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# Impact of biodiesel use on soot particle emission and regeneration particulate filter process of a modern diesel engine

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# Impact of biodiesel use on soot particle emission and regeneration particulate filter process of a modern diesel engine.

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## Introduction

It is well know that from an environmental point of view, the use of biofuels can contribute to a significant well-to-wheel (WTW) reduction of greenhouse gas (GHG) emissions.
Biofuels can be classified in first generation and second generation biofuels. First generation biodiesel designates a wide range of methyl-esters blends (generally indicated with the acronym FAME, Fatty-Acid Methyl Esters) characterized by a lower LHV and higher oxygen content. They are obtained from vegetable oils and animal fat by means of a transesterification process, and interfere with the human chain.
The second generation biofuels have minor interferences with the human chain and present a better stability in the chemical properties. These fuels can be obtained from biomass, gas, etc… by means of a Fisher-Tropsh synthesis process. They are usually indicated with XTL, where X denotes the specific source feedstock and TL (to Liquid) highlights the final liquid state of the fuel.
Several studies showed that biodiesels can have a remarkable impact on engine performance, such as Fuel Consumption (FC) and full torque/power performance, and even more significant on pollutant emissions, mainly for the modern electronically controlled diesel engines [1, 2, 3, 4, 5].
General Motors is one of the largest producers of diesel engines for passenger cars and light-trucks application in EU, Asia-Pacific and US markets and considers of high importance the test on biodiesels to analyse their effect on engine performances and emissions.
Great attention was devoted also to the interaction between biofuels and aftertreatment devices, such as diesel particulate filter (DPF). To this aim, a cooperative project between GM Europe and Istituto Motori of CNR was established. The particles emission in terms of mass, number concentration and size was investigated during the regeneration of a DPF with either a conventional diesel fuel that biofuels. In particular, measurements were performed with a fresh and aged Rapeseed- and palm-oil-based methyl-ester (RME). The measurements were carried out at the exhaust of a CR Diesel engine equipped with a Close Coupled DPF. The soot particles characterization was performed by means of a Microsoot Sensor, for soot mass concentration measurement, and a differential mobility spectrometer for particles sizing and counting.

## Experimental Apparatus

The measurements were performed on a Euro 5 CR Diesel engine, four-cylinder in-line engine equipped with a closed coupled Diesel particle filter (CCDPF) recently released by GM Powertrain. The main characteristics of the engine are reported in Table 1.

| | |
|---|---|
| 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<br>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 |

**Table 1: Main features of the engine**

The engine was installed on a dyno test bench fully instrumented for indicated signal measurements (cylinder pressure, injection pressure, energizing injector current). At the engine exhaust, upstream the CCDPF, soot was measured by the AVL Microsoot Sensor, 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 were performed by means of a Differential Mobility Spectrometer (Cambustion DMS500). The measurement principle of DMS500 is based on a deflection of electrically charged particles combined with electrical counting. In particular, the DMS500 uses a corona discharge to place a prescribed charge on each particle. The charged sample is then introduced into a strong electrical field inside a classifier column. This field causes particles to drift through a sheath flow to the electrometer detectors. Particles are detected at different points throughout the column, depending upon their aerodynamic drag/charge ratio. The outputs from the 22 electrometers are then processed in real time to provide spectral data and other desired parameters. The DMS500 has a fully integrated two-stage dilution system, this 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. Primary dilution is monitored and controlled in real time by mass flow measurement, and the secondary diluter is a rotating disc type, giving an accurate dilution ratio at all times. The measured particles concentration is automatically corrected for the applied dilution. More details on the employed instrument can be found in [6].

The engine was fuelled with a conventional diesel fuel (RF), a fresh and an aged Rapeseed- and palm-oil-based methyl-esters (RME) whose main properties are reported in Table2.

