

Oxide Based Particulate Filters for Light-Duty Diesel Applications – Impact of the Filter Length on the Regeneration and Pressure Drop Behavior

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ABSTRACT

Diesel particulate filters are becoming a standard for most light duty diesel applications designed for European EU5 and EU6 regulations. Oxide based filter materials are continuing to gain significant interest and have been in high volume serial application since 2005. Compared to carbide materials they show some unique properties.

With respect to the design, the length of a filter is a key variable. Usually the prime design consideration is the desired filter volume. The diameter or frontal area is then usually defined by packaging constraints. Finally, the length is adapted. The paper provides experimental data on the impact this key design parameter has on the pressure drop and the thermal behavior under “worst case” regeneration conditions. A wide range of soot loads (from 4 g/dm³ to 9 g/dm³) as well as filter lengths from 6” to 12” is considered and evaluated under comparable experimental conditions.

The discussion is based on experimental data as well as numerical simulations with a 2D simulator. The simulator is shown to be in good agreement with the experimental observations. In general shorter filters are found to be of advantage. They provide for lower pressure drop and yield lower temperatures and gradients during worst case regeneration conditions. Data are provided that can help to estimate the impact of the filter length on the soot mass limit.

INTRODUCTION

The application of particulate filters to European passenger cars with diesel engines continues to be growing at a fast rate. For EU5 it is expected that most diesel engines will have to be equipped with a diesel particulate filter to meet the further reduced particulate matter emission standards. After the initial introduction of SiC based filters, oxide based particulate filters are gaining significant interest [1-3]. More than 750,000 aluminum titanate filters (Corning DuraTrap® AT) will be

on the road by the end of 2007. Cordierite filters are today in series production on most heavy and a large number of medium duty applications to meet US 07 regulations [4, 5]. For the near future a number of passenger car series applications are expected as well. Although comparable from a filtration perspective [3] the oxide filters show different thermal behavior compared to SiC, especially due to the difference in thermal conductivity. The lower thermal conductivity of oxide materials generally allows for a faster heat up and regeneration but also requires some adaptation with respect to the optimal regeneration strategy [6].

Across the applications there is a clear trend towards close-coupled installations of the particulate filter. However, in some instances space constraints in the engine compartment prevent such installation. In the underfloor position usually it is easier to allocate space for the aftertreatment components. However, other than operational difficulties with heat losses etc., the underfloor installations are commonly constrained in the available frontal area and height of the filter to maintain a sufficient chassis clearance. Therefore the filter length is used to adjust the filter to the desired volume allowing for sufficient soot and ash storage capacity.

It is common understanding that the soot mass limit of a particulate filter decreases with increasing filter length [8,9]. However, very little quantitative information is available on the impact of this important design parameter especially for oxide filter materials. The objective of this paper is to address this question and provide experimental confirmation as well as a thorough fundamental understanding.

EXPERIMENTAL SETUP AND PROCEDURES

The experimental work was performed with a two liter prototype engine designed to meet EU4 standards. The engine had common rail fuel injection system, turbo charger, intercooler, and cooled exhaust gas recirculation. The engine was installed in a dynamic test bench with an

asynchronous dynamometer. The test bench was equipped with an emission bench for transient exhaust gas analysis, an AVL 415S smoke meter and a constant volume sampling (CVS) system for dedicated experiments. In addition to the engine sensor readings and the data from engine control unit (ECU), the test bed had standard instrumentation with several additional temperature and pressure sensors, mass flow controller, etc.

The aftertreatment system comprised an oxidation catalyst (400 cpsi) followed by the catalyzed diesel particulate filter (see Fig. 1). For the testing program, a series of cordierite filters (Corning DuraTrap® AC 300/15 ACT) with a nominal cell density of 300 cpsi and 15 mil wall thickness were used. The coating on the particulate filter had a relatively low precious metal content, which was mainly designed to convert the CO generated during the soot oxidation. Filters with different lengths of 6", 8", 10" and 12" were used in the program. All had the same diameter and same nominal catalyst coating. Filter data are summarized in Table 1.

