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Impacts of the exhaust gas recirculation (EGR) combined with the regeneration mode in a compression ignition diesel engine operating at cold conditions

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Abstract

Internal combustion engines working at cold conditions lead to the production of excessive pollutant emissions levels. The use of the exhaust gas recirculation could be necessary to reduce the nitrogen oxides emissions, even at these conditions. This paper evaluates the impact of using the high-pressure exhaust gas recirculation strategy while the diesel particulate filter is under active regeneration mode on a Euro 6 turbocharged diesel engine running at low ambient temperature (-7ºC). This strategy is evaluated under 40 hours of operation, 20 of them using the two systems in combination. The results show that the activation of the high-pressure exhaust gas recirculation during the particulate filter regeneration process leads to a 50% nitrogen oxides emissions reduction with respect to a reference case without exhaust gas recirculation. Moreover, the modification of some engine parameters compared to the base calibration, as the exhaust gas recirculation rate, the main fuel injection timing

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and the post injection quantity, allows to optimize this strategy by reducing the carbon monoxide emissions up to 60%. Regarding the hydrocarbons emissions and fuel consumption, a small advantage could be observed using this strategy. However, the activation of the high-pressure exhaust gas recirculation at low temperatures can produce fouling deposits and condensation on the engine components (valve, cooler, intake manifold, etc.) and can contribute to reach saturation conditions on the particulate filter. For these reasons, the regeneration efficiency is followed during the experiments through the filter status, concluding that the use of low high-pressure exhaust gas recirculation rates in combination with the regeneration mode also allows to clean the soot particles of the particulate filter. These soot depositions are visualized and presented at the end of this work with a brief analysis of the soot characteristics and a quantitative estimation of the total soot volume produced during the experimental campaign.

Keywords

Regeneration, EGR, Cold conditions, DPF, NO_x Reduction, Emissions reduction

NOMENCLATURE

Acronyms

EGR	Exhaust Gas Recirculation
HP	High Pressure
LP	Low Pressure
ICE	Internal Combustion Engine
NOx	Nitrogen Oxides
CO_2	Carbon Dioxides
CO	Carbon Monoxides
HC	Hydrocarbons
PM	Particulate Matter
NEDC	New European Driving Cycle
ECU	Electronic Control Unit
DPF	Diesel Particulate Filter
DOC	Diesel Oxidation Catalyst

GPF	Gasoline Particulate Filter
WCAC	Water Charge Air Cooler
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption

Notation

Latin

$\dot{m}$	Mass flow	kg/s
V	Engine displacement	cm^3
P	Pressure	bar
T	Temperature	°C
n	Engine speed	rpm
v	Gas velocity	m/s
i	Cycles per revolution	-
ρ	Gas density	kg/m^3

Greek letters

η	Efficiency	--
α	Leaks coefficient	--

Subscripts

eng	Engine
in	Inlet conditions
$theor$	Theoretical value
$fuel$	Fuel
air	Air
vol	Volumetric
$boost$	Boost pressure
$comb$	Combustion

1. Introduction

The introduction of the current regulations for the vehicles homologation has imposed new challenges to the car manufacturers and research institutions in this field. In this sense, the fuel consumption reduction, altitude variations, real driving emissions and cold operating conditions are considered guidelines in the current and future legislations [1] . Furthermore, the consequent reduction in the pollutant emissions levels is a second challenge to achieve for the automotive industry. Apart from the imperative reduction of the carbon dioxide (CO_2) and carbon monoxide (CO) emissions, the nitrogen oxides (NO_x) emissions reduction in diesel engines will be a major concern in future regulatory stages [2]. In order to fulfil these regulations, the internal combustion engine architecture is being continuously studied and improved by testing different strategies and systems that allow to reduce the impact of these pollutant emissions in the environment [3], [4].

In this context, a widely known strategy used and improved during the last years is the exhaust gas recirculation (EGR) in its two configurations, the low pressure (LP) EGR, with a more complex architecture, and a more simple one, the high pressure (HP) EGR [5], [6]. These strategies are presented as an effective solution to reduce the NO_x emissions levels in different engine operating points, even working at cold conditions, when the pollutant emissions are largely critical due to the combustion degradation. For these reasons, the use of EGR could be mandatory to comply with the current and future approval regulations [7].