| Feature | Method | | **RF** | **RME100** | **RME100 Aged** |
|---|---|---|---|---|---|
| Density @ 15 °C [kg/m3] | EN ISO 12185 | | 833.1 | 883.1 | 884.2 |
| Viscosity @ 40 °C [mm2/s] | EN ISO 3104 | | 3.141 | 4.431 | 4.539 |
| C.F.P.P. [°C] | EN 116 | | - | -14 | -14 |
| Oxydation stability [mg/100ml] | EN ISO 12205 | | - | 0.6 | 1.2 |
| Oxydation Thermal Stability @ 110°C [h] | EN 14112 | | - | 6.5 | 2.4 |
| Lubricity @ 60°C [□m□ | EN ISO 12156-01 | | - | 179 | 195 |
| Cetane Number | EN ISO 5165 | | 51.8 | 52.6 | 57 |
| Low Heating Value [MJ/kg] | ASTM D 4868 | | 42.965 | 37.570 | 37.430 |
| Distillation [°C] | EN ISO 3405 | IBP | 158.9 | 318.0 | 308.0 |
| °C | | 10% vol. | 194.3 | 331.0 | 328.0 |
| °C | | 50% vol. | 267.6 | 335.0 | 337.0 |
| °C | | 90% vol. | 333.4 | 344.0 | 348.0 |
| °C | | 95% vol. | 350.0 | 353.0 | 351.0 |
| °C | | FBP | 360.9 | 355.0 | 353.0 |
| Carbon [%, m/m] | ASTM D 5291 | | 85.220 | 77.110 | 76.940 |
| Hydrogen [%, m/m] | ASTM D 5291 | | 13.030 | 11.600 | 11.530 |
| Nitrogen [%, m/m] | ASTM D 5291 | | 0.040 | 0.030 | 0.040 |
| Oxygen [%, m/m] | ASTM D 5291 | | 1.450 | 11.250 | 11.490 |
| POV [meq O2/Kg] | NGD Fa 4 | | | 16.60 | 68.60 |
| TAN [mg KOH/g] | UNI EN 14104 | | | 0.13 | 0.19 |

**Table2: Main fuel parameters**

## Experimental Results

### *Test Methodology*

The DPF was loaded in a steady state engine condition. It was chosen the engine point at 2000rpm and 5bar of BMEP as representative of an urban engine operating condition. The filter was released for a loading target of 10 grams of soot every liter of DPF, 10g/l. In our case, being the DPF volume equal to 3,2l the accumulation target was fixed at 32g.

The DPF regeneration was perfomed in steady state engine operating condition in order to keep constant the engine parameters and analyze the effect of the regeneration process on the particles emission without the interference due to the speed and load changes. The engine points: 2750rpm and 12bar of BMEP and 2000rpm and 3bar of BMEP were selected as representatives of an extraurban engine operating condition and a urban engine operating condition, respectively.

The regeneration procedure is managed through an injection calibration released by the manufactures and implemented in the ECU. It applies when the pressure upstream the filter reaches a threshold value suitably chosen taking into account the features of the engine and the filter.

During a normal engine operating mode the injection strategy is based on a Pilot+Main injection; in DPF regeneration mode an After injection close to the Main and two or three post injections at the end of the exhaust stroke are added, as shown in Figure 1. The post-injected fuel that burns across the DOC leads the temperature inside the DPF to increase above 650°C so allowing the DPF regeneration. During the regeneration process the EGR was shut off to increase the oxygen content and the temperature.

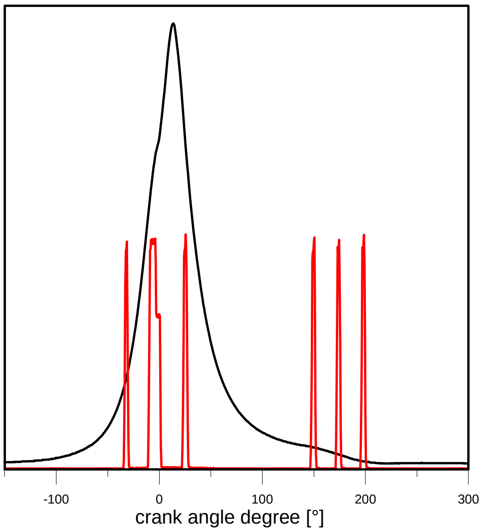


**Figure 1: Pressure signal and injection strategy during DPF regeneration**

The most widespread active regeneration procedure consists of two phases named Low Temperature Regeneration (LTR) and High Temperature Regeneration (HTR). The temperature upstream the DPF, in fact, is increased in two steps according to a predefined temperature profile to avoid a sudden increase of temperature that could cause the breakup of the filter. In particular, during the first phase, LTR, the temperature upstream the filter increases from the current value until 600°C. The temperature is further increased during the second phase, HTR, untill 650°C.

The Figure 2 shows the temperature and the fuel injected quantity (QPOI) profiles during the post injection, in the two selected test points. During the regeneration event the QPOI was automatically adjusted by the ECU varying the number and the timing of the injections to match the desired temperature profile upstream the filter.

