Energy 86 (2015) 19–30

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Impact on vehicle fuel economy of the soot loading on diesel particulate filters made of different substrate materials

Federico Millo [a, *], Maurizio Andreata [a], Mahsa Rafigh [a], Davide Mercuri [b], Chiara Pozzi [b]

[a] *Politecnico di Torino, c.so Duca degli Abruzzi, 24, 10129 Torino, Italy*
[b] *General Motors Powertrain Europe, Corso Castelfidardo 36, 10138 Torino, Italy*

ARTICLE INFO

Article history:
Received 4 October 2014
Received in revised form
30 December 2014
Accepted 8 March 2015
Available online 7 May 2015

Keywords:
Diesel particulate filters
Filter regeneration
Soot loading
Vehicle fuel consumption

ABSTRACT

Wall flow DPFs (Diesel Particulate Filters) are nowadays universally adopted for all European passenger cars.

Since the properties of the filter substrate material play a fundamental role in determining the optimal soot loading level to be reached before DPF regeneration, three different filter material substrates (Silicon Carbide, Aluminum Titanate and Cordierite) were investigated in this work, considering different driving conditions, after treatment layouts and regeneration strategies.

In the first step of the research, an experimental investigation on the three different substrates over the NEDC (New European Driving Cycle) was performed. The data obtained from experiments were then used for the calibration and the validation of a one dimensional fluid-dynamic engine and after treatment simulation model. Afterward, the model was used to predict the vehicle fuel consumption increments as a function of the exhaust back pressure due to the soot loading for different driving cycles. The results showed that appreciable fuel consumption increments could be noticed only in particular driving conditions, and, as a consequence, in most of the cases the optimal filter regeneration strategy corresponds to reach the highest soot loading that still ensures the component safety even in case of uncontrolled regeneration events.

1. Introduction

Since 2009 wall flow DPFs (Diesel Particulate Filters) have been adopted for all European passenger cars, in order to comply with the PM (Particulate Matter) EU5 emission limits.

Several studies [1–6], demonstrated that DPFs are capable of physically capturing diesel particulates with extremely high filtration efficiencies, thus preventing their release into the atmosphere. However, the accumulation over the filter of the solid fraction of particulate matter, which is mostly represented by elemental carbon or soot, would eventually lead to the build-up of excessively high back pressures at the engine exhaust, if the accumulated particles were not removed, by means of the so called filter regeneration process, which basically consists in the oxidation of soot.

Unfortunately, while temperatures above 600 °C are necessary in order to burn out soot, such temperatures may hardly be reached in the exhaust gas stream of a diesel engine, especially under part load condition, thus requiring the adoption of specific regeneration strategies. These specific combustion modes generally delay the start of the main injection and introduce additional post injections, usually with injection timings close to the BDC (Bottom Dead Center), in order to increase the exhaust temperatures. The fuel introduced by these post injections does not burn inside the cylinder, but increases the unburned hydrocarbons concentration in the exhaust gas stream. The unburned hydrocarbons are then converted over the DOC (Diesel Oxidation Catalyst) which is generally placed upstream of the DPF, thus leading to the desired exhaust stream temperature increase, and making the oxidation of the soot accumulated over the filter possible. However, since the soot combustion can lead to extremely high heat release rates inside the DPF, the maximum amount of soot accumulated over the filter before regeneration must be limited. Moreover, the filter must be capable to absorb part of the heat generated by the regeneration process in order to prevent too high temperatures and temperature gradients, which can produce high thermal stresses and the occurrence of micro-cracks in the filter. Furthermore, it must also be capable of maintaining its filtration efficiency even after several

* Corresponding author. Energy Dept., Politecnico di Torino, c.so Duca degli Abruzzi, 24, 10129 Torino, Italy.
E-mail address: federico.millo@polito.it (F. Millo).

http://dx.doi.org/10.1016/j.energy.2015.03.076
0360-5442/

regeneration events, especially as far as the new limits introduced by Euro 6 in terms of particle numbers are concerned, since even micro cracks that would keep the DPF below the particulate matter mass limit, would not allow fulfilling anymore the particulate number requirements.

Finally, further issues are related to the possible integration of the DPF with a downstream SCR (Selective Catalytic Reduction) system, since the more severe limitations for NOx introduced by Euro 6 would probably call for the adoption of NOx after treatment devices. One of the most critical parameters for the SCR conversion efficiency is its operating temperature: this places additional requirements in terms of temperature levels downstream of the DPF, since a lower thermal loss through the DPF itself would result in a faster SCR warm up. All the above mentioned issues make the choice of the DPF material and of its structure of crucial importance in the design of the future after treatment systems in order to achieve the best integration between all the components, minimizing the overall drawbacks.