The conventional HP EGR circuit, where the EGR rates are limited by the pressure difference among the inlet and outlet manifolds, is a low cost and effective solution due to its simple architecture and high potential to reduce the

NO_x emissions [8]. Taking this into account, the evaluation of this strategy, in combination with other engine working conditions, as per example, the particulate filter regeneration, is a necessary study point for manufacturers and researchers. This regeneration process consists of increasing the temperature of the exhaust gas and is controlled by the electronic control unit (ECU) in order to burn off and remove the particulate matter (PM) and soot depositions collected in the after treatment system of gasoline and diesel engines [9], [10]. When saturation conditions are detected by the ECU, active regeneration strategies as per example post injection and separate diesel injection are performed [11]. These strategies lead to higher pollutant emissions levels and deposits due to the additional fuel mass required to cause this regeneration [12]. For these reasons, a possible scenario in which the engine is working at cold conditions, activating the HP EGR for reducing the NO_x emissions and carrying out a diesel particulate filter (DPF) or gasoline particulate filter (GPF) regeneration due to a saturation condition in the filter has not been studied before, but it is very interesting to be evaluated from an experimental point of view.

Nevertheless, the use of HP EGR to reduce the NO_x levels presents some issues, as per example the appearance of condensation and fouling depositions resulted of a degraded combustion, specially working at low temperatures [13], [14]. The soot particles can affect the main components of the EGR line (i.e. EGR valve, EGR cooler, intake manifold) reducing its life span [15]. In addition, it could contribute to accelerate the DPF loading, thus affecting its normal operation [16]. Lapuerta et al. investigated the effect of the soot accumulation in a DPF of a common rail diesel engine on the combustion process and pollutant emissions, reproducing a New European Driving Cycle (NEDC) [17], [18]. The investigation concluded that performing a DPF regeneration without controlling the injection settings parameters and the EGR ratio could increase the NO_x emissions around 60% and the fuel consumption around 4%. This is caused by the higher back pressure and the higher temperature of the recirculated gas, which modifies the combustion process and moves the engine operation away from its optimum conditions.

Afterwards, the authors carried on evaluating these issues and presented some strategies for the active DPF regeneration modifying the engine control parameters. The selected parameters to be studied were the injection timing, exhaust gas recirculation and amount of post injected fuel. In this case, the work was performed at steady-state conditions at 2000 rpm of engine speed and 94 Nm of torque, as a representative point of the NEDC cycle. The relevant findings of the authors were that eliminating the EGR during the regeneration process is an optimal option for a fast DPF regeneration and reduced fuel consumption. However, low values of EGR rate could contribute to avoid excessively fast or uncontrolled regeneration in the cases of very high soot load at the DPF and to reduce NO_x emissions. Regarding the injection timing and the amount of post injected fuel, it was concluded that keeping the optimal temperature conditions is essential for an efficient DPF regeneration.

Regarding the impact of fouling depositions in the EGR line components and its characterization, several studies have been performed in the literature. Arnal presented the characterization of five different types of diesel soot, which were collected from several high pressure EGR coolers working at different conditions (engine bench and vehicle) [19]. The authors highlighted the fact that the fouling depositions on the EGR components, as EGR coolers and valves, decreases their thermal efficiency and increases the pressure drop producing the malfunctioning of the device, implying the non-compliance of the NO_x standard regulations. In addition, these depositions are composed of adsorbed compounds like lube oil and unburned fuel that could aggravate this issue.

According to the previous paragraphs, this work aims to study the impact of using the HP EGR while the DPF is under active regeneration process in a 4-cylinder diesel engine working at cold conditions (-7ºC). The results of the study are divided into two main sections. The first section presents the impacts of using HP EGR together with the regeneration mode on the regulated diesel emissions, NO_x and fuel consumption, as well as on the combustion engine efficiency. In addition, the DPF regeneration process efficiency is analysed. In the second section, a brief analysis of the fouling phenomena observed on the HP EGR line components is presented. This analysis includes an approximated estimation of the soot mass and volume collected from the HP EGR line during the experimental campaign.

2. Experimental setup and methodology

2.1. Test bench description and configuration

In order to perform this theoretical-experimental work, an in-line 4 cylinders, 1.6 liter, turbocharged, diesel engine was used. Table 1 summarizes the technical features of the engine used. To carry out the experiments at cold conditions, the engine was installed in a climatic test bench, where the temperatures of the test bench air, fuel and coolant are under control. The test bench is instrumented to measure the torque, speed, temperatures and pressures at different locations of the installation. The injected fuel mass flow and the intake air mass flow are also measured. Fig. 1 shows the engine configuration and its instrumentation.