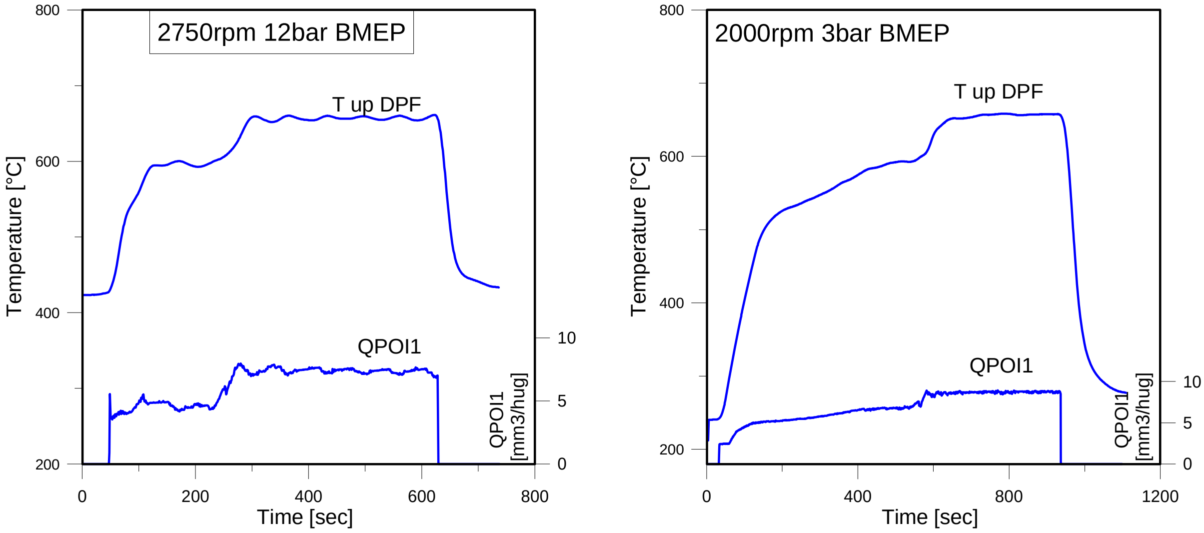


**Figure 2: Post injection quantity and temperature profiles measured upstream the DPF during the regeneration of a loaded filter at 2750rpm and 12bar BMEP (left) and 2000rpm and 3bar BMEP (right) for diesel feeding.**

In the case of RME100 and RME100Aged fuels the regeneration was performed lonely at 2750rpm and 12bar BMEP. It was necessary to recalibrate the ECU to obtain a temperature profile similar to that observed during the regeneration with the reference fuel.

In particular, for FAMEs fuels it was necessary to inject a larger amount of fuel due to their lower LHV, resulting in a longer regeneration process with respect to the conventional diesel fuel, as illustrated in Figure 3, where QPOI and temperature upstream the DPF are plotted for the three tested fuels.

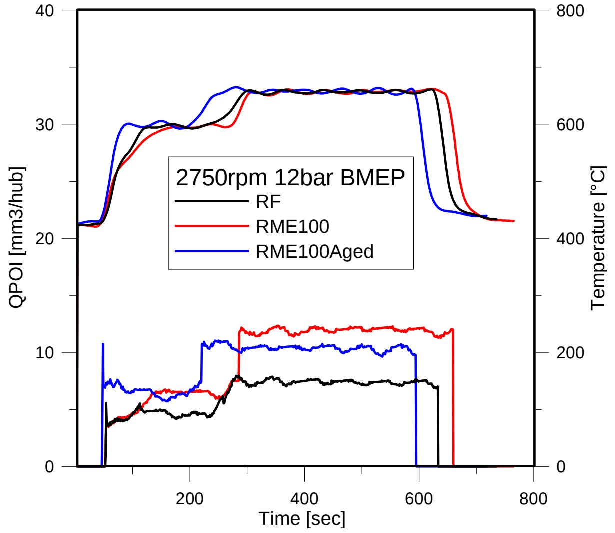


**Figure 3: Post injection quantity and temperature profiles measured upstream the DPF during the regeneration of a loaded filter at 2750rpm and 12bar BMEP for RF, RME100 and RME100 Aged fuels.**

## *Particles Mass and Number Analysis*

The particles mass and number concentration measured during the regeneration for conventional diesel and FAMEs are presented in this section.

Figure 4 reports the particles mass concentration measured during the normal engine operating mode and the regeneration of a loaded and an empty filter at 2750rpm and 12bar BMEP and at 2000rpm and 3bar BMEP for conventional diesel fuel.

