

Analysis of Particle Mass and Size Emissions from a Catalyzed Diesel Particulate Filter during Regeneration by Means of Actual Injection Strategies in Light Duty Engines

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ABSTRACT

The diesel particulate filters (DPF) are considered the most robust technologies for particle emission reduction both in terms of mass and number. On the other hand, the increase of the backpressure in the exhaust system due to the accumulation of the particles in the filter walls leads to an increase of the engine fuel consumption and engine power reduction. To limit the filter loading, and the backpressure, a periodical regeneration is needed.

Because of the growing interest about particle emission both in terms of mass, number and size, it appears important to monitor the evolution of the particle mass and number concentrations and size distribution during the regeneration of the DPFs. For this matter, in the presented work the regeneration of a catalyzed filter was fully analyzed. Particular attention was dedicated to the dynamic evolution both of the thermodynamic parameters and particle emissions.

The measurements were performed at the exhaust of a Euro 5 CR Diesel engine equipped with a Close Coupled DPF. The regeneration process was investigated in a point representative of an extraurban engine operating condition. The regeneration was managed by the electronic control unit (ECU). In particular, an injection calibration was implemented taking into account the engine and the filter features.

The particle size distribution evolution during regeneration phase was measured in the size range 5-1000 nm using a differential mobility spectrometer. The particle mass concentration was monitored by means of a microsoot sensor.

Particle mass and number concentrations strongly increase during the regeneration process. Moreover, a high concentration of the number of particles smaller than 30nm was observed in some critical phases of the regeneration process.

INTRODUCTION

The diesel engines have been gaining a great consensus in the end-users of automobile market for their higher fuel efficiency, reliability, and high torque. On the other hand, they are one of the major sources of particulate matter (PM) and NOx in the urban area. As known, these pollutants are associated to environmental and health issues.

Good results in terms of PM mass reduction were achieved by combustion system re-design, engine layout modification and the use of more efficient aftertreatment devices. Nevertheless, in the new generation engines an increase of the number of particles smaller than 100nm (ultrafine particles) [1,2] was observed. Several studies highlight that these particles are very dangerous for human health [3, 4]; this aspect has led to the formulation of standards regulations including limits also on particle number [5].

DPF is very effective to reduce the particle emissions in terms of both mass and number. It does not work directly as a sieve because the size of the soot particles emitted from current diesel engines is usually much smaller than the filter pore. The main filtration mechanisms are the deep bed and the soot cake filtrations [6]. The deep bed filtration mechanism prevails in a first phase of the soot accumulation of a new and clean filter. The soot particles are trapped in the filter pore matrix through filtration or deposition mechanisms [7]. In this phase, the filter efficiency strongly depends by filter characteristics such as pore size, shape, and porosity. As the filter loading goes on, the particles deposited on the filter surface form a so-called “soot cake”. In this phase, the filtration efficiency is significantly enhanced by the “cake” filtration mechanism as it acts as an “additional” filter [8].

As the particles are trapped, the filter becomes clogged and the exhaust backpressure increases leading to the decrease of the engine efficiency and to a larger fuel consumption and CO₂ emissions. The loaded soot is eliminated by means of the filter regeneration during which the accumulated soot is burned away by exothermic reactions. In the most widespread active filter for diesel engines, the regeneration is activated by means of post-injections in the late expansion stroke. The post-injected fuel oxidizes in DOC resulting in an increase of exhaust temperature that favors the oxidation of the soot particles deposited on DPF walls.

To guarantee a complete regeneration various parameters have to be defined, such as the start and the timing of the regeneration [9, 10]. The amount of soot loaded in the filter is a key parameter to define the optimal conditions for these parameters in order to reduce the regeneration negative effect on engine operation and fuel consumption. The regeneration of an over-loaded filter could, in fact, lead to DPF damage whereas for under-loaded filter the regeneration is performed at price of fuel consumption and CO₂ emissions. Nevertheless, other factors, mainly depending on the engine operating point, such as the engine out temperature, the gas flowrate, the oxygen concentration and so on have to be taken into account.

