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Next Generation Aluminum Titanate Filter for Light Duty Diesel Applications

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ABSTRACT

With the introduction of the current EU5 standards the diesel particulate filter has become a key element in the aftertreatment of diesel passenger cars. The upcoming future emission standards target primarily a further reduction in NOx emission as well as reduced fleet average CO_2 emissions. Although the particulate filter has no direct influence on the reduction of these species, the needs of future aftertreatment systems impose additional requirements on advanced filter technologies. In this paper we are introducing two new filter products based on a new low porosity aluminum titanate family that complement the current DuraTrap ® AT filter products. The new products offer the potential for an increased soot mass limit or a significant reduction in pressure drop. The enhanced performance of the new filter products is discussed and demonstrated in a large number of experimental data obtained in engine bench tests. Pressure drop, filtration, survivability, and durability data are presented.

INTRODUCTION

Diesel engines with their superior efficiency continue to represent a key element towards meeting future reduced fleet CO_2 targets. The reduction in particulate matter emission limits from EU4 to current EU5 and EU5b legislation has resulted in diesel particulate filters (DPF) being used in essentially all light duty diesel vehicles certified for this emission standard. While first applications have relied primarily on filter products made of SiC, Aluminum Titanate filters introduced in 2005 [1, 2, 3] have since found broad commercial application, i.e. [4-5], with millions of filters installed. They have proven to provide excellent filtration and pressure drop behavior combined with reliability and robustness [4, 5, 6].

The focus of future EU6 legislation is a further reduction of NOx emissions from diesel engines. In addition, a reduction in CO_2 emissions will be required to meet the fleet average targets. For the reduction in NOx emissions different approaches are considered, see Figure 1. Especially for vehicles with low to medium weight a reduction of the engine out emissions are considered, enabling them to potentially meet the regulated emissions either without the use of DeNOx catalyst technologies or by means of a Lean NOx Trap (LNT) catalyst. For medium to heavy vehicles, current systems involving SCR technology appear most attractive. The integration of the SCR system, involving urea dosing unit and the catalyst, into the aftertreatment system is expected to be, for most systems, downstream of a catalyzed DPF, as shown for example in reference [7, 8]. Some key advantages of this configuration are that the DPF can be installed in a close-coupled location, which facilitates the management of the active regeneration of the filter due to low heat losses and it also provides a maximum of passive soot oxidation by NO_2. In addition, a catalytic coating on the DPF helps adjusting the NO_2/NO_x ratio to values optimal for the performance of the SCR system. A key downside of the configuration is that due to the location and the thermal inertia of the upstream DOC and DPF it takes longer to heat up the SCR system to temperatures required for the injection of urea and the function of the catalyst. An alternative solution, in which the SCR system is installed upstream of the DPF to enable faster heat up and function of the SCR system, has been proposed in reference [9]. In this case a fuel born catalyst (FBC) additive is used to lower the soot oxidation temperature and compensate for the challenges

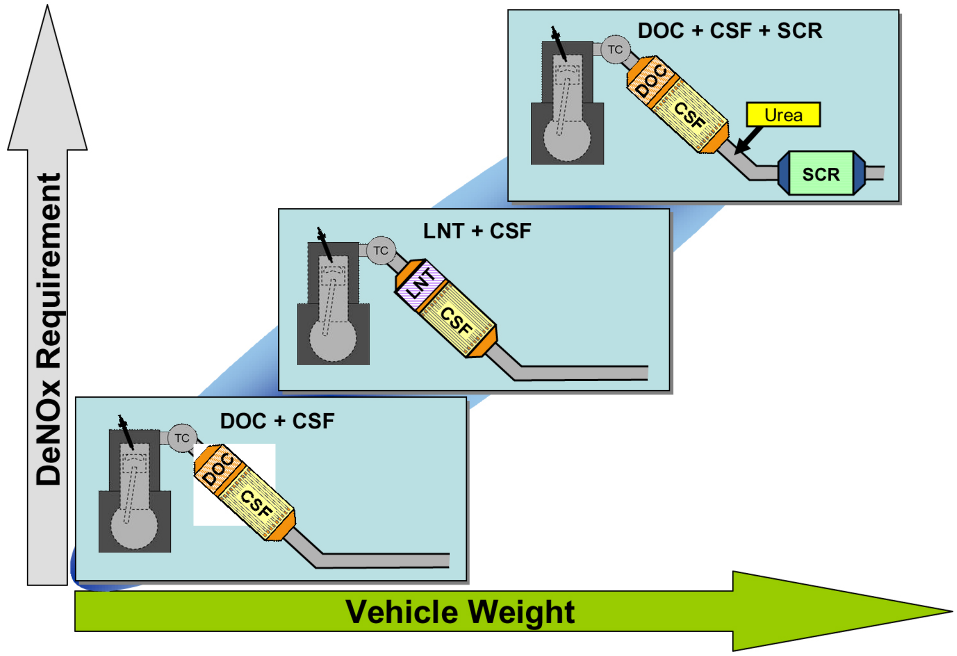

Figure 1. Possible aftertreatment configurations to address EU6 emission standards. (Note that all may also include engine hardware modification and EGR which is not shown)

with heating a DPF that is positioned behind the DOC and SCR system.

Independent of the system configuration and technology used, the need for advanced particulate filters is very similar. Obviously, providing high filtration efficiency to meet the particle number standard of 6×10^{11} #/km is a given. Due to the challenges in obtaining high DeNOx efficiency in the low temperature light duty drive cycle (NEDC), it is expected that the engine out soot emissions will either be comparable to EU5 or increase slightly due to the NOx/PM trade-off. Therefore, the need for filter products with sufficient soot mass limit is generally maintained. In the case of SCR systems the added catalyst components increase the overall backpressure of the aftertreatment system. Reduced pressure drop across the DPF is in general beneficial but in case of applications utilizing SCR components is especially desirable. Finally, the need to provide high ash storage capacity to enable a long filter life is expected to remain equally important as it has been for EU5 systems.

In this paper we will introduce a new family of low porosity aluminum titanate filters designed to address the enhanced needs of future aftertreatment systems and offer a broadened portfolio of aluminum titanate filter products. This new generation of aluminum titanate filter materials represents an extension and further development of Corning's current DuraTrap® AT filter products.

