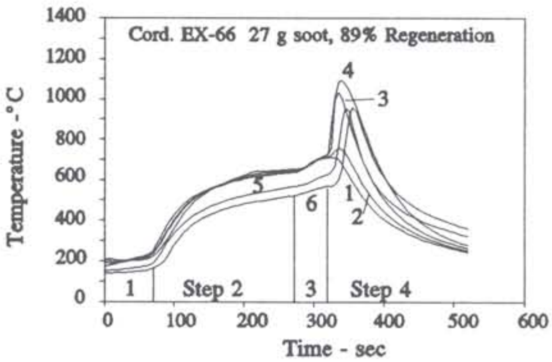

Figure 6. Measured temperature distribution for a severe regeneration of the Cordierite filter.

In Figure 6 and Figure 7, a SiC 5.8 liter filter is compared to a 5.8 liter Cordierite filter. Severe uncontrolled regeneration was performed according to the cycle given in Table 3. It is clearly seen that the temperature increase in the beginning of step 4 is lower in the case of SiC and that the temperature peaks during the uncontrolled oxidation are substantially higher for the Cordierite. The increase in filter temperature is consistent with that predicted by a comparison of the thermal inertias of the filters. A consequence of the lower temperatures is that the oxidation process in the SiC filter ceases and regeneration is limited to half the amount of

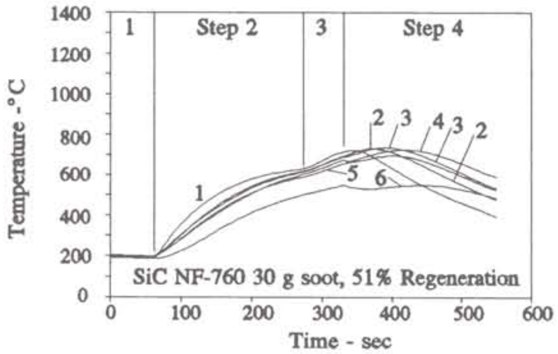

Figure 7. Measured temperature distribution for a severe regeneration of the SiC filter.

the available soot compared to nearly full regeneration for the Cordierite filter.

These regeneration events have also been analyzed with the dynamic model described in the previous section. The model input is the material characteristics from Reference (1) and regeneration data chosen as close to experimental conditions, that is a reaction rate of 0.2 cm/s giving a total regeneration time of 150 seconds, exhaust gas temperature and initial filter temperature of 550°C and 700°C respectively. The remaining parameters in the model which are not defined are then restricted to the width of the reaction zone, the regeneration efficiency and an arbitrary convection factor controlling the rate of heat removal by the exhaust gas flow. The convection term was determined by comparison with temperature changes during periods where the filter changed in the absence of regeneration reactions.

It was found that relatively narrow reaction zones characterizing a wave like progression of the regeneration gave unsatisfactory results as shown in Figures 8 and 9, in which the temperature peaks in positions 1-4 are distinctly separated in time unlike the actual observations in Figures 6 and 7. In order to obtain a nearly simultaneous temperature increase throughout the filter, the model dictated a broad reaction zone converging to nearly the whole filter length as shown in the Figures 10 and 11. The agreements between model predictions and actual

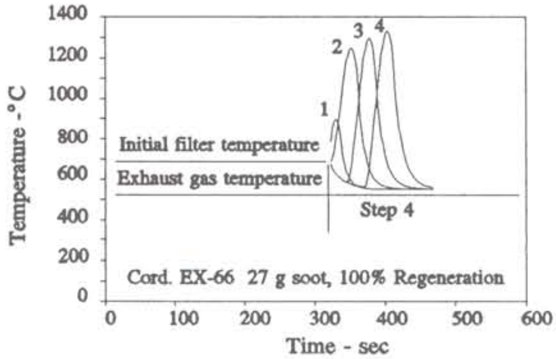

Figure 8. Simulated temperature distribution for the Cordierite filter for the conditions of Figure 6, with a narrow combustion wave.

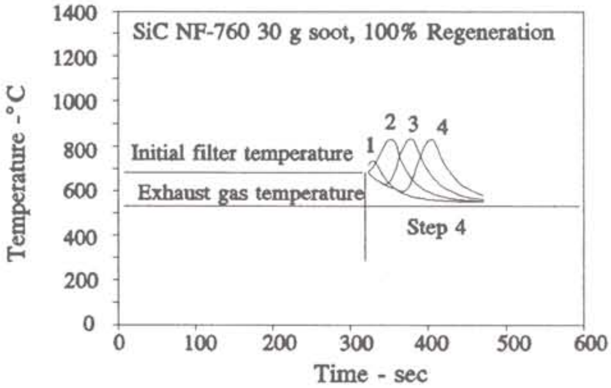

Figure 9. Simulated temperature distribution for the SiC filter for the conditions of Figure 7, with a narrow combustion wave.

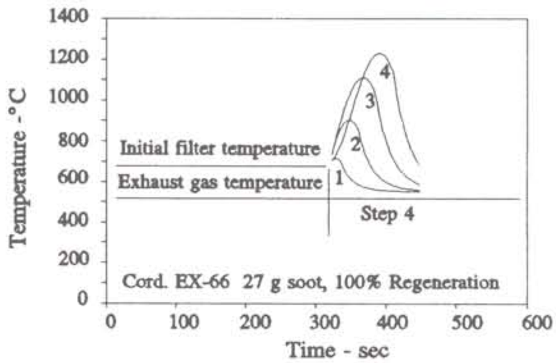

Figure 10. Simulated temperature distribution for the Cordierite filter for the conditions of Figure 6, with a broad combustion wave.

observations are acceptable.