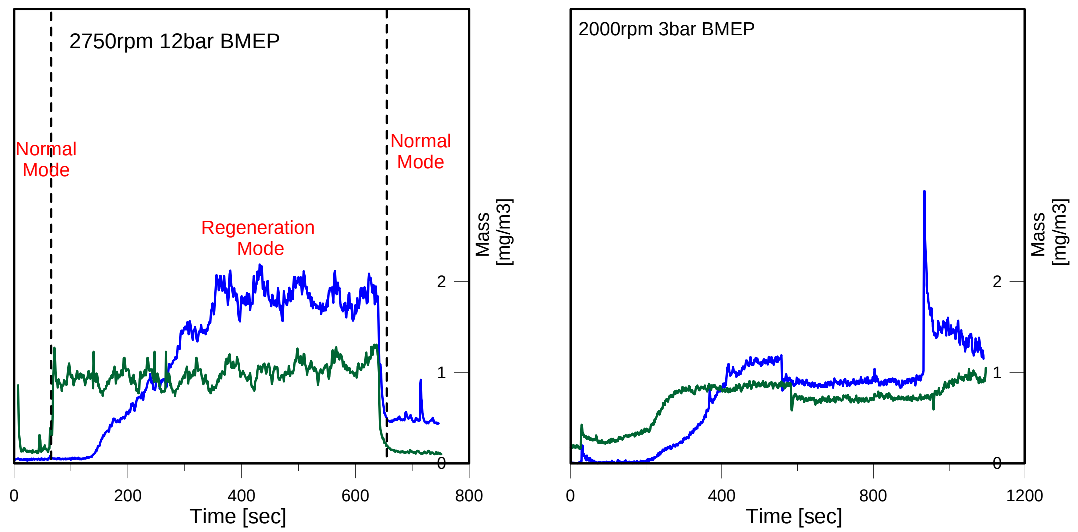


**Figure 4: Temporal evolution of particles mass concentration during normal mode and regeneration mode of a loaded (blue line) and empty (green line) filter measured at 2750rpm and 12bar BMEP (left) and 2000rpm and 3bar BMEP (right) for conventional diesel feeding.**

At high engine speed and load, passing from the normal engine operating mode to the regeneration mode an increase of particles emission of around one order of magnitude is observed. In the case of an empty filter the particles mass concentration is fairly constant both during regeneration and normal engine operating modes. On the other hand, during the regeneration of a loaded DPF the particles mass concentration slightly increases as the filter gets empty. This result can be due to the different trap efficiency throughout the regeneration process, as just observed by other authors [7]. It is interesting to highlight that in case of the regeneration of a loaded filter the particles mass concentration measured downstream the filter before the regeneration is considerably lower than after the regeneration. The lower filtration efficiencies of a freshly regenerated filter could be due to the absence of a soot layer on DPF walls that favours the entrapment of the particles [8].

At low engine speed and load, the mass concentration of particles emitted during the regeneration process evolves slower than in the previous case because of the different temperature profile and injection strategy. As just observed at 2750rpm and 12bar BMEP, the particles mass concentration increases while the filter gets empty. Moreover, the particles emission slightly decreases during the HTR phase because of a reduction of the main injection. The higher mass concentration of particles observed after the regeneration both in case of an empty and a loaded filter can be due to the transitory operating conditions of the engine, characterized by different values of the EGR rates.

The larger amount of particles measured downstream a freshly regenerated DPF highlights the strong influence of the regeneration on the filtration efficiency.

Similar results are observed also for RME100 and RME100 Aged as it is possible to observe in Figure 5. It is interesting to highlight the lower particles emission overall the entire regeneration process in case of biofuels fuelling.

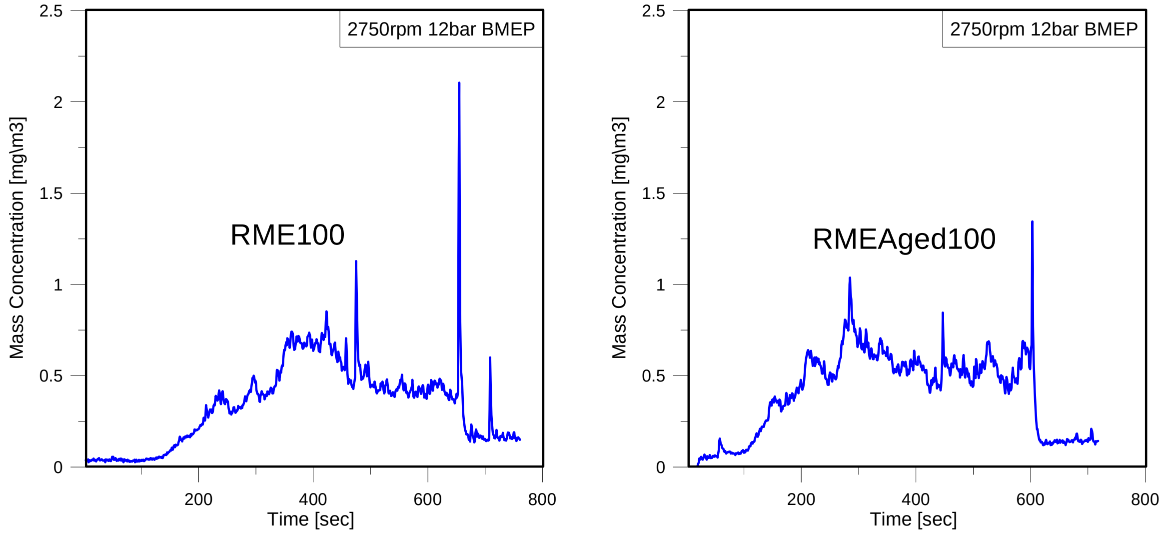


**Figure 5: Temporal evolution of particles mass concentration during normal mode and regeneration mode measured at 2750rpm and 12bar BMEP for RME100 (left) and RME100 Aged (right) feeding.**

The temporal evolution of particles number concentration and of temperature inside the filter during the regeneration with the reference fuel of a loaded and an empty filter at 2750rpm and 12bar BMEP and 2000rpm and 3bar BMEP are presented in Figure 6.