PRODUCT CONCEPT

The development program for a next generation of aluminum titanate filter products has been designed to address the needs for advanced aftertreatment systems. The key objective of the program was to maintain the excellent performance features of the current aluminum titanate filter product but offer either a higher soot mass limit at equal pressure drop or a further reduction in pressure drop at equal soot mass limit.

The soot mass limit of filter products is in general defined by the maximum stress that can be tolerated without failure with respect to the filtration function. Typically the stress correlates to the temperature field the filter is exposed to during severe regeneration events and often the maximum temperature and gradients can be used as representatives for this stressor. The correlation to the actual soot mass limit in use is then obtained through the correlation of, for example, the maximum temperature in the filter and the soot load. The soot mass limit is a strong function of the operating conditions and can be significantly influenced through controls [10]. For a given regeneration condition the soot load to reach a given peak temperature inside the filter is strongly correlated to its thermal mass. The latter is the product of the specific heat capacity and the density. For a given material the heat capacity is a constant and even comparing currently used commercial filter materials, AT, SiC and Cordierite, one finds very comparable specific heat capacities (in J/kgK). As a result the thermal response correlates primarily to the density of a filter product (in kg/m^3). This is shown in Figure 2, in which experimental data are shown, providing the

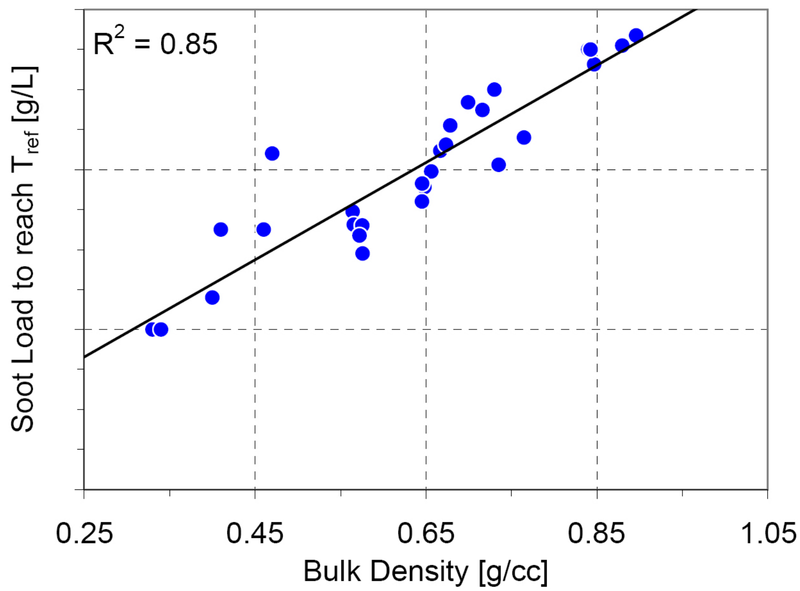

Figure 2. Experimental data showing the correlation between the filter bulk density and the soot load to reach a target peak temperature during severe regeneration conditions.

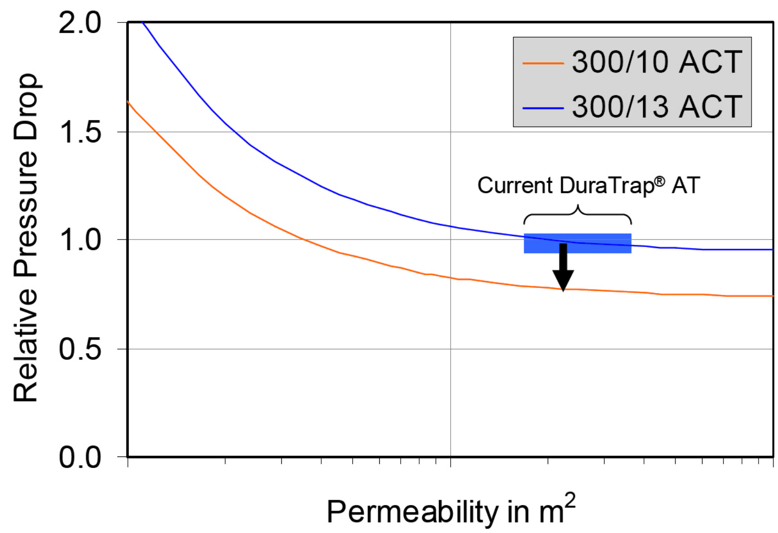

Figure 3. Correlation between pressure drop and permeability of 300cpsi diesel particulate filters with different wall thickness.

correlation of the soot load to reach a target peak temperature as function of the filter bulk density. The experimental data cover a wide range of experimental filter samples, including different materials, porosities and cell configurations.

The pressure drop of a diesel particulate filter of given size and under a given flow condition is primarily determined by the permeability of the wall material and the cell geometry of the filter. This is shown in Figure 3. For filter products, such as the current aluminum titanate products having a high permeability, the pressure drop is relatively insensitive to the permeability. Hence a further improvement would not lead to an appreciable reduction in filter pressure drop. Reducing the cell density would be an option but due to the reduced filtration area this would actually increase the soot loaded pressure drop, especially with ash present. Therefore, a reduction in web thickness is the most effective way to reduce the pressure drop. The reduction in wall thickness also increases the inlet channel volume and, to a minor extent, the filtration surface area. Both are of benefit with respect to the ash storage capacity. A downside of the reduction in web thickness is that for a given material this would also decrease the bulk density of the filter, which would reduce the soot mass limit as has been shown in the previous paragraph. In addition, the mechanical strength would be decreased.

Table 1. Summary of the characteristics of the new aluminum titanate products.