As seen in both the model results and the test

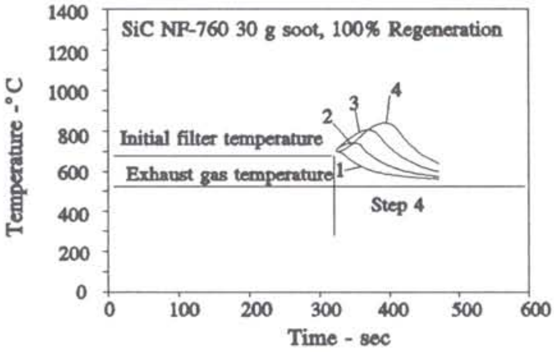

Figure 11. Simulated temperature distribution for the SiC filter for the conditions of Figure 7, with a broad combustion wave, 100% regeneration efficiency.

observations, the temperature increase in position 1 close to the filter inlet is low, presumably due to the rapid convective cooling by the exhaust gas in step 4. The model can simulate this phenomenon by starting the sinusoidal maximum reaction at a position half a wave length (half reaction zone width) inside the filter thus disregarding a total soot combustion on the inlet side of the reaction zone. This detail is confirmed by numerous observations from regeneration tests where soot is often seen in the inlet even at high overall regeneration efficiency.

Finally the model can simulate a reduced regeneration efficiency as observed for the SiC filter in Figure 7 with a regeneration efficiency of 51%. By accounting for the regeneration efficiency, even the predicted absolute filter temperatures are quite reasonable as seen in Figure 12.

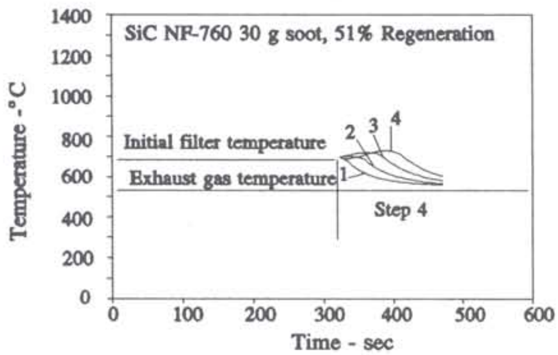

Figure 12. Simulated temperature distribution for the SiC filter for the conditions of Figure 7, with a broad combustion wave, 51% regeneration efficiency.

The model, although simple, and one-dimensional, seems to explain the observations on major differences between SiC and Cordierite as filter materials. The SiC filter has a higher thermal inertia, which limits the effect of the thermal loading. A trade-off then exists between thermal integrity and regeneration efficiency, as the reduction of the temperature can stop the regeneration. This is an additional advantage in the case of a potential uncontrolled reaction, provided that normal regeneration occurs normally by conventional means such as the use of an additive or external heating of the filter.

CONTINUOUS REGENERATION - Continuous regeneration was performed according to the cycle given in Table 3 and the results are given in Figure 13 and 14. As seen in the severe tests, the temperature rise is slower for the SiC filter and the maximum temperatures attained are at roughly the same level throughout the entire filter, while rim temperatures (position 5 and 6, in Figure 4) in the Cordierite trap stabilize at 60-90°C below temperatures in the central part. For both cases, the 15 min. duration of step 2 is insufficient to ensure full regeneration of the uncoated filters, and step 3 initiates a

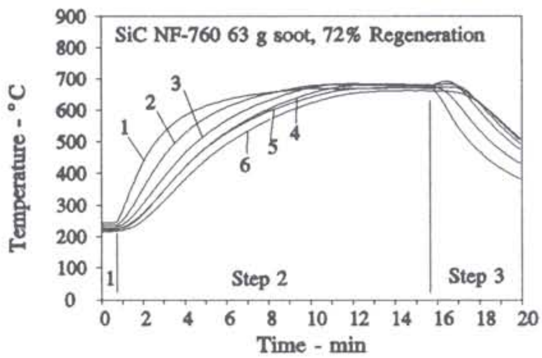

Figure 13. Measured temperature distribution for a continuous regeneration of the SiC filter.

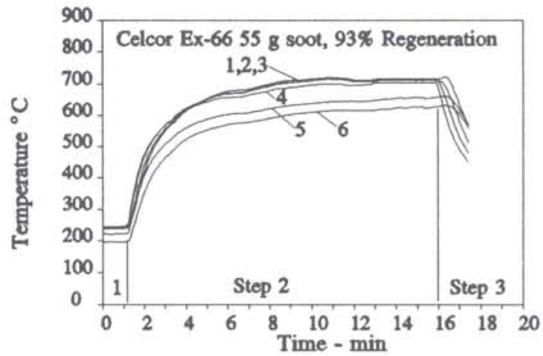

Figure 14. Measured temperature distribution for a continuous regeneration of the Cordierite filter.

small "uncontrolled" oxidation reflected by a modest temperature raise in the beginning of this period. The different degree of regeneration in these tests (72% and

93% for SiC and Cordierite respectively) is probably to a higher extent a reflection of the SiC filter's lack of a self-perpetuating regeneration in step 3 than it is due to some lack of ability to regenerate in a continuous mode.

CONCLUSIONS

The different regeneration behavior observed between filters of SiC and Cordierite is explained by a one-dimensional regeneration model taking conductivity, convection and filter design into account. The observed temperature-time distribution in different positions in the filter is predicted by assuming a broad reaction zone extending to nearly the whole filter length. The higher thermal inertia of the SiC filter reduces the effects of the thermal loading during severe regeneration thus restricting the temperature peaks to fractions of the peaks seen in Cordierite filters. This feature will reduce the risk of unrestrained regeneration, but on the other hand also reduce the probability of full regeneration. The trade-off then stands between thermal integrity and regeneration efficiency in a severe regeneration. In a continuous regeneration mode the filters are comparable.

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