

Analysis of Nozzle Coking Impact on Emissions and Performance of a Euro5 Automotive Diesel Engine

Pierpaolo Napolitano, Chiara Guido, and Carlo Beatrice
Istituto Motori CNR

Claudio Ciaravino
General Motors Powertrain - Europe S.r.l

ABSTRACT

The present paper reassumes the results of an experimental study focused on the effects of the nozzle injector's coking varying the flow number (FN); the performance and emissions of an automotive Euro5 diesel engine have been analyzed using diesel fuel. As the improvement of the diesel engine performance requires a continuous development of the injection system and in particular of the nozzle design, in the last years the general trend among OEMs is lowering nozzle flow number and, as a consequence, nozzle holes size. The study carried out moves from the consideration that a reduction of the nozzle holes diameter could increase the impact of their coking process.

For this purpose, an experimental campaign has been realized, testing the engine in steady state in three partial load operating points, representative of the European homologation driving cycle, and in full load conditions. Three sets of injectors with different flow number (480 cc/30s, 390cc/30s, 300cc/30s) have been used for the experimental campaign; in a first phase new injectors have been used, then, after an accelerated coking procedure of the same injectors, the tests have been repeated to compare the results. The impact of the different FN and coking grade on the engine behaviour has been investigated performing exhaust gas recirculation ratio and lambda sweeps, at partial and full load engine conditions, respectively.

The study has evidenced the benefits of the FN reduction on smoke emissions especially at low load conditions. Also as expected, it has been observed a general deterioration of engine performance in the tests carried out after the injectors' coking procedure, that is evidenced by an increase of smoke, CO and HC; moreover the results have shown a greater tendency to suffer the effects of coking for the nozzle with lower FN.

CITATION: Napolitano, P., Guido, C., Beatrice, C., and Ciaravino, C., "Analysis of Nozzle Coking Impact on Emissions and Performance of a Euro5 Automotive Diesel Engine," *SAE Int. J. Engines* 6(3):2013, doi:10.4271/2013-24-0127.

INTRODUCTION

In the framework of automotive diesel engine development, fuelling related parameters, such as injector and nozzle design, remain some of the most important components affecting emissions and performance [1, 2, 3]. In the aim to satisfy the incessant requirement of NO_x-CO₂ (Nitrogen Oxides-Carbon dioxide) trade-off improvement and the continuous request of low displacement engine with high specific power, in the last years fuel injection pressure has been increased and, simultaneously, the size of the nozzle holes has been progressively reduced, as it remains a matter of fact that the greatest potential in the diesel engine performance improvement lays in the combustion process

itself. Indeed, ultra high injection pressure up to 2000 bar and small-orifice multi-hole nozzle below 100-120 μm represent the new features of the upcoming diesel injection technology. A high injection pressure and a reduced injection hole diameter leads to smaller droplets in the spray and therefore to an improved vaporization of the fuel due to the larger surface-to-volume ratio of the droplets [4].

However, the respect of the exhaust pollutant emission level, as well as the full power/torque performance over a long mileage (e.g. 160.000 km for EU regulation), requires the preservation of the injector fuelling and the spray pattern characteristics as the engine accumulates miles. The nozzle coking is one of the main deterioration phenomena affecting the nozzle characteristics and the most evident effect is the

reduction of the injector fuelling, the alteration of the nominal injection rate profile, the reduction of the maximum tip penetration [5] and so the maximum power reduction of the engine. Previous researches have put in evidence both the controlling factors and the mechanism that generate the coking process [6, 7, 8, 9, 10].

In the present work, the attention was paid on the impact of the nozzle coking phenomena on the emission and performance of an automotive Euro 5 engine. Therefore a four-cylinder 2 liter Diesel engine was installed on a dyno test bench and an experimental procedure was setup in order to compare the performance of the engine when equipped with new and coked nozzles.