<table>
<tr><th></th><th>Approach</th><th>Porosity</th><th>Pore Size Distribution</th><th>Cell design</th><th>SML</th><th>Pressure Drop</th><th>Strength</th></tr>
<tr><td>DuraTrap® AT</td><td>Base</td><td>~50%</td><td>Base</td><td>300/13 ACT</td><td>Base</td><td>Base</td><td>Base</td></tr>
<tr><td>DEV AT LP</td><td>Increased bulk density</td><td rowspan="2">~44-45%</td><td rowspan="2">Improved</td><td>300/13 ACT</td><td>+ 2-3 g/l</td><td>~ Base</td><td>Increased</td></tr>
<tr><td>DEV AT TW</td><td>Reduced wall thickness</td><td>300/10 ACT</td><td>~ Base</td><td>- 20-25%</td><td>Base</td></tr>
</table>

Considering the data discussed above leads to the conclusion that a product that offers an increased soot mass limit at a pressure drop comparable to the current commercially used aluminum titanate product in 300/13 cell geometry can be obtained by increasing the bulk density while maintaining the same cell geometry. To achieve this we have developed a new aluminum titanate composition with a reduced porosity in the range of nominally 44-45% vs. ~50% for the current product. Combined with improvements in the intrinsic material robustness and advancements in the plug composition this is expected to offer an increase in soot mass limit in the range of 2-3 g/l, as will be shown later. Since the permeability is a function of the porosity and to avoid a penalty on pressure drop, the pore distribution of the new material has also been improved. Through use of engineered raw materials and advanced processing we have been able to further improve the pore structure of the new low porosity aluminum titanate composition achieving a narrower pore size distribution that compensates for the reduced porosity. These characteristics are summarized in Table 1 and we will reference this new filter product as DEV AT LP 300/13 throughout the remainder of this paper.

The same material from the new low porosity AT family but extruded in a modified cell configuration with a reduced web thickness of 10mil (=0.01inch) is used for a second new product targeting a reduction in pressure drop. Compared to the current commercially used aluminum titanate product a reduction in pressure drop by 20-25% is expected. An additional benefit obtained via the thinner webs is an increase in inlet channel volume for enhanced storage of ash. The bulk density, and hence the soot mass limit, as well as the strength of this new thinwall product is comparable to the current commercial aluminum titanate product in 300/13 cell configuration. The properties for this new filter product are summarized in Table 1 and we will use DEV AT TW 300/10 as reference throughout the remainder of this paper.

Although optional in all cases, the asymmetric cell technology, ACT [2,3,11], has been assumed in the summary in Table 1 as it offers significantly increased ash capacity and is used in most of the current applications of aluminum titanate filters.

In the following sections examples of performance test data will be discussed, covering pressure drop, filtration and thermal behavior and robustness. It will be demonstrated that the targets for the two new product concepts, based on the new developed low porosity aluminum titanate composition, are achieved.

PRESSURE DROP BEHAVIOR OF THE NEW FILTER PRODUCTS

The pressure drop of the new filter products was tested in cold flow lab benches as well as on engine bench. Filters were tested in a bare, uncoated as well as in a coated state. For the latter different coating technologies were considered. In the following paragraphs examples of these tests will be discussed demonstrating that the above described pressure drop product targets were met.

In Figure 4 pressure drop data as a function of the soot load are shown for the current commercial AT product as well as the two new filter products. The data are for bare filter, measured on a cold flow lab bench. Printex U is used as soot. The comparison of the two filters with 300/13 cell geometry shows that the target of maintaining the pressure drop despite the reduction in porosity is met. The comparison of the pressure drop of these filters with the thinwall filter in 300/10 geometry shows the desired and expected decrease in pressure drop.

Figure 5 compares the clean and soot loaded (6 g/l) pressure drop for the current commercial aluminum titanate product in 300/13 and the new thinwall product in 300/10 configuration. Both filter technologies use the asymmetric cell design. Measurement was done on 5.66″×8″ filters and a four cylinder common rail engine. Two different types of catalyst coatings are considered. Under all conditions, the new thin

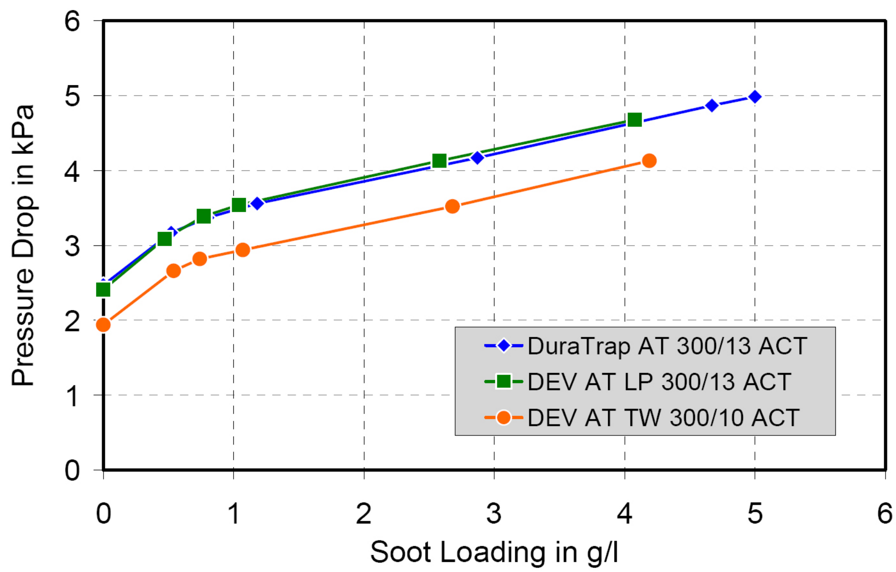

Fig. 4. Pressure drop measured on a cold flow lab bench with bare, uncoated filter samples.

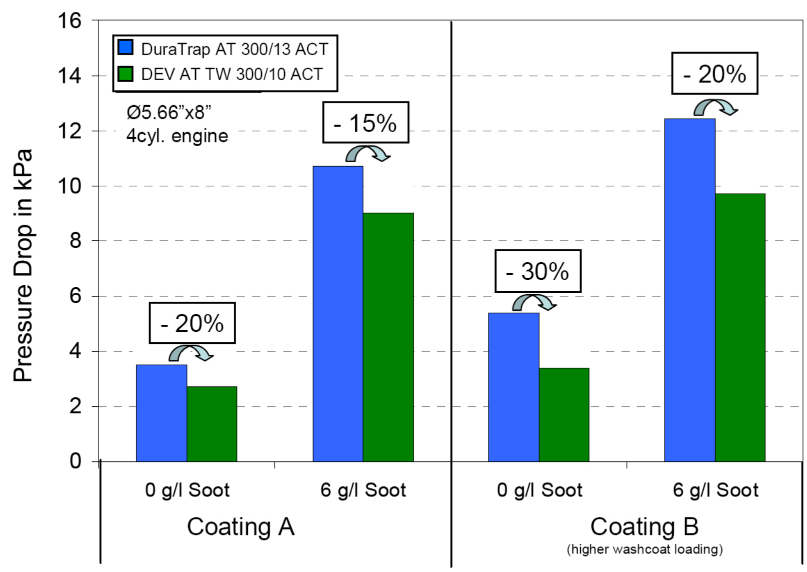

Fig. 5. Comparison of clean and soot loaded pressure drop measured on DuraTrap® AT and DEV AT TW 300/10 samples. Results with two coating technologies are shown.

wall design filter shows the targeted reduction in pressure drop.