Table 1. Dimensions of filters used. All were Advanced Cordierite filters with nominal cell density/wall thickness of 300/15 and asymmetric cell technology (ACT).

Filter	A	B	C	D
Length	6 inch 152.4 mm	8 inch 203.2 mm	10 inch 254.0 mm	12 inch 304.8 mm
Diameter	5.2 inch 132.1 mm			
Volume	2.09 dm ³	2.78 dm ³	3.48 dm ³	4.18 dm ³

To record the thermal events during severe regeneration experiments all filters were equipped with 28 thermocouples. Schematics of the thermocouple patterns used for the filters with different lengths are shown in Figure 2. In all cases the main focus was to capture the temperatures in the rear of the tested filter.

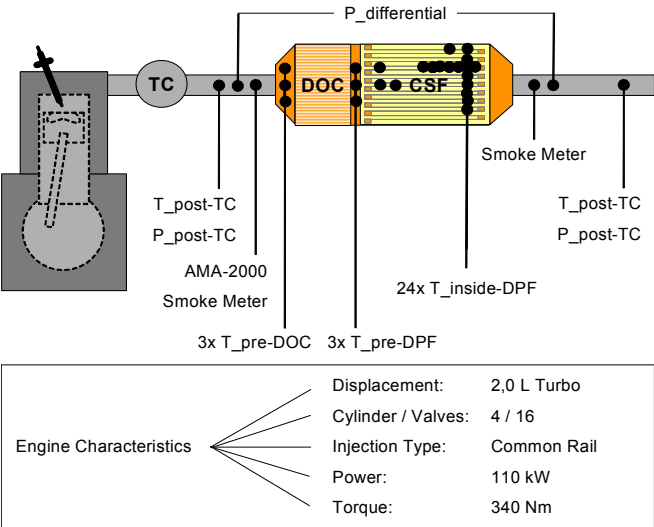


Figure 1. Schematic of the test setup.

Due to imperfections in the radial temperature distribution at the filter inlet, 3 additional thermocouples in different radial positions have been installed just at upstream of both the diesel oxidation catalyst (DOC) and the filter.

For the tests, the filters were canned by a simple stuffing method. To stabilize the weight of the canned filters, especially with respect to the mat, the canned filters were heat-treated in a furnace for several hours.

Different experiments were performed on engine bench. Prior to all tests the filters have been conditioned by several hours of operation of the filter on engine bench at full load and speed. The soot loading was done at a steady state engine operating point with a relatively high soot loading rate of 5-6 g/h. The soot mass accumulated on the filter was monitored through weighing and adjusted to within +/- 0.5 g/dm³ of the target soot load. Experiments at different specific soot loads up to 9 g/dm³ were included.

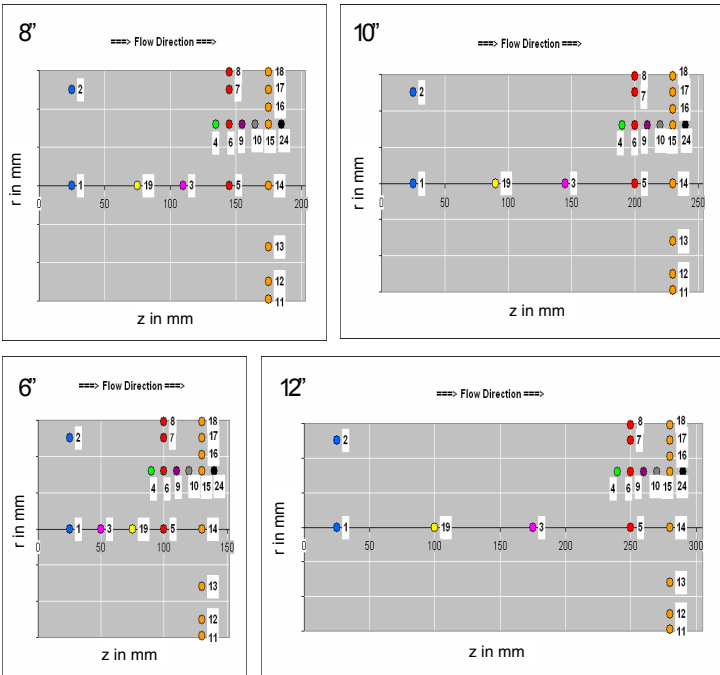


Figure 2. Thermocouple patterns used within the filters of different lengths. Shown is the 0°-180° plane.