Table 1. Engine Specifications

Number of Cylinders	4
Number of Valves	16
Bore x Stroke (mm)	80 x 79.5
Total Displacement (cc)	1598
Maximum Power (kW/rpm)	96/4000
Maximum Torque (N m/rpm)	320/1750
Compression Ratio	15.4 : 1
Fuel Injection System	Common Rail Direct Injection
EGR System	HP and LP Cooled EGR
Intake Cooling System	Water Charge Air Cooler (WCAC)

The engine has two EGR circuits. The first one is the LP EGR circuit, in which the exhaust gas pass through the catalyst and the DPF, and then it is redirected to the turbo compressor inlet. However, for this particular study, this circuit is not enabled. The second circuit is the HP EGR. In this case, the exhaust gas is directly cooled in the cylinder head and mixed with the fresh air that comes from the intake line. This circuit consists of an internal duct that guides the exhaust gas coming from the exhaust manifold through a compact section of the cylinder head (without EGR cooler) to reduce its temperature, a HP EGR valve controlled by the ECU, and a HP EGR rail, where the exhaust gas is driven and distributed to the engine intake manifold and mixed with the air at the intake of the four cylinders. The water charge air cooler (WCAC) is activated with a constant regulation in order to control the engine intake temperature due to the higher temperatures reached during the DPF regeneration mode.

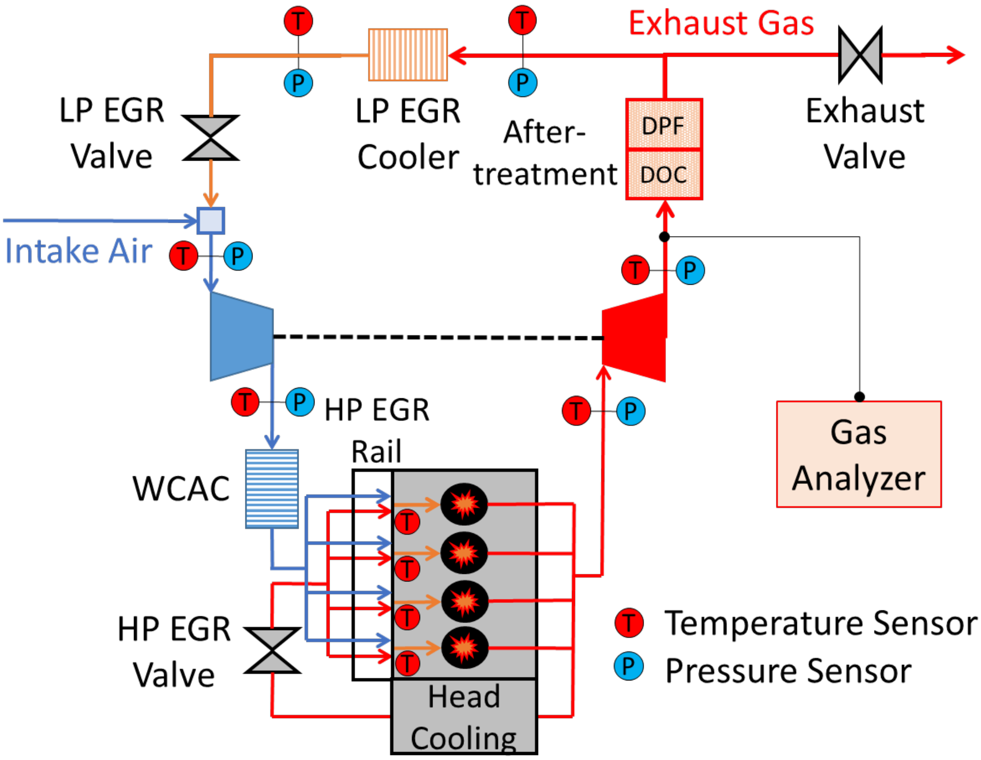

Fig. 1. Engine configuration

Several engine parameters were measured to assess the engine performance and to analyze the impact of the proposed configuration. The measured parameters together with the sensors features are presented in Table 2.