Figure 6 provides another comparison of the soot loaded pressure drop measured on engine bench in samples with 5.66″×6″ size. The samples were coated with the same comparable coating technologies. As in the previous examples, the expected benefit of the thinwall design was confirmed. In this case a reduction by roughly 30% was observed. Figure 6 also shows data for a competitive SiC product with a 300/10 design and asymmetric cells. The SiC sample was a commercial sample obtained as replacement part at a dealer and the coating technology used was for a comparable application as used for the aluminum titanate samples shown in Figure 6. It can be clearly seen that the reduced wall thickness of the SiC product enables it to achieve a pressure drop similar to the current commercial aluminum titanate product in 300/13. However, due to the area lost for the cement seams and differences in material permeability it does not meet the low pressure drop of the new thinwall aluminum titanate 300/10 sample.

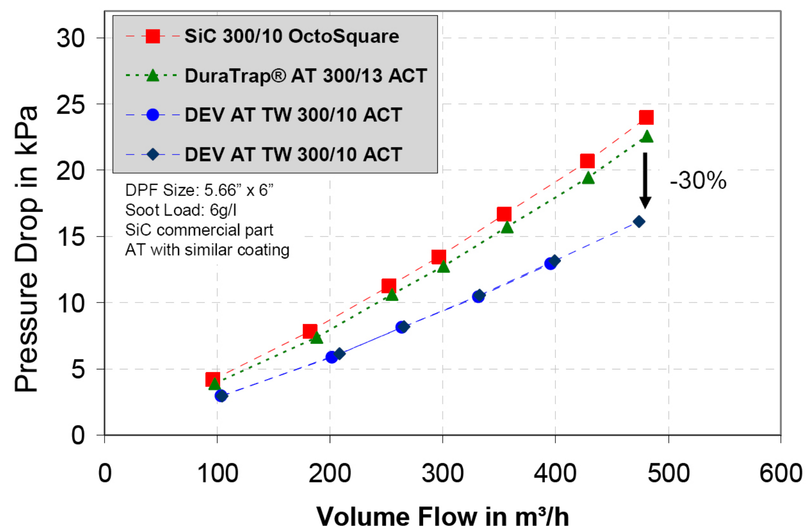

Fig. 6. Comparison of soot loaded pressure drop measured on current commercial AT 300/13, DEV AT TW 300/10 and a reference SiC 300/10 sample. All filters have asymmetric cell design and comparable coating.

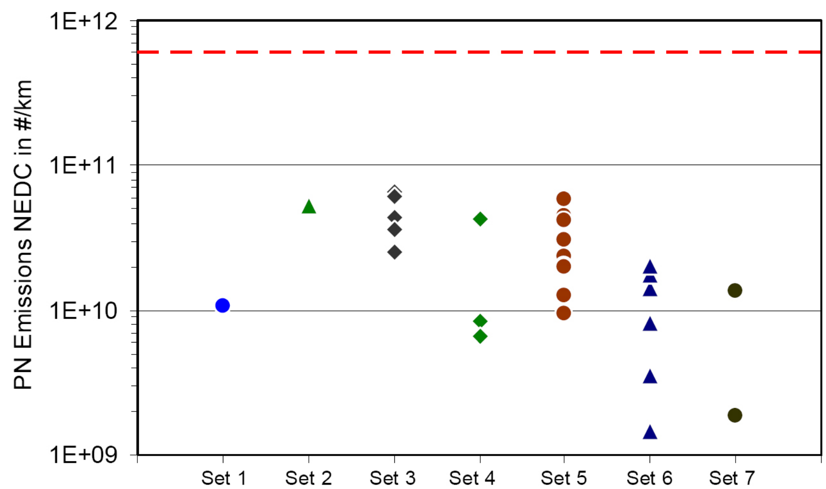

Fig. 7. Particle number based emissions measured over a large number of the new low porosity AT filters. Data for a number of sets of filters of different size and coating technology are shown. Data were measured over a simulated NEDC drive cycle on a dynamic engine bench with full CVS and PMP compliant particle counting technology.

FILTRATION BEHAVIOR

The introduction of current EU5 regulations reduced the permitted emissions of particulate mass from 25mg/km to 5mg/km over the NEDC. The upcoming introduction of the EU5b and EU6 standards will introduce the measurement of not only the particulate mass but also the particle number emissions. To meet these standards the particle number emissions have to be less than 6×10^{11} #/km. For most applications this number based limit is equivalent to particulate mass emissions below the limit set for PM of 5mg/km measured with the current protocol and 4.5mg/km with the PMP protocol. Therefore, the PN measurement is the more critical one and has been the focus of our evaluations.

In Figure 7 a large number of PN emission data measured over the NEDC are shown for several sets and samples of the new filter products in different size, with different coating technologies as well as bare (set 1 and 2). The data were measured on a four cylinder EU5 engine on a dynamic engine bench. The bench is equipped with a full CVS system and a PMP compliant particle count (TSI Rotating Disc Diluter and CPC) and PM equipment (Horiba HF-47). Prior to the emission test the filters were completely regenerated and then conditioned over 3 consecutive EUDC followed by a cold soak. The data shown in Figure 7 show that, as expected, the different aluminum titanate products tested delivered number emissions well below the required limit.