The inclusion of the regeneration phase in the emission test certification procedure is currently under discussion, and then it appears important to monitor the particle emission in terms of mass, number concentration and size during the DPF regeneration of a modern light duty diesel engine for passenger cars employing an actual regeneration strategy.

The present paper was addressed to a detailed evaluation of the DPF behaviour when the regeneration process occurs. The regeneration of a thermocouples instrumented catalyzed filter (CCDPF) was fully analyzed under a steady-state engine condition in terms of dynamic evolution both of the thermodynamic parameters and particle emissions.

EXPERIMENTAL APPARATUS ENGINE

The measurements were carried out at the exhaust of a four-cylinder in-line Euro 5 diesel engine equipped with a closed coupled Diesel particle filter (CCDPF). The main characteristics of the engine are reported in Table 1, while the whole test layout is sketched in Figure 1.

Table 1. Main features of the multi-cylinder engine.

	EURO 5
Engine type	4 cylinders in-line
Bore x Stroke [mm]	83.0 x 90.4
Displacement [cm ³]	1956
Compression Ratio	16.5
Valves per cylinder	4
Rated power and torque	118kW @ 4000rpm 380Nm @ 2000rpm
Injection system	Bosch Common Rail EDC17
Injector and nozzle	Solenoid CRI 2.2+, 7 holes, 480cc/30s
Turbocharger	Garrett single stage VGT GTB1549MV
Swirl control	Rotary flap on secondary duct
Catalyst system	Integrated closed-coupled DOC & DPF

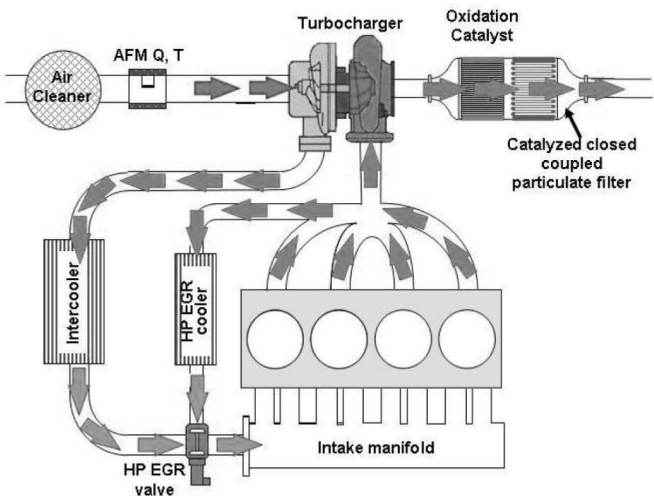


Figure 1. Scheme of the multi-cylinder engine and the aftertreatment device.

The engine was installed on a dyno test bench fully instrumented for indicated signal measurements (cylinder pressure, injection pressure, energizing injector current) and for the whole thermal characterization both at the intake and exhaust line (with pressure and temperature sensors).

The DPF was instrumented with seven “internal” thermocouples in order to follow the temperature profile

inside the filter during the regeneration. The thermocouples were placed in different points in longitudinal and transversal direction. The scheme in [Figure 2](#) shows the position of all the thermocouples.

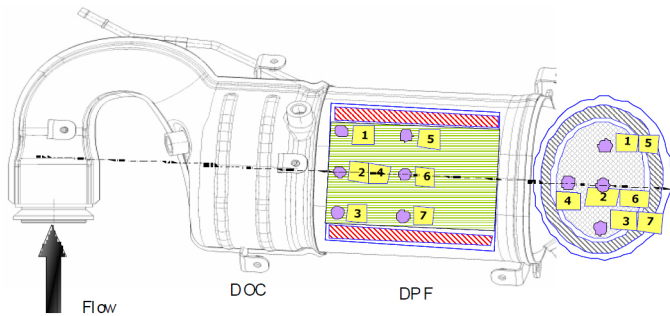


Figure 2. Scheme of the thermocouple location within DPF.