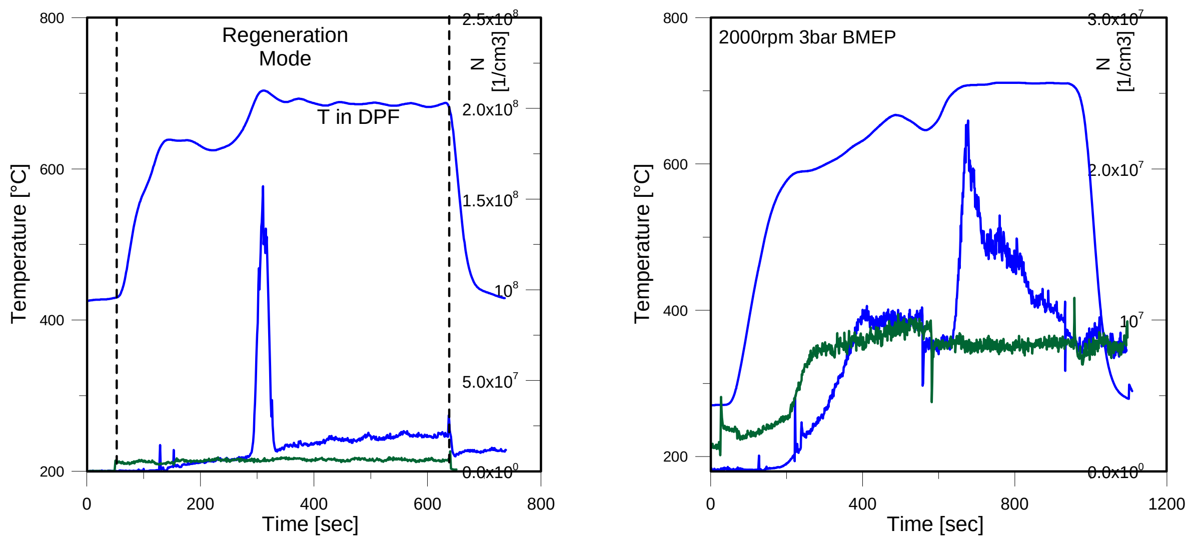


**Figure 6: Particles number concentration and temporal evolution of the temperature inside the DPF during the regeneration measured at 2750rpm and 12bar BMEP (right) and 2000rpm and 3bar BMEP (left) for conventional diesel fuel.**

The particles number and mass concentrations show a similar behaviour. In particular, as the soot layer burns, the particles number increases. Moreover, after the regeneration a higher number of particles are enabled to pass because of the lower filtration efficiency.

At high engine speed and load, in correspondence of the peak of temperature, the particles number increases of about two orders of magnitude. This peak is evident only in case of the regeneration of a loaded filter.

At low engine speed and load, a weaker peak of particles is evident as the temperature is around of 700°C, then the number concentration slowly decreases.

The different evolution of particles emissions observed at high and medium engine speed can be ascribed to the different temperature profile.

RME100 and RME100 Aged present similar results as possible to observe looking the diagrams reported in Figure 7.