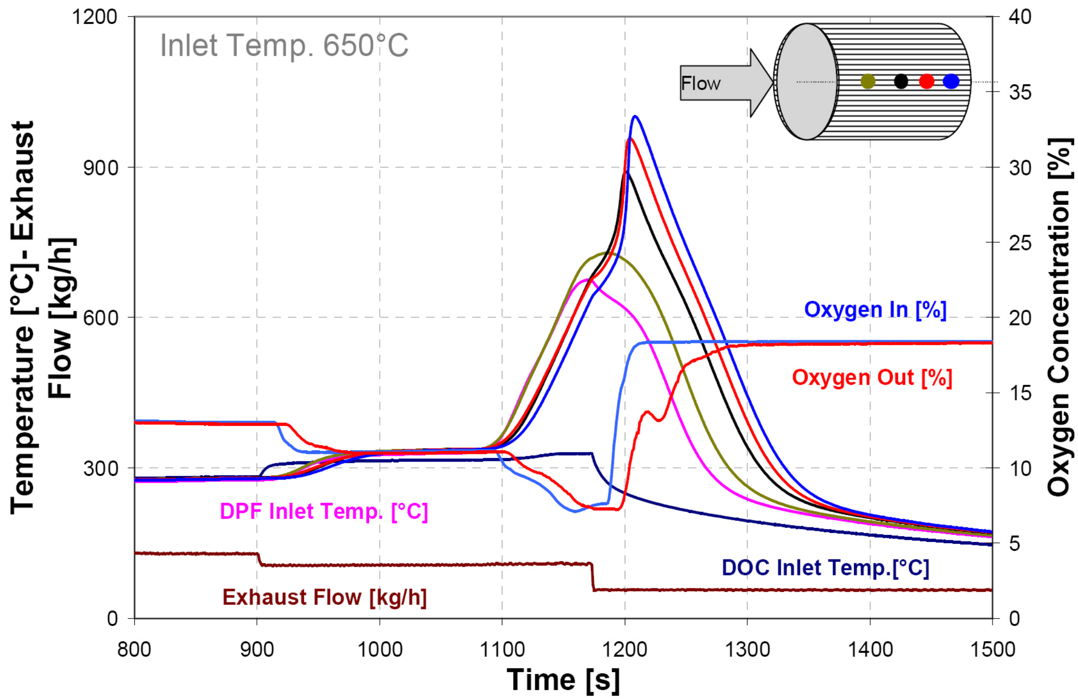

Fig. 8. Example of the transient conditions and temperatures inside a DPF during a worst case drop to idle regeneration.

SURVIVABILITY AND SOOT MASS LIMIT UNDER WORST CASE REGENERATION CONDITIONS

During use diesel particulate filters can be exposed to conditions causing extreme temperatures and temperature gradients. Typically this is observed during regenerations with high soot load and a drop into idle early in the regeneration. In this condition the low idle flow rate has limited ability to convectively remove the heat released from the oxidation of soot and, at the same time, the oxygen concentration is generally high promoting the oxidation [10]. Although other severe conditions exist, this drop to idle test is generally viewed as a representative worst case used to test the filter limit. An example of such a drop to idle worst case regeneration is provided in Figure 8. The active regeneration is initiated at roughly 1100s, resulting in an increase in the inlet temperature to the filter. At roughly 1160-1170s the engine is switched into idle, as can be seen from the drop in exhaust mass flow, followed by the increase in inlet oxygen concentration. As a result the temperature measured inside the filter increases rapidly with the highest temperatures usually observed towards the back of the filter. In Figure 8 this is shown for the thermocouples installed in the center of the filter at different axial positions.

In general it is instructive to differentiate between survivability, discussed in this section, and durability, discussed in a later section. The objective of the survivability testing, sometimes also called soot mass limit testing, is to identify the limiting thermal exposure the filter can survive. In a typical experiment the soot load is incrementally increased until a decrease in filtration performance is observed, resulting in a failure to meet the particle number standard of 6×10^{11} #/km. The number of exposures or worst case regenerations during this kind of testing is generally low and typically in the range of 5-10. The conditions until the failure in emissions is observed represent the operating window of the filter. Since it is the thermal stress applied rather than the soot load itself [10] the operating window is typically represented by using relevant stressors such as, for example, the maximum temperature and the maximum temperature gradient inside the filter. This has been discussed for the current commercial aluminum titanate product in detail elsewhere [12]. Although some of the filters discussed in reference [12] failed at higher temperatures and gradients a guidance of a maximum temperature of 1200°C and a maximum temperature gradient of 600°C/cm has been provided. Note that these numbers require temperature measurement according to the detailed procedures described in reference [12] since, for example, the temperature gradient is extremely sensitive to the placement of the thermocouples. In our experiments, thermocouple spacing for maximum radial gradients is always 10mm and care is taken to ensure that the outermost thermocouple is placed close to the skin.

Figure 9 shows data from drop to idle testing with the current and the two new filter products. Plotted is the maximum temperature inside the filter as a function of the soot load at the start of the regeneration. The data show that for the two designs with a 300/13 cell geometry the increased thermal

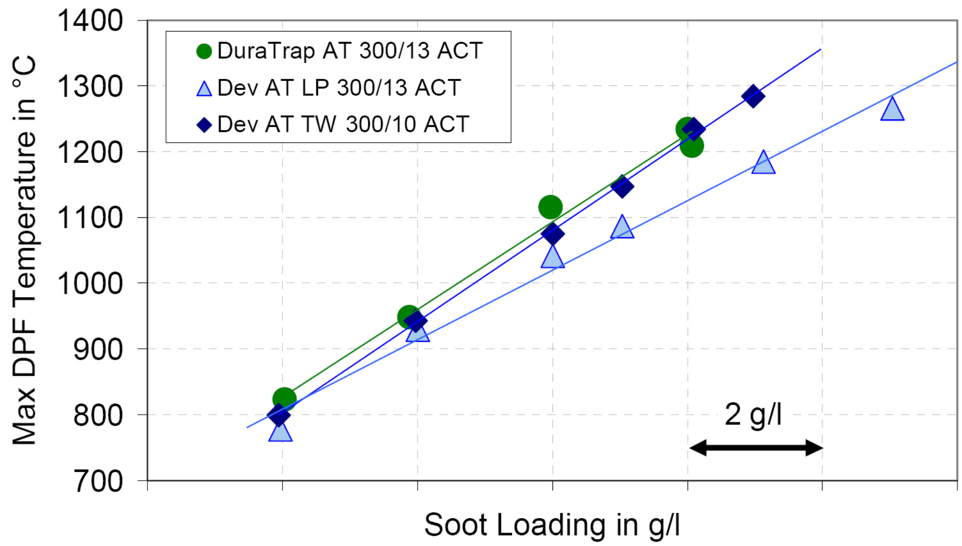

Fig. 9. Peak temperatures observed inside the different aluminum titanate filters during drop to idle regenerations as function of the soot load.

mass of the DEV AT LP filter leads to lower temperatures at a given soot load, confirming the expected behavior described above. At the high temperatures the difference is equivalent to about 2g/l soot load. As will be shown later, the data available so far suggest that the new generation of aluminum titanate products also meet the target of an improved survivability and extended operating window. This ability to withstand higher peak temperatures will allow a further increase in soot mass limit vs. the current DuraTrap® AT product.