A dynamic test procedure was used for the pressure drop experiments. This procedure consists of a short conditioning phase, where the filter is stabilized at ~250 °C followed by a rapid increase in engine speed and load (up to the maximum fueling rate). Then the fueling is decreased to zero within a short timeframe, e.g. the torque is reduced to zero while the speed is maintained. The entire procedure takes only a few minutes and has been found to deliver reliable results. Due to the short duration the temperature at the filter inlet stays relatively constant at ~350-400 °C throughout the relevant test phase.

The regeneration experiments were limited to severe drop to idle tests (DTI experiments). In these experiments an active regeneration is initiated at a low load, medium speed engine operating condition. After a fixed time, when the filter inlet temperature reached 600 °C, the engine is switched back to idle. This results in a sudden increase in the oxygen concentration of the exhaust gas and a significant decrease in mass flow. An example of the conditions during such a DTI test is shown in Figure 3. This test has been found to represent some of the worst case conditions as the soot has started to burn, sufficient oxidant (O_2) is provided and the convective heat removal is drastically reduced. The rate at which the heat is released exceeds the heat that can be removed from the system, leading to an increase in the temperature inside the filter, resulting in thermomechanical stress. After each regeneration experiments the soot mass burned was determined gravimetrically. Then the residual soot was burned in a clean out regeneration step at constant engine operating conditions. At the end of the clean out step another weight measurement was used to check that all soot had been burned. Prior to the next regeneration experiment, the filter was reloaded to the desired soot level.

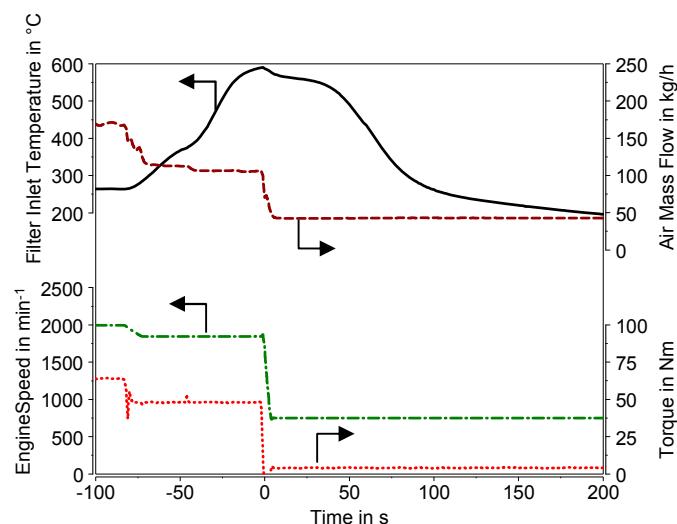


Figure 3. Example of a severe drop to idle (DTI) regeneration experiment. Time zero indicates when the engine is switched to idle.

MODEL

Two types of models were used for the analysis and interpretation of the results, as well as the extrapolation to other relevant conditions

For the pressure drop calculations a 0-dimensional model was used that separates between the various pressure losses in the filter, namely inlet/outlet effects due to contraction/expansion, friction along the channels and resistance across the soot layer and the wall. The model also considers the deposition of ash as layer on the walls and as plug in the back. The model treats every

resistance separately and allows consideration for non-symmetrical channel geometries such as the asymmetric cell technology (ACT) applied to the filters used in this program [1, 2].

The simulation of the regeneration events was done by using Cornings simulator, based on a dynamic heterogeneous model of a particulate filter. The model considers for conservation of mass, enthalpy and momentum in the inlet and outlet channel as well as the channel wall. Compared to the original model described in [7] several advancements were made in the model formulation. The advanced model consists of three scales of modeling: (1) filter-scale transient heat conduction of filter volume include insulations, (2) channel scale gas flow continuity, momentum, energy balances and species transports, and (3) wall (“web”) scale gas flow, species transport, and soot chemical reactions.

