Detailed Investigation on Soot Particle Size Distribution during DPF regeneration, using Stantard and Bio-Diesel

J.C. Caroca 1, F. Millo 2, D. Vezza 2, T. Vlachos 2, M. De Filippo 3, S. Bensaid 1, D. Fino 1, N. Russo 1

1. Department of Materials Science and Chemical Engineering – Politecnico di Torino – ITALY
2. Department of Energetic Engineering – Politecnico di Torino – ITALY
3. General Motors Powetrain Europe – ITALY

1. Introduction

Although diesel engine emission regulations throughout the world have always been based on gravimetric methods for the PM measurement, there is increasing concern about PM health and environmental effects based on the number of particles. There is increasing alarm that reductions in PM mass, which can be achieved through engine and aftertreatment measures, are not always accompanied by decreases in the total particle number and surface area. This has led to the introduction of new PM limits, in terms of particle number (2008/692/EC, 2008), and has created interest among researchers about the particle number and size characteristics, especially as far as engines equipped with Diesel Particulate Filters (DPF) are concerned [1].

The aim of this work was therefore to collect further information on the particle number and size for emissions from a small displacement Euro 5 common rail automotive diesel engine, equipped with a close coupled aftertreatment system, featuring a DOC and a DPF integrated in a single canning, especially during regeneration events at low engine speeds and loads, which is representative of urban driving conditions. Finally, due to the growing interest in alternative fuels for diesel engines [2-7], the impact of a biofuel on the PM characteristics has also been evaluated, by fuelling the engine with neat FAME (Fatty Acid Methyl Ester).

2. Experimental set-up

The experimental tests were carried out at the ICE Advanced Laboratory at the Politecnico di Torino on the test rig, which is equipped with an eddy current dynamometer connected to a passenger car turbocharged Common Rail DI Diesel engine, the main characteristics of which are listed in Table 1. The engine is equipped with an aftertreatment system, featuring a DOC and a catalyzed DPF integrated in a single canning, the main features of which are shown in Table 2.

The exhaust gas was sampled at the engine outlet downstream from the turbine, at the DOC outlet and at DPF outlet, in order to characterize the particle numbers and sizes throughout the whole exhaust system. The tests were performed fuelling the engine with an ultra low sulfur diesel fuel, which complies with Directive 2003/17/EC (S content < 10 mg/kg).

The sampling system consists of two dilution stages connected to a TSI 3080 SMPS. A first sampling pipe, namely Line A, made of a heated and insulated inox pipe, connects the sampling point to the first dilution stage (first dilutor of a DEKATI DI-2000 package), which is heated at 250 °C to avoid nucleation. In the first dilution stage, filtered compressed air, heated to 150 °C, flows through an orifice placed on the sample flow axis. In order to obtain a higher dilution ratio, a second dilution stage has been used (second dilutor of a DEKATI DI-2000 package). The second stage is not heated and it is directly connected to the TSI 3080 SMPS by means of a
flexible pipe. A higher total dilution ratio than 60 was achieved, which, according to the literature, should reduce particle agglomeration.

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Diesel 4 stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>1248 cm³</td>
</tr>
<tr>
<td>Cylinders</td>
<td>4 in line</td>
</tr>
<tr>
<td>Max Power</td>
<td>55 kW @ 4000 rpm</td>
</tr>
<tr>
<td>Bore x Stroke</td>
<td>69.6 mm x 82 mm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>16.8 : 1</td>
</tr>
<tr>
<td>Turbocharger</td>
<td>Single-stage with waste gate</td>
</tr>
<tr>
<td>Fuel injection system</td>
<td>Common Rail</td>
</tr>
</tbody>
</table>

Table 1 - Characteristics of the engine  
Table 2 - Characteristics of the after-treatment line

At the end of the above described sampling system, the exhaust gases reach the TSI 3080 SMPS, which is composed of:

- An electrostatic classifier TSI 3080 with a Kr-85 Bipolar Charger using Kripton as ion source
- An inlet impactor 1035900
- An differential mobility analyzer TSI 3081
- A condensation particle counter TSI 3025A

The exhaust gases were also sampled at the engine outlet by means of a Fisher-Rosemount NGA-2000 gas analyzer, for the measurement of the gaseous emission; furthermore, an AVL 415S smoke meter, for the measurement of the particulate filter smoke number FSN, was also used for repeatability checks.