Moreover, since previous studies have evidenced that the reduced spray hole diameters can significantly improve emissions of passenger car Diesel engine with conventional combustion, three set of nozzles with different FN were employed in the study [11].

The present study is a part of a co-operative research project between GM Powertrain Europe and Istituto Motori - CNR aimed to carry out a comprehensive analysis of the coking phenomena on spray formation, combustion process, fuel consumption and emissions in the modern light duty Diesel engine for passenger car application. The analysis discussed in the paper represents the completion of the work started two years ago whose results are partially presented in a previous paper from the same authors [12]. The experimental results of the combustion performance versus FN are described in the following.

THE EXPERIMENTAL EQUIPMENT

The experimental layout comprises a 4-cylinder in-line LD (Light Duty) diesel engine installed on a dyno test bench. The engine, whose main characteristics are reported in Table 1, was released by GM Powertrain featuring the Closed-Loop Combustion Control (CLCC). In particular, based on in-cylinder pressure trace measurements by means of instrumented glow plug with piezo-resistive sensors, the ECU controls cylinder per cylinder and cycle per cycle the actual values for 50% of the fuel burned mass fraction (MBF50) and Indicated Mean Effective Pressure (IMEP). The engine was fully instrumented for indicated signal measurements in each cylinder (cylinder pressure, injection pressure, energizing injector current). At the engine exhaust, engine out gaseous emissions were measured by means of an analysis test bench (AVL-CEB-II). Smoke mass concentration was measured by means of a high-resolution (0.01 Filter Smoke Number, FSN) smoke meter (AVL415S). Additional details on the engine features and testing facilities can be found in [13]. Figure 1 reports a sketch of the piston bowl (on the left) together with the typical scheme and geometrical details of the injector nozzle (on the right).

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

Engine type	In-line 4 cylinders
Bore/ Stroke/ Compression Ratio	83.0 mm/ 90.4 mm/ 16.5
Injection system	CR/Bosch Solenoid CRI 2.16, 8 holes
Turbocharger	Single stage Variable Geometry Turbine (VGT)
After-treatment system	Closed-couple Catalyzed Diesel Particulate Filter (CC-CDPF)
Maximum Power	112 kW @ 4200 rev/min

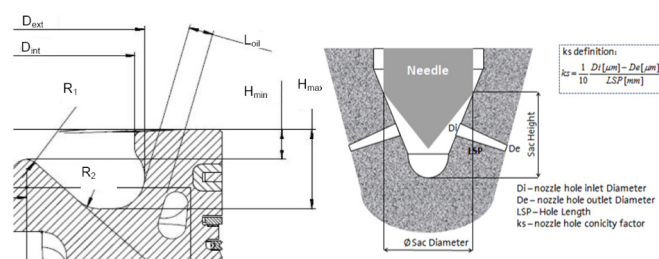


Figure 1. Piston bowl (on the left) and injector nozzle schemes (on the right).

The characteristics of the three sets of nozzles are reported in Table 2.

Table 2. Main features of the tested injector nozzles

Nozzle label	Hole number/ Cone angle	Flow number [cc/30 sec, $\Delta p=100$ bar]	Hole diameter [μm]
A	8/148°	480	136
B	8/148°	390	122
C	8/148°	300	107

Looking at Table 2 it is evident that only hole diameter has been changed among all nozzle sets. In particular, the nozzle A is representative of the hole diameter range currently adopted in the class of the tested engine. The nozzle B can be considered as a possible target value for the future engines. The nozzle C was chosen as extreme limit, in order to highlight the effects of a sharp FN reduction and also to design a trade-off of the engine behaviour versus FN. The fuel adopted for the experiments was a commercial low-sulphur diesel fuel, compliant with EN590 standard on fuel quality.

