

The Legislative Impact of New Particle Number Standards on the DPF Operational Efficiency

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ABSTRACT

On September 1st 2011, the Euro 5⁺ emission legislation will apply to passenger cars in Europe. It is characterized by the introduction of a new regulation concerning the number of soot particle emissions, whereas Euro5 legislation only applies to soot mass. This new regulation makes it necessary to investigate the impact of filter design on filtration efficiency as it pertains to particle number and to the Diesel Particulate Filter (DPF) operating window. This paper describes the investigation performed on a light duty test bench equipped with a Differential Mobility Spectrometer (DMS) which measures soot concentration number and soot particle size distribution in the exhaust gas effluent. Specific protocols were developed to be able to evaluate filtration efficiency in particle number when the DPF is empty of soot and also when the filter is soot loaded. Several DPF parameters such as filter length, filter diameter, cell geometry, and microstructure were studied. Moreover, in order to define the DPF operating window, severe active regenerations were also performed to determine the filtration efficiency in particle number as a function of DPF damage.

Thanks to this ambitious test program, it was observed that the DPF operating window is impacted by filter design. The DPF thermal behaviour depends on filter size and microstructure. However, the DPF operating window is not significantly impacted when the filtration efficiency of particle number is considered in addition to filtration efficiency in mass.

INTRODUCTION

EURO5+ LEGISLATION

The introduction of Euro 5+ will be characterized by a new regulation concerning soot emissions in number [1]. The future homologation tests will be performed as usual on

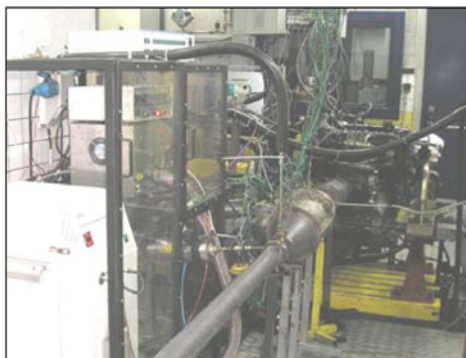
chassis dynamometer with a complete vehicle. In addition to the traditional Constant Volume Sampling (CVS) tunnel, the soot sampling has a new modification. The soot collection for PM counting will go through an evaporation tube heated at 300°C to remove all the volatile part of the raw emissions. For bigger particles, a cyclone will remove them if they are above 1 µm. The diluted sample goes through a Condensation Particle Counter (CPC), in which only solid particles bigger than 23 nm are taken into account. [2]

With the introduction of Euro 5 regulation, the DPF on a Diesel passenger car is now quasi compulsory to fulfill soot emission limitation in mass. Does the compliance with the new regulation in particle number for Euro 5+ require a new design of the DPF? Will this new PM in number limitation be more stringent than the previous PM in mass limitation? Moreover, will filter performances be modified by this new regulation?

EXPERIMENTAL METHODS

ENGINE BENCH

For this study a commercial 2-liter, common rail injection, turbocharged diesel engine (DW10ATED4 from PSA) together with a Schenck brake was used. A serial cordierite Diesel Oxidation Catalyst (DOC) and a Diesel Particulate Filter (DPF) are located under-floor. The DOC is located one meter after the Turbocharger. An AVL415S smoke meter equipped with heated lines is used to measure Filter Smoke Number (FSN) index upstream and downstream of the filter.



Picture 1. Test Bench set-up

For all experiments, a Diesel fuel fulfilling EN590 regulation with sulphur content below 10 ppm is used. As lube oil, Total MA4 5W30 with low saps is utilized.

Table 1 summarizes the main data of the test-engine.

Table 1. Test-Engine data

Model	PSA DW10ATED4
Configuration	L4, turbocharged
Fuel injection	Injectors (Pre, Main & Post)
Displacement	2 L
Rated Speed	4500 rpm
Maximum Torque	250 Nm
Maximum Power	80 kW / 110HP

The use of dismountable cannings gives the flexibility to test different filter sizes which will be described in the next paragraphs.

DMS500 IMPLEMENTATION

To measure the number of PM contained in the raw emission and after the DPF, this bench is equipped with a Cambustion DMS 500. The machine is capable to charge, to separate by size, and to count the PM quantity with electrometer technology. Besides, the DMS500 provides the soot size distribution.