In order to define the optimum soot loading level to be reached before regeneration for each DPF substrate material, that may ensure the lowest fuel consumption in the trade-off between back pressure increase and regeneration frequency reduction [4], both experimental and simulation activities were performed in this work. Firstly, three different substrates (made of, respectively, Silicon Carbide, Aluminum Titanate and Cordierite), were experimentally characterized over the NEDC (New European Driving Cycle) at different soot loadings. This provided a first data set for the calibration and validation of a 1-D engine model, which allowed predicting the fuel consumption increase as a function of back pressure over a large variety of driving conditions. Appreciable fuel consumption increments as a function of back pressure could be noticed only for particular driving conditions, and, as a consequence, in most of the cases the optimal condition for DPF regeneration corresponds to the highest soot loading that minimizes the risk of the component damage during the regeneration event. Several regeneration tests were therefore performed in order to define the different soot mass limits of the different substrates.

2. Tested substrate materials

In order to allow a more clear understanding of the different performance of the three tested substrate materials, the most important properties for DPF substrate materials will be briefly summarized hereafter.

- **SFA (Specific Filtration Area)**

This parameter represents the total channel surface for DPF volume unit. It is computed by dividing the total channel surface area (TFA (Total Filtration Area)) by the DPF volume.

$$SFA\left[\frac{1}{cm}\right] = \frac{TFA\ \left[cm^2\right]}{V_{DPF}\ \left[cm^3\right]}$$

Equation 1 Specific Filtration Area definition.

A higher filtration area, theoretically, leads to higher soot loading capability. However, in most of the applications, the maximum soot loading is limited by the maximum temperatures reached inside the filters during an uncontrolled regeneration event.

- **CTE (Coefficient of Thermal Expansion)**

The thermal expansion coefficient represents how much a material expands (or contracts) when is heated. When a thermal gradient is generated inside the DPF, the hotter region expands compressing the colder one. This generates a mechanical stress inside the component, which can eventually lead to micro cracks occurrence [7]. Therefore a smaller thermal expansion coefficient will lead to a lower thermal stress for the same thermal gradient. If the thermal stress overcomes the maximum material tensile strength the component will crack.

- **Heat Capacity**

The heat capacity is a material property that measures the energy which has to be provided to the object, in order to obtain a defined temperature increase. In the case of a DPF this parameter is a function of the material specific heat capacity and of DPF construction parameters which are wall porosity and cell structure. A substrate with a high heat capacity requires more energy to reach the soot combustion temperature, but on the other hand, if uncontrolled regeneration occurs, it may protect the component from damages.

- **Thermal Conductivity**

The thermal conductivity is the property of a material to conduct heat. On one side, a high thermal conductivity allows a better distribution of the heat inside the component, leading to a better thermal shock resistance in case of uncontrolled regenerations; on the other side, it requires more energy to heat the component and perform the DPF regeneration.

- **Maximum operating temperature**

This parameter represents the maximum temperature at which the most important material properties are still preserved. In any case it cannot be greater than the material melting temperature. For example, despite Silicon Carbide outstands a very high melting temperature (about 2200 °C), it cannot be operated above 1300 °C. As a matter of fact, above this temperature, a glassy surface layer may form on DPF substrate [8], sealing the material pores and thus leading to a permanent increase of the filter back pressure.

- **Pore Characteristic**

The pore characteristics such as volume percentage, size and distribution determine the capability to filter the soot. The porosity influences both mechanical and thermal substrate properties [9–11]: a lower number and a smaller pore dimension lead to a higher filtration efficiency and thermal robustness, but at the same time, increase the filter back pressure. As a consequence, a trade-off between mechanical robustness and back pressure has to be found.

- **Cell structure**

Cell structure is usually referred to the combination of cell shape (square, hexagonal, octagonal) and disposal (symmetric or asymmetric). Experimental investigations [12,13], indicated how this parameter strongly influences the filter mechanical robustness, pressure drop and ash storage capability.

The combination of the above mentioned filter characteristics results in three main DPF properties:

- **Filtration efficiency**

The filtration efficiency represents the property of the DPF to collect particulate and to prevent its release in the atmosphere. During the DPF loading different filtration mechanisms come in