Also shown in Figure 9 are data for the thinwall DEV AT TW 300/10 filter. As expected based on the comparable bulk density, a similar thermal response is observed for this filter and the current DuraTrap® AT 300/13 filter. This suggests that the lower porosity compensates for the reduced web thickness and enables a comparable soot mass limit for this low pressure drop filter.

The data from 18 filters tested for survivability are summarized in the form of the thermal operating window of the new low porosity AT filter products in Figure 10. The data were obtained with filters that were either bare (open symbols) or were coated with different technologies (solid symbols). The filters tested and shown were also of different size and cover 300/13 as well as 300/10 cell geometry, with the latter representing the majority of the data. The maximum radial gradient measured inside the filter vs. the maximum temperature (thermocouple placement as specified in [12]) is shown. The blue and red symbols indicate how far the PN emissions measured after the drop to idle regeneration have been below or above the limit of 6×10^{11} #/km, respectively. Also shown is the guideline provided for the current commercial aluminum titanate product in reference [12]. The data shown suggest that the new materials indeed have the potential for an increased operating window.

To obtain a reference with competitive SiC products the new DEV AT TW 300/10 thinwall product has been tested in comparison to a commercially available and purchased SiC product with comparable cell density of 300/10. Both products had asymmetric cell design, comparable coating technology and the filters tested were of 5.66″×6″ size. The same severe drop to idle test procedure has been used with a high regeneration temperature of 650°C. Results are provided in Table 2. As can be seen both filter types failed at comparable soot mass values. The temperatures at failure were about 40-60°C higher for the aluminum titanate filter, indicating its higher thermal robustness.

REGENERATION BEHAVIOR

With respect to the practical application the regeneration behavior of a particulate filter is of significant relevance. During active regenerations, the engine is operated under non ideal conditions to enable an increase in the exhaust temperature to a level that enables the oxidation of the deposited soot by oxygen. The result is an increase in specific fuel consumption during this event, which is proportional to the temperature level that is targeted as well as the duration. Therefore, achieving high regeneration rates already at low temperatures and after short regeneration durations is desirable.

Figure 11 shows experimental results from controlled active regenerations performed on a 4 cylinder light duty engine at different temperature levels. In all cases the filters were initially loaded to the same soot load. Then an active regeneration was initiated and performed for a constant

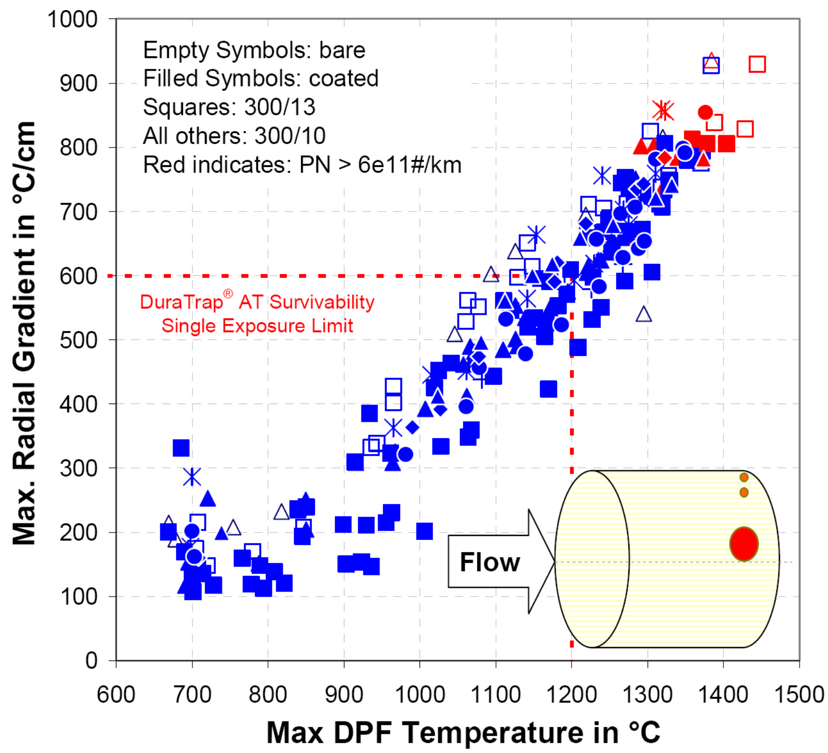

Fig. 10. Thermal operating window data for 18 filters with the new low porosity aluminum titanate composition. Shown is the maximum temperature gradient vs. the maximum temperature in the filter [12]. Blue and red symbols indicate number based emissions below and at or above the limit of 6×1011 #/km, respectively. Data are for different filter geometry, coating technology or bare. Each symbol represents one or more filters of a given condition.

Table 2. Comparison of soot mass limit test results with DEV AT TW 300/10 and a commercial SiC 300/10 product Provided are first failed soot loads.