Picture 2. DMS500 Machine

The DMS500 is able to count PM during transient or static operating points. The device can measure upstream and downstream of the DPF without stopping the engine. A specific sampling and conditioning system illustrated in [figure 1](#) is used. This flexible structure is composed by 2 diluters heated at 400°C which play the role of evaporation tube to remove the volatile components of the sample. A valve allows switching from upstream to downstream DPF positions. Then, the sample goes through a heated and flexible sampling line with a length of 5 meters to DMS500 to be counted. The DMS500 is an accurate measurement system. When used on chassis dynamometer, the results are very close to recommended PMP method.

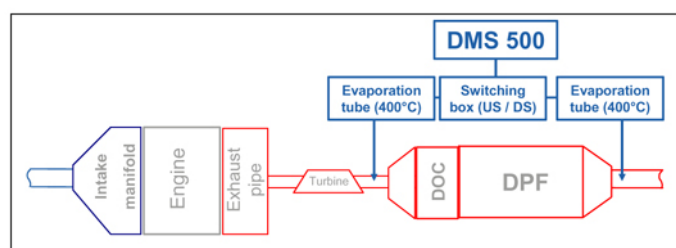


Figure 1. DMS Implementation

ENGINE CYCLES & PM MEASUREMENTS

The Maximum Soot Load (MSL) of the DPF is defined based on the frequency between two active regenerations. It has to be as high as possible to minimize the number of active regenerations. The MSL is currently defined as the maximum amount of soot tolerated by the filter without inducing a loss of filtration efficiency after severe regenerations. In case of

severe regeneration, the filter performances must be maintained. To estimate this MSL, a robustness test is performed. Filter performances are evaluated by measuring filtration efficiency in number [3]. The MSL value depends on the regeneration protocol which is used.

Robustness test

The robustness test consists of performing successive severe regenerations on the same filter. The amount of soot is increased between each regeneration cycle and the filtration performance is measured. The robustness test is stopped when a significant loss of filtration efficiency is observed.

Prior to starting the first regeneration, each new filter is canned and stabilized. This stabilization is performed on the engine bench at 4000 rpm and full load conditions during 45 minutes in order to reach a temperature higher than 650°C into the filter. Then, the filter is loaded with soot using a stabilized operating point of 3000 rpm and 30 Nm. The loading time depends on the desired soot mass, which is checked by weighing the filter at 150°C before and after soot loading.

The severe regeneration test, intended to create a strong thermal field with high temperatures and gradients, consists of drop to idle conditions [4] as soon as soot combustion starts. The protocol used has two main phases:

- Start of the regeneration by triggering the post injection at 1700 rpm and 95 Nm. The temperature in front of the DPF will be about 640°C. The drop to idle occurs when the temperature inside the filter (thermocouple A2 - [figure 2](#)) is higher than the temperature upstream the filter.
- Idle phase to accelerate soot combustion by increasing the oxygen content and limiting the exhaust flow (limited thermal exchange). Thermocouples (type K, 0.5mm diameter) are placed inside the DPF to measure temperatures and calculate gradients ([figure 2](#)).

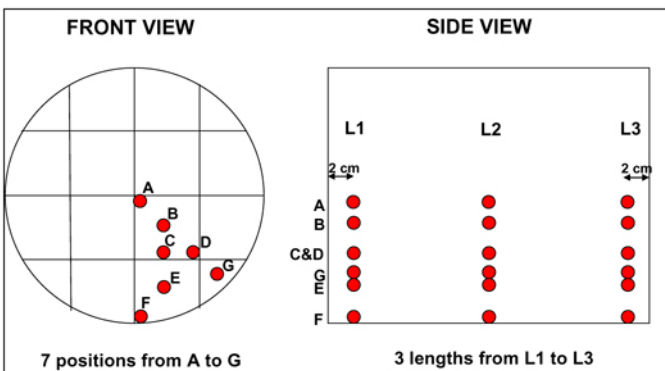


Figure 2. Thermocouples (Tck) positions during regeneration

After each regeneration a filter cleaning is performed using the same operating point as during stabilization (30 minutes at 4000 rpm and full load conditions in order to have 650°C in the filter). Thus, the remaining soot is removed. Then, a new soot loading can be done for the following regeneration.