Table 2. Instrumentation Accuracy

Sensor	Variable	Accuracy [%]	Range
Thermocouples type K	Temperature	1	-200-1250ºC
Pressure sensor	Pressure	0.3	0-10bar
Gravimetric fuel balance	Fuel mass flow	0.2	0-150kg/h
Hot wire meter	Air mass flow	1	0-720kg/h
Dynamometer brake	Torque	0.1	0-480Nm

The air mass flow through the intake line of the engine was measured by means of a hot wire anemometer with a measurement error of 1%. The fuel consumption during the cycle was measured with an AVL fuel balance, which has a measurement error of 0.2%. A Horiba Mexa 7100 DEGR was used to measure CO, CO2 and HC emissions using a non-dispersive infrared analyzer, and nitrogen oxides (NO_x) emissions with a chemiluminescent detector. The error of the gas analyzer is in the range of 2%. The measurement point is located upstream of the after-treatment system in order to show the engine-out pollutant emissions levels.

The HP EGR rate was not possible to be obtained from the CO_2 measurement due to the complexity of the line and its disposition (inside of the cylinder head). Instead, the HP EGR rate was mathematically estimated using the engine volumetric efficiency as it will be explained in the methodology subsection.

2.2. Methodology and strategies

The ambient temperature inside the climatic chamber was set at -7ºC. Tests are performed in steady-state conditions with an engine speed of 2000 rpm and 4 bar of brake mean effective pressure (BMEP). The engine working condition was defined as a representative point for the DPF regeneration, comparable to a real engine operation on a highway at 120 km/h with medium load.

The OEM engine calibration is not prepared to perform LP EGR at low ambient temperatures. Under the standard engine calibration, only the HP EGR is enabled after the engine coolant temperature is increased. For this experimental work, the engine has been running during 40 hours at -7ºC activating the HP EGR, 20 of them activating the regeneration mode together. Fig. 2 shows the process to carry out each test. First, the engine warm-up process is performed in standard conditions (without EGR and without regeneration) until the engine coolant temperature reaches 60ºC, then, a 20% of HP EGR rate is activated by the ECU and the active regeneration mode is forced manually. A post injection is enabled in this mode with the aim of increasing the exhaust gas temperature and burn the soot particles off bonded on the DPF. This condition is maintained along 30 minutes and then the regeneration mode is deactivated, returning to the standard engine calibration. To hold fouling conditions in the DPF at the end of each test is the aim of working with the base calibration (only HP EGR performed), this methodology allows to check the DPF regeneration process during the first 30 minutes of the test. This procedure is repeated continuously until reaching a testing time of one hour per test.