The in-cylinder pressure was acquired by means of piezoresistive pressure transducers integrated in the glow plugs: the pressure signals were sampled by means of a 12-bit high-speed multichannel data acquisition system (National Instruments DAQCard-Al-16E4), coupled to a high-resolution (0.4°) crank angle encoder. Injector command signals were also acquired by means of a Tektronix TCPA300 current probe.

### 3. Particle size and number measurement

The particle number and size distribution were evaluated at part load both under normal operating conditions and at the DPF regeneration mode, in order to highlight the impact of the different combustion processes on the PM characteristics. Two different engine operating conditions, 1750 rpm / 3.5 bar bmep and 1500 rpm / 2.2 bar bmep were selected, as representative of low-load urban driving conditions, which can be critical as far as DPF regeneration is concerned. During normal operating conditions at low load, the injection pattern usually shows one pilot injection, followed by the main injection (first two injections in Figure 1-left), while, under the DPF regeneration mode, the main injection pulse is delayed and is then closely followed by an after-injection, plus an additional post injection (all injections in Figure 1-left). While the delayed main injection along with the after injections allows an increase in the engine exhaust temperature of up to about 300 °C even at the low load tested operating points, the post injected fuel is mainly burned across the DOC, as its increased HC conversion efficiency suggests; thus raising the DPF inlet temperature above 600°C to promote DPF regeneration, as shown in Figure 1-right.
3.1 Normal engine operating conditions

The particle sizes and numbers measured under normal operating conditions are shown in Figures 2-left. Logarithmic diagrams have been used. Figures 2-left show that no substantial modification in particle size and number can be observed across the DOC for either operating condition, with the number and mass distributions showing peaks at about 50nm and 100nm, respectively. On the contrary, the particle number is reduced by two or three orders of magnitude across the DPF. As a result, the DPF filtration efficiency, defined on a particle number basis is extremely high, approaching unity values, as shown in Figure 2-right.

3.2 DPF regeneration conditions

It should be pointed out that all the experimental tests were carried out on an freshly regenerated DPF, i.e. only after completing a regeneration event, even though lower filtration efficiency could be expected due to the absence of the soot cake bed inside the DPF filter. This procedure was preferred in order to fully eliminate any soot load from the particulate trap and to evaluate the effects due only to the engine regeneration mode operation and not those related to the
combustion of the soot accumulated over the DPF. It can clearly be noticed that, during DPF regeneration, the particle numbers increase by about one order of magnitude, while the number distribution peaks are shifted towards larger diameters, passing from 50 nm to 100 nm. The post-injected fuel dramatically increases the number of particles, as well as their mass, due to the large amount of unburned hydrocarbons in the exhaust stream.

As far as the effects of the aftertreatment system on the particle number size distributions are concerned, the experimental results shown in Figure 3-left demonstrate remarkable differences from the normal operating conditions: the particle number, which, under normal operating conditions remained almost unchanged across the DOC (see Figure 2-left), during DPF regeneration shows a relevant reduction for larger particles than 40nm; the number distribution peak shifts down from 100nm to 40nm, with a reduction in concentrations of one order of magnitude. Similar remarks can also be made for the mass distribution for both operating conditions. A further drop in particle number is produced, as expected, by the DPF.

It is worth noting that, thanks to the high temperature levels attained during the regeneration event (compare Figures 1-left and 2-left), the DOC is capable of effectively oxidizing unburned hydrocarbons, thus leading to a significant reduction in particle number, especially as far as larger particles are concerned, and to an "apparent" high filtration efficiency of the DOC. Though the regeneration causes an increase in particle dimension and number concentration and the DPF was freshly regenerated, its filtration efficiency results to be high (Figure 3-right).