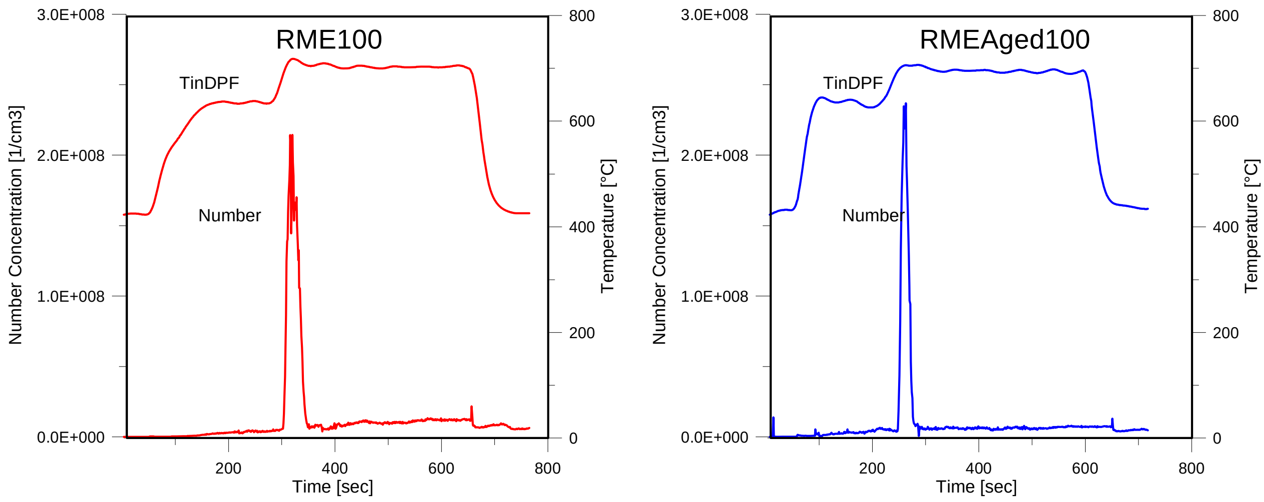


**Figure 7: Particles number concentration and temporal evolution of the temperature inside the DPF during the regeneration measured at 2750rpm and 12bar BMEP and for RME100 (right) and RME100 Aged (left).**

It is interesting to observe that although the particles number concentration is lower than the RF fuel one, both RME and RME Aged present a peak of particles of the same order of magnitude of the conventional diesel fuel, as shown in Figure 8, where the particles number concentration curves for all the fuels are plotted.

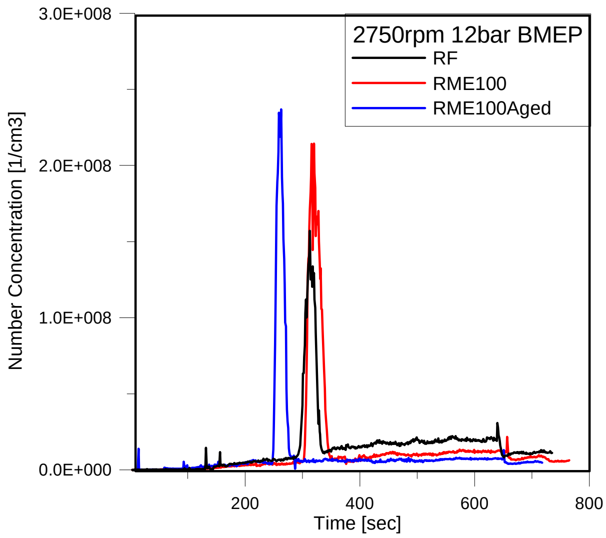


**Figure 8: Particles number concentration and temporal evolution of the temperature inside the DPF during the regeneration measured at 2750rpm and 12bar of BMEP for conventional diesel fuel, RME100 and RME100 Aged.**

### *Particles Size Analysis*

The particles size distribution measured in three significant moments of the regeneration process at 2750rpm and 12bar BMEP and 2000rpm and 3bar BMEP for conventional gasoline fuel are shown in Figure 9.