THE ENGINE TEST METHODOLOGY

The experimental campaign foresaw the evaluation of the coking nozzle impact in partial and full load engine

conditions. Three partial load operative points have been selected, they are representative of some operating conditions of the engine when running the New European Driving Cycle (NEDC) procedure. In particular, engine has been run at 1500 rev/min and 2 bar of Brake Mean Effective Pressure (BMEP), 2000 rev/min and 5 bar of BMEP and 2500 rev/min and 8 bar of BMEP (in the following also called 1500×2, 2000×5, 2500×8). The engine performance with nozzles for the three selected FN before and after the coking process were completely characterized in terms of fuel consumption, combustion noise and exhaust emissions. In particular, trade-offs with EGR sweep have been performed in the selected test points to assess the influence of the nozzle design and the coking phenomena in terms of pollutant emissions optimization. In order to describe the engine behaviour at different lambda values, four EGR rate levels have been selected in each test point: EGR = 0%, EGR rate according to the Euro5 calibration, the maximum EGR level in terms of highest admissible either smoke or CO emissions and an intermediate value between the Euro5 value and the EGR = 0%. As above mentioned, the partial load activity has been carried out adopting the CLCC implemented in the employed engine version.

The tests in full load condition have been performed with the engine running at 3500 rev/min. Within the boundaries constrains like $P_{FP_{max}}$, T_{in_turbo} , maximum FSN etc., the most important parameter affecting the engine performance at full load is the utilization coefficient of the air trapped mass with respect to the fuel injected mass. More in details, the utilization of the in-cylinder trapped air is dependent on different factors, as the combustion system design that controls the internal fluid-dynamics and the nozzle design that affects the spray evolution inside the combustion chamber. The maximum exploitation of the trapped air permits the maximum conversion of the fuel chemical energy in mechanical energy. At constant engine speed, the conversion depends on the efficiency of both the engine and the turbocharger. An experimental method for the evaluation of the air utilization versus FN, in full load condition, consists in performing the trade-off of engine power versus lambda at constant boost pressure until the rack of the variable geometry turbine reaches its maximum closure position (VGT_{max}). The engine power reduction is obtained reducing only the fuelling. A typical resulting trade-off curve of the engine power versus lambda is reported in the [Figure 2](#).

Since the optimum trapped air utilization maximizes the engine efficiency and the exhaust gas temperature, the highest attainable lambda, for VGT_{max} at constant P_{boost} (Intake Manifold Pressure), corresponds to the nozzle with maximum utilization of the trapped air. So, a trade-off of power versus lambda was carried out for each FN, starting from the full load point and gradually reducing the fuel injected mass. The trade-offs were performed with nozzles before and after the coking process and keeping all other engine variables fixed and measuring both the operating

parameters and the emissions. As allowed by the CLCC system, also the full load tests were done adopting the ECU control on the start of the main injection (SOI_{main}) in order to keep the crank angle corresponding to the 50% of the fuel burned mass fraction (MBF50%) constant.

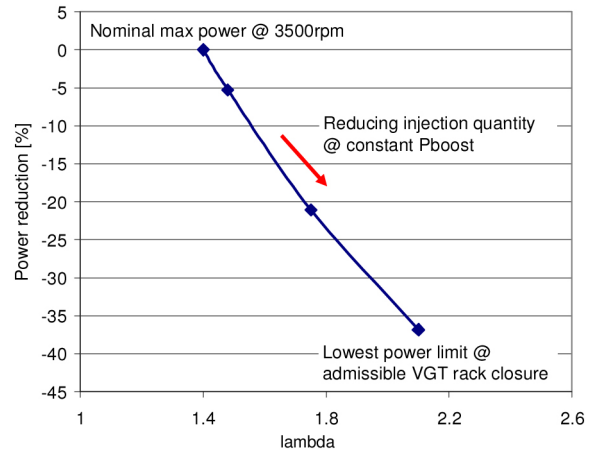


Figure 2. Power reduction versus lambda at constant P_{boost}

THE NOZZLE COKING PROCEDURE

At the start of the test campaign, the engine performance and emissions were completely characterized in all operating points as described in previous section using three new sets of injectors. Then the same injectors were subjected to an accelerated coking procedure according to a specific confidential GM process. The procedure adopted is able to guarantee a coking level comparable to the one reachable during a typical on-vehicle long mileage test. More in detail, the procedure was designed to realize an injector flow rate reduction, like that one measured after a mileage of 160.000km. Such procedure was validated by several tests performed on different vehicles and injector types.