![Figure 3. Left: Particle number size distributions under DPF regeneration conditions (1750 rpm /3.5 bar bmep) on a log scale (bottom) Right: DPF filtration efficiency under DPF regeneration conditions (1750 rpm / 3.5 bar bmep and 1500 rpm / 2.2 bar bmep).](image)

Further tests have been conducted modifying the regeneration injection strategy, i.e. suppression of post injection, have taken place in order to investigate the post-injection influence on the PM particle number and mass distribution. Figure 4-left shows the injection strategy during this particular operating mode; Figure 4-right illustrates the engine and DOC outlet temperatures during normal, standard regeneration and regeneration without post injection operating conditions. The experimental results highlight that the main differences between regeneration and normal operating mode particle distribution could be attributed to the HC generated by the post injection; thus most of the engine-out PM consists of HC.
3.3 Fuel effects: neat FAME usage

Finally, the particle number size distribution at the engine outlet were also assessed, fuelling the engine with neat FAME (Fatty Acid Methyl Ester), in order to evaluate the impact of alternative fuels on PM characteristics.

The experimental results of this preliminary investigation, reported in Figure 5, show a comparison between the engine-out particle number size distribution under normal operating conditions with diesel fuel (B0) and with neat biodiesel (B100). The reduction, in terms of particle number, that can be achieved by means of the neat FAME usage is about 80%, with a slight shift of the particle number peak from 50nm to 40nm, as demonstrated in previous studies [2-7]. Neat biodiesel usage allows even more significant benefits to be obtained in terms of mass size distribution (not shown in Figure 5), with reductions that can exceed 90% for the higher engine load.

4. Conclusion

The particle number and size distributions were evaluated on a small displacement Euro 5 common rail automotive diesel engine, at part loads which are representative of urban driving, both under normal operating conditions and at the DPF regeneration mode, in order to highlight the impact of the different combustion processes on the PM characteristics.

Under normal operating conditions, the engine and DOC outlet particle number size distributions appeared to be very similar, without any appreciable effect of the DOC, while the DPF exhibited high filtration efficiency values on a particle number basis, even in the nano-particle range. This
is to be expected considering that the DOC only affects the gaseous phase of the exhaust gases, and does not interact with the soot and condensed hydrocarbon fraction of the PM. Moreover, the temperature reached by the DOC was under its light-off value, and this limits the DOC effect on gaseous hydrocarbons. As far as the behavior of the DPF in under normal operating conditions is concerned, the filter reduced the number of emitted particles by two or three orders of magnitude, regardless of the particle diameter.

The regeneration mode caused a particle number increase of one order of magnitude, with a substantial shift of the number distribution peaks towards larger diameters, passing from 50 nm to 100 nm. Moreover, due to the higher temperatures attained in the DOC, and to the high HC oxidation efficiencies, the particle number, which under normal operating conditions was almost unchanged across the DOC, showed a remarkable reduction during DPF regeneration for larger particles than 40 nm, with a concentration reduction of one order of magnitude.

Other tests, conducted by modifying the regeneration injection strategy, i.e. suppression of the post injection, highlighted that the differences between the regeneration and normal operating mode particle distribution could be attributed to the HC generated by the post-injection. Interestingly, DPF shows a high conversion efficiency for each engine operating mode, even when it has been freshly regenerated. The DPF efficiency remains extremely high during regeneration, even when only the deep bed filtration mechanism is available. The tests carried in regeneration mode without post-injection, showed that most of engine-out PM consists of HC.

Finally, the impact of alternative fuels on the PM characteristics has also been evaluated, by fuelling the engine with neat FAME (Fatty Acid Methyl Ester): remarkable reductions, both in terms of particle number and mass, have been achieved (up to 80% and 90%, respectively) under normal operating mode conditions.

Using the actual after-treatment configuration, the deep bed filtration results to be a suitable filtration mechanism. It would be convenient to increase the HC filtration efficiency of DOC when it is operating at low temperatures. Under regeneration mode, the DPF works well and the particle number across the DOC is reduced, due to particle oxidation; thus a DOC filtration efficiency increase, when it is operating at low temperatures, is beneficial for regeneration.

5. References