Filter Type	Sample 1	Sample 2	Sample 3
DEV AT TW 300/10 ACT	8.6 g/l	8.8 g/l	9.1 g/l
SiC 300/10 assym. (commercial)	9.1 g/l		

duration of 10 minutes, starting and ending when the inlet temperature reaches 450°C, respectively. All other operating conditions, including speed and torque, were maintained the same. The regeneration efficiency was determined gravimetrically from the difference in soot load before and after the regeneration. For all aluminum titanate filters tested, the exponential increase with temperature can be seen, showing significant regeneration rates (or indirectly soot burning rates) for temperatures above roughly 550°C. The two thinwall AT filters used in these experiments had different catalyst coatings. The results, however, are very comparable; suggesting that under these conditions the impact of the catalyst technology is only moderate (assuming a typical CSF coating technology is used). The comparison with the current series product shows some benefits. For reference are also data added from two different SiC filters obtained as replacement parts at different car dealers, both having oxidation coatings. The results are very similar for the two different SiC filters. The results suggest that under the given set of regeneration conditions, lower regeneration temperatures can be used for the AT filter to achieve comparable regeneration efficiency as for the SiC filter. This behavior is attributed to the higher thermal conductivity of SiC materials, resulting in higher local and integral heat losses during heat up.

Another important factor, especially considering highly transient urban driving patterns with a large number of stops and idling, is that the time available for regeneration is used efficiently to oxidize the soot. One simple way of assessing this behavior is to evaluate the regeneration efficiency during drop to idle events performed at different temperatures or

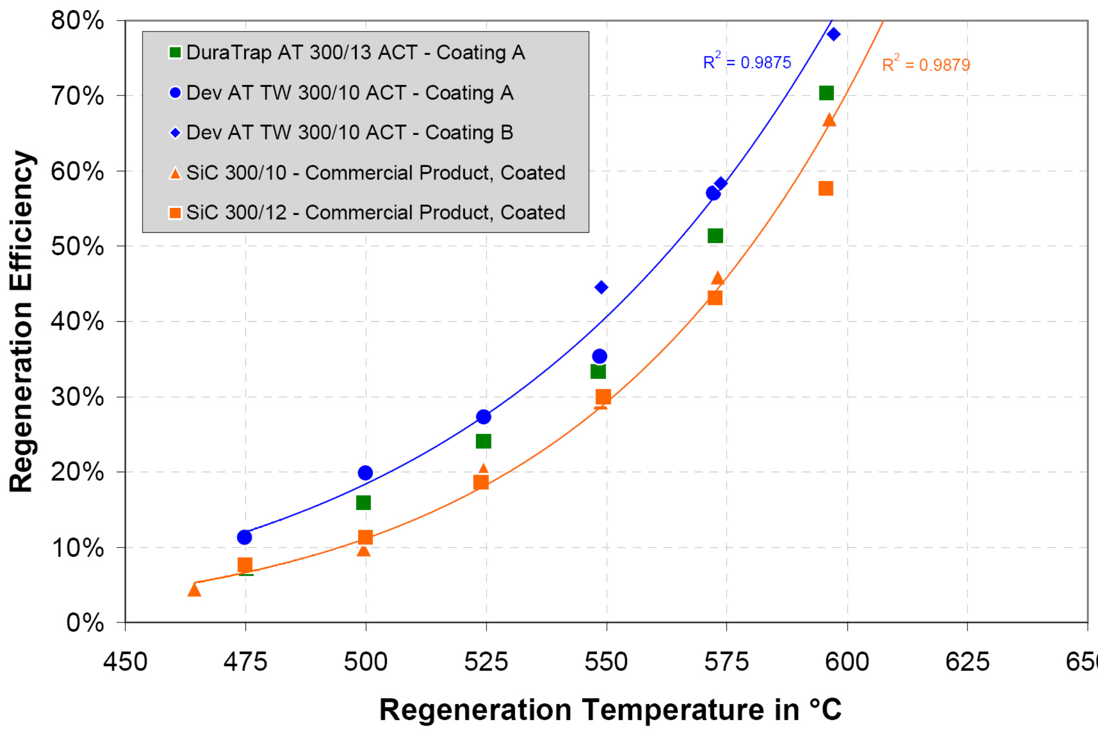

Fig. 11. Regeneration efficiency as function of the regeneration temperature obtained under constant, controlled regeneration conditions (identical soot load, flow rate, heat up rate and duration).

times into the active regeneration. Results from such experiments are shown in Figure 12 for the same filters already discussed in the previous section. In these experiments the filters were also loaded to a defined soot load and then an active regeneration was initiated. The engine was switched into idle at different temperatures. During the idle operation the active regeneration strategy was turned off. The regeneration efficiency at the end of the test has again been determined gravimetrically by determining the mass of soot that was oxidized.

The results again show very comparable results for the two thinwall AT filters and the AT series product, which makes sense as all have comparable thermal mass and conductivity. The two different SiC filters also behaved very comparable to each other. Of practical interest is the significant difference in the regeneration efficiencies achieved with the different types of materials, SiC and AT. Whereas almost no soot is oxidized with the SiC filter up to maximum inlet temperature before the drop into idle below ~625°C, the AT filter already shows an appreciable amount of soot that is burned during this short event. In the range between 600-625°C maximum inlet temperature prior to idle, the observed difference in regeneration efficiency has been as much as 20-30%. Under cyclic urban driving conditions this can facilitate the regeneration of the particulate filter, since even short regeneration events, which are interrupted by a switch to an idle condition can be used to oxidize some of the accumulated soot. The results shown here are consistent with results discussed in reference [10] and are explained by the increased heat dissipation due to a higher thermal conductivity for SiC materials.

LIMITED DURABILITY DATA UNDER REPEATED SEVERE REGENERATION CONDITIONS

The objective of limited durability testing is to expose the filter over a larger number of severe regeneration events. The testing is done on engine bench with repeated soot loading cycles followed by drop to idle regenerations. After the drop to idle regenerations the filters are always completely regenerated prior to the next loading step. Every 7-8 cycles the filters are tested for filtration efficiency. The filtration efficiency is measured on the fully regenerated filter, to enable a sensitive assessment of the function of the filter. In larger intervals and after completion the filters are also tested for PN filtration over the NEDC. During the drop to idle regenerations care is taken to ensure a narrow distribution in maximum filter temperature throughout the many cycles.