The quality of fuel used during the coking test and all the engine conditions have been monitored and controlled to reach the same coking level for the three sets of injectors.

RESULTS

The discussion of the experimental results will be divided into a first part dedicated to the results of the partial load tests and into a second part relative to the full load conditions activity. All the data at partial loads are reported as percentage variation of nozzle B and C with respect to the reference nozzle A, assumed as reference value. The effects of the FN reduction on engine performance and emissions were already presented in a previous paper describing the results of the first part of this research project [12]. Therefore, in the present paper, the discussion will be focused mainly on the nozzle coking effects on the engine behaviour and on the interaction between coking phenomena and FN reduction.

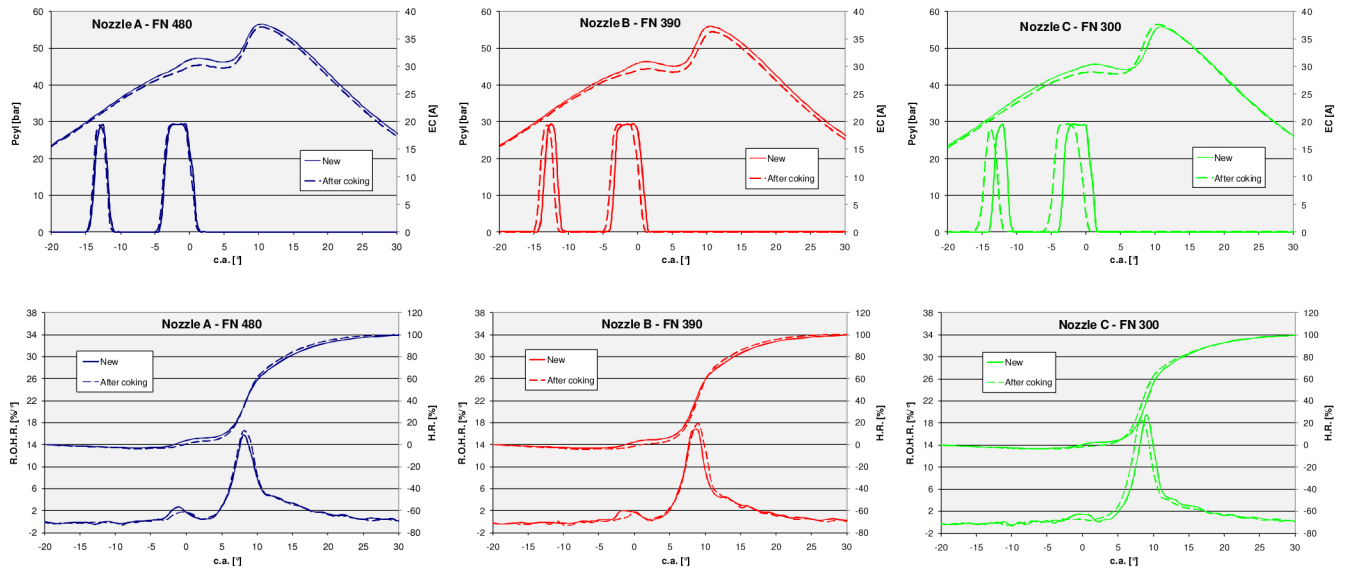


Figure 3. Upper row: Cylinder pressure and injector energizing current in the test point 1500×2 and $\lambda=1.7$ (EGR 55%) for the three nozzles A, B and C. Bottom row: HR and ROHR in the test point 1500×2 and $\lambda=1.7$ (EGR 55%) for the three nozzles A, B and C.