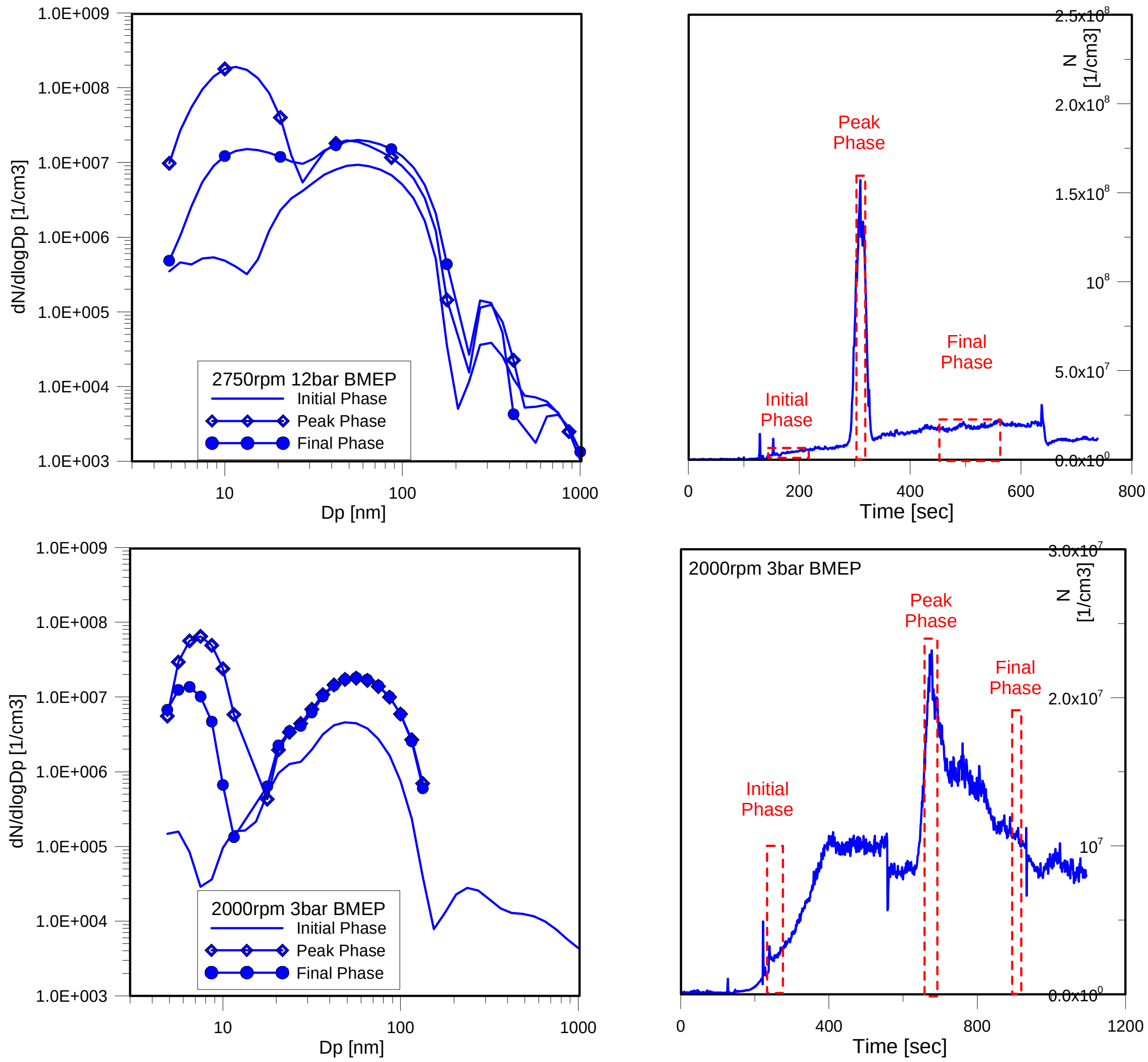


**Figure 9: Particles size distribution measured in the initial, peak and final phases of the regeneration at 2750rpm and 12bar BMEP (up) and 2000rpm and 3bar BMEP (down).**

During the regeneration event, particles show a bimodal number size distribution. It is interesting to observe that the weight of nuclei mode differs according to the regeneration phase, for the reference fuel.

At 2750rpm and 12bar BMEP, during the initial phase of the regeneration process particles emission is lower over all the size range. As the regeneration goes on, the accumulation mode remains almost constant contrary of the nucleation mode. In correspondence of the peak of the temperature, in fact, the numbers of the particles lower than 30nm increases of around two orders of magnitude. During the last phase of the regeneration the number of nuclei particles decreases. Nevertheless, it remains higher of about one order of magnitude with respect to the initial phase. These results point out that the peak of particles number is due to a strong release of particles smaller than 30nm. This may explain why the microsoot did not detect these type of particles.

At 2000rpm and 3bar BMEP similar results are observed.

Particles size distribution measured during the regeneration with FAMEs fuels are reported in Figure 10.