GASEOUS AND PARTICLE EMISSIONS MEASUREMENTS

At the engine exhaust, a transient high sensitive soot photo-acoustic sensor, the AVL Micro Soot 483 [11] measured soot mass emission, while gaseous emissions were measured upstream and downstream of the diesel aftertreatment device by means of a raw emission analysis test bench (AVL-CEB-2).

The counting and sizing of particles was performed by means of the Differential Mobility Spectrometer (Cambustion DMS 500). The measurement principle of DMS500 is based on a deflection of electrically charged particles combined with electrical counting [12, 13]. Particles are classified according to their charge to aerodynamic drag ratio, yielding an electrical mobility equivalent diameter. The counting is computed from the outputs current of the electrometers toward which the charged particles are shifted. The DMS500 has a fully integrated two-stage dilution and sampling system that provides primary dilution at the point of sampling to avoid condensation and agglomeration issues, and a high ratio secondary stage to allow sampling from a very wide range of aerosol concentrations. After the first dilution, the sample was transported to the DMS500 through a heated sampling line. The first and the second dilution ratios set points were 10:1 and 20:1, respectively. The temperature of the heated line was set at 40°C.

The exhaust gas for pollutants and particles analysis was sampled at engine outlet downstream of the turbine and 0.5 meters downstream the CDPF in order to fully characterize particle number and size through the whole exhaust system. The measured particulate concentration is automatically corrected for the applied dilution.

TEST METHODOLOGY

The DPF regeneration was performed under a steady state engine condition in order to keep the engine parameters constant and to analyze the regeneration process and its effects on particle emission without the interference of the engine variation due to speed and load changes. The operating point at 2750 rpm and 12bar of BMEP, indicated in the following as 2750×12, was chosen as representative of a highway engine operating condition.

Three regeneration tests were performed with the filter loaded at its reference accumulation target of 10 g of soot every liter of DPF. For each test the filter was weighed before and after the soot accumulation procedure.

In order to perform an accurate characterization of the phenomena related to the soot cake oxidation, a regeneration test was also carried out with an empty filter and compared with the loaded one.

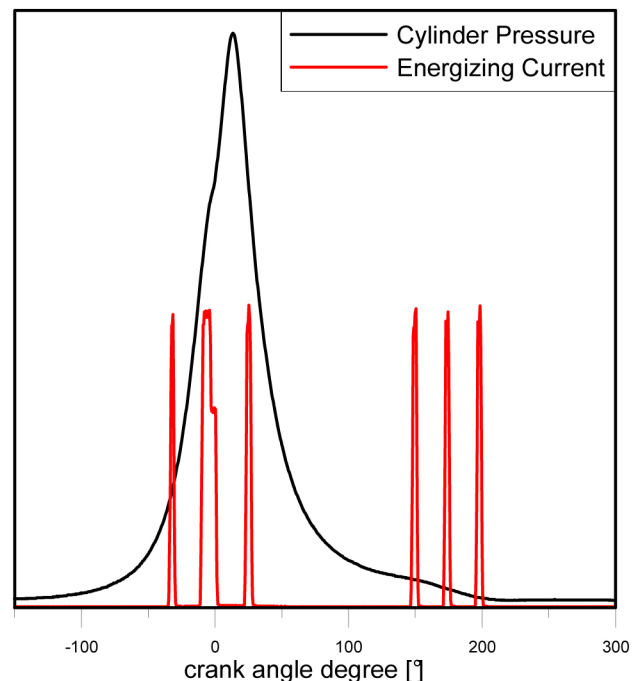


Figure 3. Injection strategy for DPF regeneration as energizing current signal versus crank angle and pressure signal.

The regeneration procedure was managed by means of an injection calibration released by the manufactures and implemented in the ECU. The regeneration was started taking into account the accumulated soot (on the base of a simple model implemented in the ECU) and a threshold value of the pressure upstream the filter.