The filter scale heat conduction deals with the transient thermal conduction in solid (monolith filter substrate). The monolith is treated as a continuum media with anisotropic “effective” heat conduction property. The heat source accounts for heat exchange between the gas flowing in the channels and the solid walls, and also the heat generated in soot oxidation reactions and/or in any other species reactions which leads to species conversion either in soot layer or channel wall.

Channel scale model is a simplified one dimensional model for compressible gas flow with accompanying species transports. It includes viscous drag force in momentum balance of fluid flow and species mass transport perpendicular to the channel flow direction by using channel friction factor and mass transport coefficients.

Wall scale model is used for gas flow through the porous wall and associated species transport with chemical reactions. The gas flow is treated as Darcy flow with thermal equilibrium and species transport. The latter is described as purely advective (plug flow reactor model) or as advective-diffusive transport (either with a continuous stirred tank reactor model or a more accurate full advection-diffusion reactor model). The source term is derived from the kinetics of the chemical reactions occurring in the soot and the wall. For the filter scale the model is formulated for either one (axial only) or two dimensions (axial and radial). In the current study the two dimensional model was used, as the objective was to not only capture the maximum temperatures, but also the radial temperature distribution and the regeneration efficiency.

RESULTS

PRESSURE DROP EXPERIMENTS

The pressure drop experiments were done at clean and 8 g/dm³ soot load. For the soot loading in general an accelerated method with ~5-6 g/h was used. Results are shown in Figure 4.

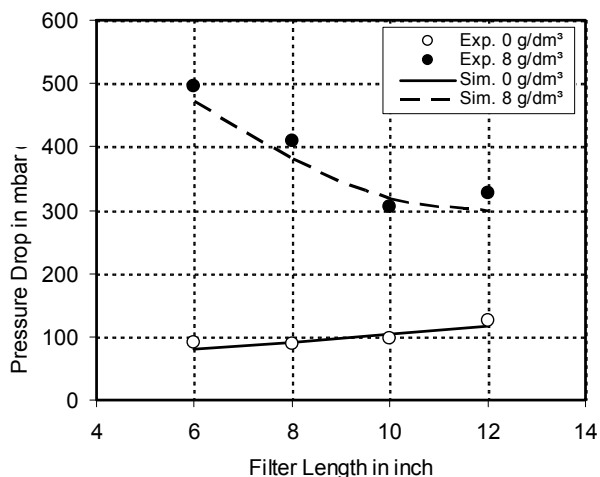


Figure 4. Effect of filter length on the pressure drop at 600 m³/h (note: Experimental data were at 8.0-8.4 g/dm³)

The clean pressure drop increases slightly with the filter length. This is due to the increased frictional pressure losses along the inlet and outlet channels which represent a major contribution to the overall pressure drop. The effect of a reduced pressure loss across the filter wall, due to the lower wall flow velocity with increased area, is relatively small in case of advanced filter materials with high permeability and not sufficient to balance the increased frictional losses.

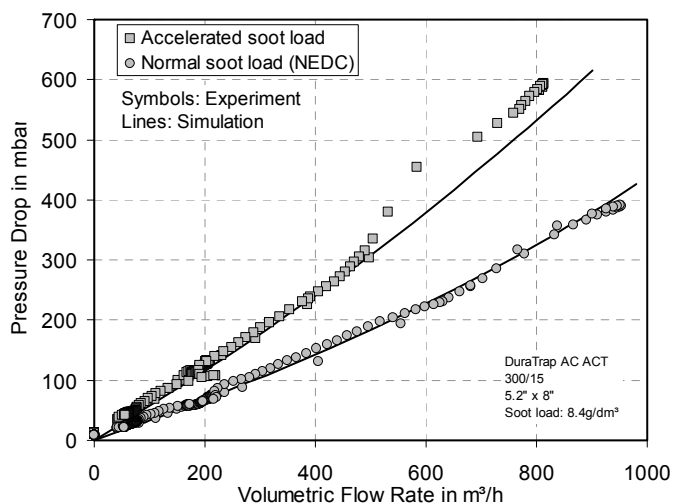


Figure 5. Comparison of pressure drop observed for the same filter at a soot load of 8.4 g/dm³ but different soot loading procedure – accelerated vs. normal loading over simulated New European Driving Cycle (NEDC).