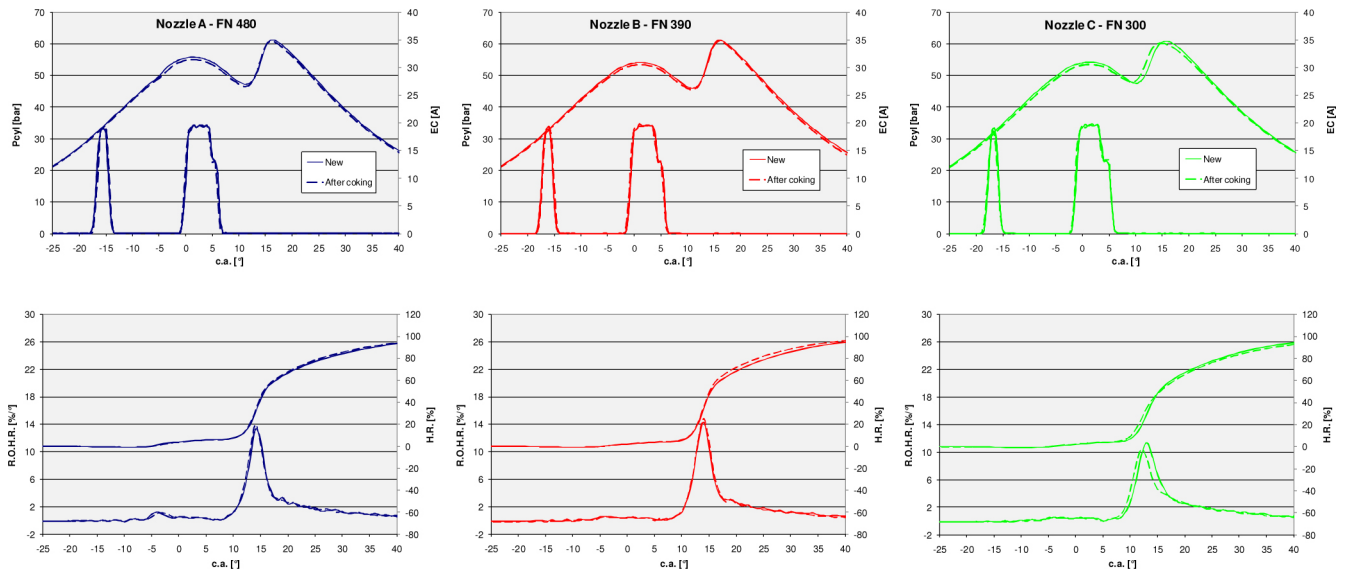


Figure 4. Upper row: Cylinder pressure and injector energizing current in the test point 2000×5 and $\lambda=1.4$ (EGR 30%) for the three nozzles A, B and C. Bottom row: HR and ROHR in the test point 2000×5 and $\lambda=1.4$ (EGR 30%) for the three nozzles A, B and C.

Partial Load Activity

Indicated signal analysis

The next Figures 3, 4 and 5 report the plots of the indicated signals: cylinder pressure, injector energizing current, combustion heat release (HR) and the relative rate of heat release (ROHR). All the curves in the three figures clearly explain as the nozzle coking tends to affect the combustion pattern. Due to the lowering of the fuelling rate for nozzles after the coking, the CLCC automatically adjust

early the SOI_{main} in order to keep constant the MBF50 and the injector energizing time in order to keep constant the injected fuel mass, and these corrections are more and more evident lowering the FN. This is well evidenced for the smallest nozzle (C). At 2500×8, the ROHR comparison for the smallest nozzle clearly shows the maximum combustion rate reduction associated to the lowering of the fuelling rate for the nozzle after the coking.

The indicated signal analysis justifies the emission results described in the following.