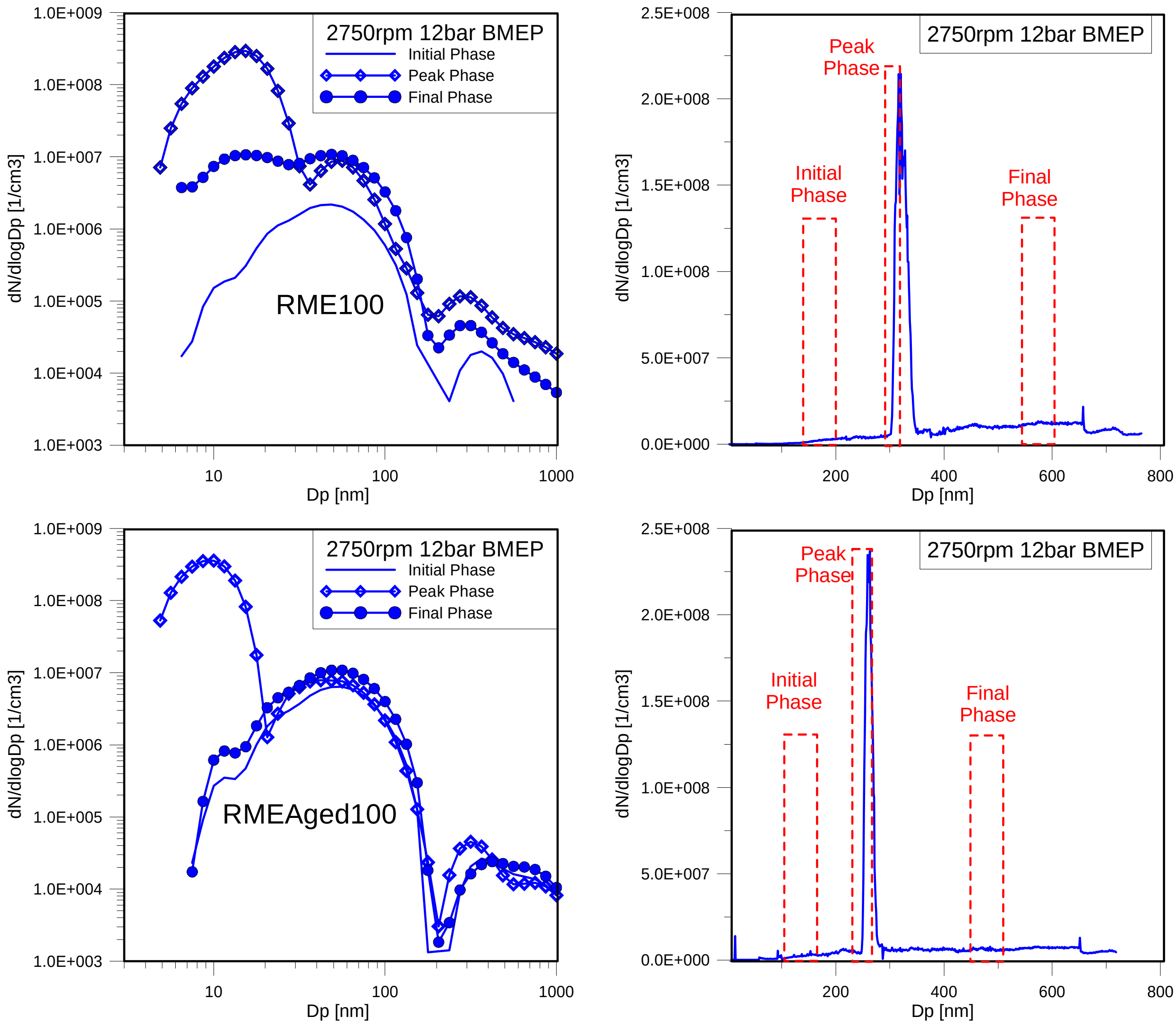


**Figure 10: Particles size distribution measured in the initial, peak and final phases of the regeneration at 2750rpm and 12bar BMEP for RME100 (up) and RME100 Aged (down).**

Particles size distribution evolves as RF fuel does. Moreover, it is interesting to highlight a weaker presence of particles smaller than 20nm for RME100 Aged during the final phase of the regeneration.

Actually, our data cannot provide information about the chemical nature of these particles. Anyway, several hypotheses can be made [9].

As known, the nuclei mode particles could be volatile particles formed downstream the DPF during the cooling and dilution of the exhaust [10, 11, 12] because of the condensation of sulphates droplets formed [13, 14], or of unburned fuel and hydrocarbon desorbed from the soot cake. Nevertheless, in this case we can expect the presence of these particles throughout the entire process of the regeneration.

The strong presence of nuclei mode particles during the regeneration of a loaded filter could be due to the shrinkage in size of the carbonaceous particles deriving from the fragmentation of the soot cake [15, 16] due to the fast combustion process and the resulting high temperature. These particles are swept away from the filter not completely oxidised.

Furthermore, a thermal expansion of the filter due to a transient effect resulting from a strong increase of the temperature associated to the oxidation of the soot cake could enable the particles smaller than 30nm to pass.

The analysis reported in [9] suggests that the emitted particles are mostly constituted by carbon, favouring the hypotheses of fragmentation of soot cake.

## Conclusions

The effect of biodiesel on DPF regeneration was analysed. The measurements were carried out at two engine operating conditions: 2750rpm and 12bar of BMEP and 2000rpm and 3bar of BMEP, representatives of an extraurban engine operating condition and a urban engine operating condition, respectively. The DPF regeneration with FAMEs fuels (a fresh RME and an Aged RME), was performed only at 2750rpm and 12bar of BMEP.

The effect of the biofuels on temperature during the regeneration process is strong; with the standard calibration the target temperature of 650°C was not reached. Therefore, a first attempt of recalibration of the regeneration strategy was carried out.

For all the fuels, particles emissions both in terms of mass and number concentrations increase as the regeneration goes on because the filtration efficiency decreases, due to the soot cake reduction.

A high number concentration of particles smaller than 30nm was emitted during the regeneration of a loaded filter. These particles could be due to the fragmentation of the soot cake.

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