For the soot loaded pressure drop (~8 g/dm³) the opposite trend is observed. In this case the pressure loss across the soot layer is significant and exceeds the pressure loss due to friction. As a result, the effect of the decreasing wall flow velocity for the longer filter with higher total filtration area (and thinner soot layer) results in a lower overall pressure drop.

As mentioned earlier, the data shown in Figure 4 were obtained for soot loaded at accelerated conditions. Based

on our experience, this can lead to soot properties that are different to those of soot loaded under normal engine operation. To evaluate this effect we have also performed one experiment in which the soot was loaded over the 8" filter, but with the engine being operated over a simulated New European Driving Cycle (NEDC) with a normal calibration (EU4). This leads to a much lower soot loading rate of ~0.5-1 g/h. Results comparing the two conditions are shown in Figure 5. A significantly lower pressure drop is observed for the soot generated under the conditions with a lower soot loading rate. This would also apply to the results with filters of different length.

REGENERATION EXPERIMENTS

The regeneration experiments were performed with all filters at comparable inlet conditions (see example shown in Fig. 3) and three different soot loads: 4 g/dm³, 6 g/dm³ and 9 g/dm³.

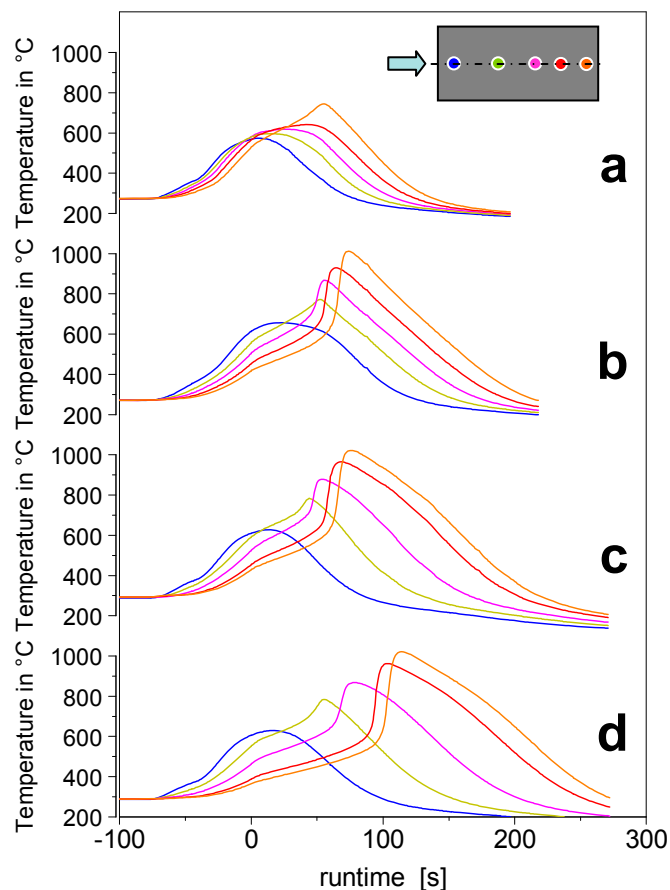


Figure 6. Transient temperature readings during drop to idle regeneration experiments with filters of (a) 6", (b) 8", (c) 10" and (d) 12" length. Shown are the readings at different axial positions along the center line. Initial soot load: 6 g/dm³.

Results at Comparable Specific Soot Load

Examples of the transient temperature readings at the thermocouples located along the central axis are shown in Figure 6. The initial soot load in these cases was 6 g/dm³. The switch back to idle occurred at the relative