Filtration efficiency (FE) in Number: Measurement

The DMS500 is used to measure FE in number. This measurement is done on clean and soot loaded filter. The two following parameters are used in the next parts:

“Cleaned filtration efficiency in number”: This measurement is performed at the end of the stabilization and the cleanings at 4000 rpm and full load conditions. At this stage, the filter is empty of soot. Temperature within the filter is 650°C and the exhaust flow is 450kg/h.

“Loaded filtration efficiency in number”: This measurement is performed after one hour of loading. At this stage, around 3.5 grams of soot are inside the DPF. Temperature within the filter is 250°C and the exhaust flow is 250kg/h.

Filtration Efficiency (FE) Number: Calculation mode

For each operating point described just before, the DMS500 measures the PM concentration in number contained in the raw emission upstream the DPF (US) and in the filtered emission downstream the DPF (DS).

[Figure 4](#) shows the expression to obtain the filtration efficiency in number (%).

$$FE_{[\%]} = \left(1 - \frac{DS_{[PM/cc]}}{US_{[PM/cc]}} \right) * 100$$

Figure 4. Filtration Efficiency in number calculation

Mini durability test

The mini durability test is done after the robustness test to confirm the MSL value. This test is very close to the robustness test. The main difference is that the regenerations are performed successively with the same amount of soot. Filter performances are regularly controlled by measuring the filtration efficiency after each cleaning and they have to be maintained at the end of the mini durability test.

DESCRIPTION OF PROTOTYPES

All the filters used during these tests were produced by Saint-Gobain. The Re-crystallized Silicon Carbide (RSiC) wall flow filters are characterized by an asymmetrical wavy design (figure 5) [6,7,8,9] which allows an increase of ash storage capacity and a reduction in filter pressure drop during the soot accumulation phase.

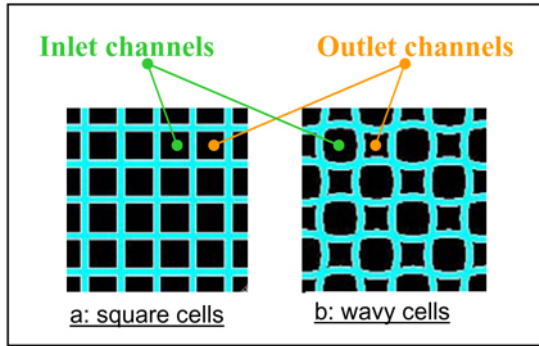


Figure 5. schematic description of honeycomb

In this program, 6 different filter families are studied. Family 3, namely SG3, is the reference family. All other families are compared with this reference to estimate the impact of the following filter design parameters on the DPF performances:

- catalytic coating:

Table 2. Prototypes description for coating impact

Families	2	3
Cells density (CPSI)	191	191
Wall thickness (μm)	350	350
Porosity (%)	47	47
d50 (μm)	15	15
Diameter (inch)	5,66	5,66
Length (inch)	10	10
Washcoat (g/cu.ft. PGM)	No	40
L/D Ratio	1,77	1,77
Volume (Liter)	4,12	4,12
Impact	No PGM	Réf

Reference family 3 is compared to family 2 which is the same product without catalytic coating. (Table 2)

- cell geometry:

Table 3. Prototypes description for cell geometry impact

Families	3	10
Cells density (CPSI)	191	281
Wall thickness (μm)	350	300
Porosity (%)	47	47
d50 (μm)	15	15
Diameter (inch)	5,66	5,66
Length (inch)	10	10
Washcoat (g/cu.ft. PGM)	40	40
L/D Ratio	1,77	1,77
Volume (Liter)	4,12	4,12
Impact	Réf	Cells geometry

Reference family 3 is compared to family 10, which is a product with a higher cells density and a lower wall thickness (Table 3).

- microstructure:

Table 4. Prototypes description for microstructure impact

Families	2	11
Cells density (CPSI)	191	191
Wall thickness (μm)	350	350
Porosity (%)	47	40
d50 (μm)	15	11
Diameter (inch)	5,66	5,66
Length (inch)	10	10
Washcoat (g/cu.ft. PGM)	No	No
L/D Ratio	1,77	1,77
Volume (Liter)	4,12	4,12
Impact	No PGM	micro-structure

Note that both families 2 & 11 described in table 4 are uncoated. Family 2 is compared to family 11, which is a product with a lower porosity (40%) and a lower mean pore size diameter ($d50 = 11\mu\text{m}$).