Examples of test results obtained on several DEV AT TW filters over a large number of drop to idle regeneration cycles is shown in Figure 13. Shown are the average peak temperatures measured inside the filter, with the symbols representing in all cases the values during the preceding 7-8

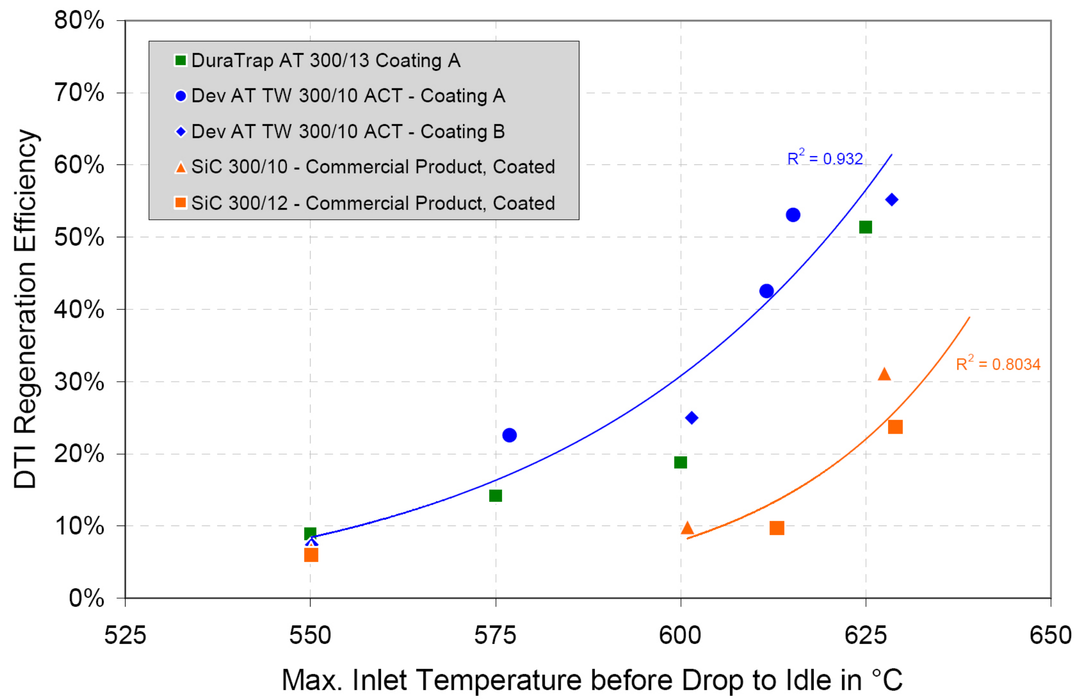

Fig. 12. Regeneration efficiency as function of the regeneration temperature obtained under drop to idle (DTI) regeneration conditions (identical soot load, flow rate pre and post drop to idle, heat up rate and duration in idle).

drop to idle regenerations. The error bars show the absolute peak temperature the filter had been exposed to during the cycles. The exposure temperature was varied with target ranges of-1125-1150°C, 1150-1200°C and 1200-1250°C. For all the data shown below the filtration efficiency remained high and the filters maintained PN emissions below the required limit of 6×10^{11} #/km, as measured on the engine bench and described in a previous section.

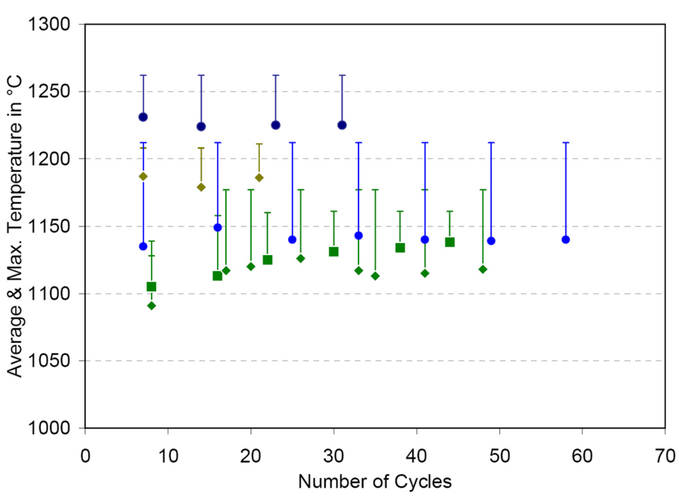

Fig. 13. Limited durability test results over repeated drop to idle regenerations.

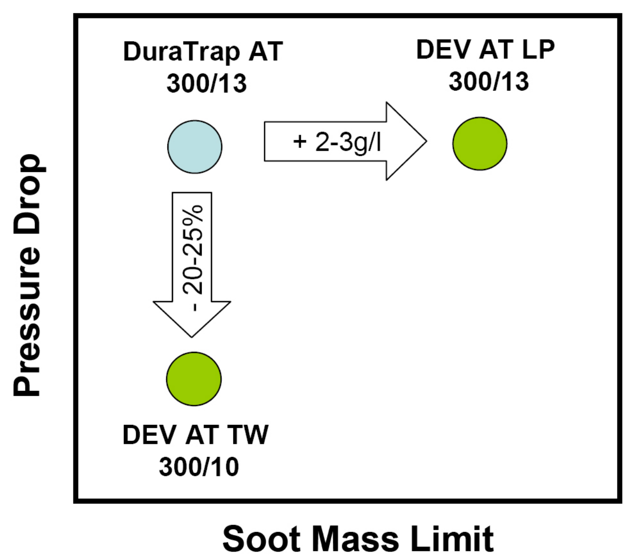

Fig. 14. Increased portfolio of Corning's aluminum titanate filter products.

SUMMARY AND CONCLUSIONS

A new generation of low porosity aluminum titanate filters has been developed, offering an increased portfolio of diesel particulate filters based on this material family. Compared to the currently commercialized DuraTrap AT filter product the new developmental products offer either an even higher soot mass limit or a significantly reduced pressure drop. This is shown schematically in Figure 14.

The experimental data discussed in this paper have demonstrated the achievement of the targets described in Figure 14. Low pressure drop, combined with excellent filtration and survivability or soot mass limit has been observed.

The low pressure drop DEV AT TW 300/10 appears to be especially beneficial for applications in which pressure drop is critical or in which added DeNOx components have increased the overall system backpressure. In addition, the thinner walls combined with the asymmetric cell technology, ACT, allow for the highest specific ash capacity.

The low porosity DEV AT LP 300/13 with a further increased soot mass limit compared to current products will be especially attractive for applications with challenging soot mass requirements or in cases where space allows only for a small filter volume demanding higher specific soot capabilities.

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