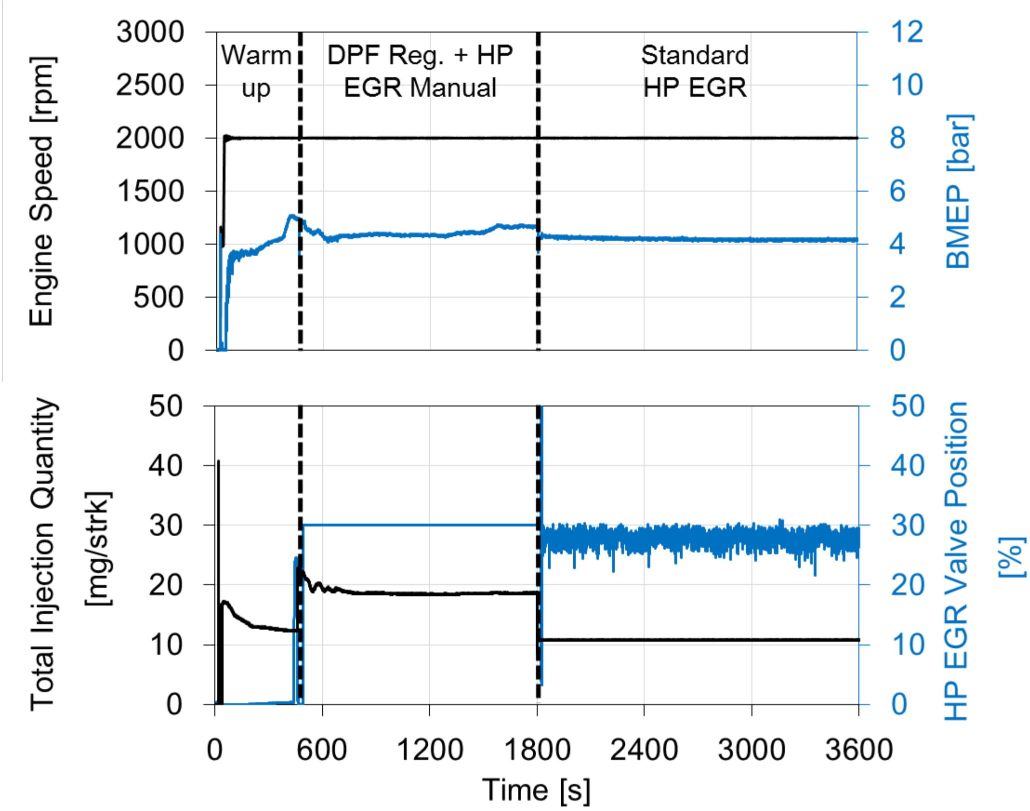

Fig. 2. Profile of the tests performed

To achieve an efficient DPF regeneration process, some relevant variables are followed during the experiments. The post injected fuel quantity and the turbine outlet temperature are verified [11]. These parameters allow to control a key condition to conduct a DPF regeneration process, as the exhaust gas temperature. In order to check the DPF loading process, two reading calibration variables are recorded. First, the pressure difference (ΔP) between the DPF inlet and outlet (measured by a differential pressure sensor), as an indicator of the back pressure generated in the engine exhaust line that could modify the HP EGR rate performed and as a consequence the engine intake temperatures. And second, the particulate filter soot mass estimated by the ECU, as a reference parameter to check the DPF loading conditions. This estimated value is an internal calculation, based on the DPF status and several variables calculated and measured by the ECU, as per example, DPF pressure difference, upstream and downstream temperatures, engine working conditions, DPF diagnosis, etc.

Due to the abovementioned impossibility to obtain a HP EGR rate estimation from the CO_2 measurement, it was necessary to estimate the engine volumetric efficiency for this engine configuration at 2000 rpm with no EGR and constant load. Equation 1 shows the engine volumetric efficiency as a function of the air mass flow ($\dot{m}_{air}$), the engine parameters (*engine speed, displacement, etc.*), the boost pressure (P_{boost}) and the intake temperature (T_{intake}). When the volumetric efficiency is assessed, the theoretical air mass flow is calculated with the measured boost pressure ($P_{boost\,EGR}$) and intake temperature ($T_{intake\,EGR}$) at active EGR mode (Eq. 2). Finally, it is possible to obtain the EGR rate as a relation between the air mass estimated theoretically by using the volumetric efficiency and the air mass flow measured. Equation 3 shows the HP EGR rate estimation.

$$\eta_{vol} = \frac{\dot{m}_{air}}{\frac{P_{boost}}{R\,T_{intake}} \,.\, V_{eng} .\, n \,.\, i} \qquad (1)$$

$$\dot{m}_{theor} = \eta_{vol} \cdot \frac{P_{boost\,EGR}}{R\,T_{intake\,EGR}} \,.\, V_{eng} .\, n \,.\, i \qquad (2)$$

$$EGR_{rate} = \frac{\dot{m}_{theor} - \dot{m}_{air}}{\dot{m}_{theor}} * 100 \qquad (3)$$

Finally, to visualize the impact of performing HP EGR combined with the DPF regeneration at cold conditions (-7ºC) on some engine components (i.e. HP EGR valve, HP EGR Rail, WCAC), they were disassembled and cleaned before starting with the experimental work.

3. Results and discussion

In order to present how the use of the HP EGR combined with the active regeneration mode could affect the engine behavior and its performance under cold operating conditions, this section is divided into two different parts. In the first subsection, the impact of this configuration on the engine thermal behavior, DPF regeneration efficiency, pollutant emissions and fuel consumption is presented. In the second subsection, the fouling phenomena evolution inside the EGR line components is presented.

3.1 Impact of the HP EGR combined with the regeneration mode on the engine behavior

Performing HP EGR while the DPF is being regenerated leads to a higher temperature in the engine intake line. In order to show the main results of this work in terms of repeatability and dispersion between tests, a group of representative tests is selected. First, a reference test performed at -7ºC activating the regeneration mode at the end of the engine warm-up (500 s) and only performing HP EGR in standard engine conditions after the second 1800. Later, a group of five tests using HP EGR with the regeneration mode activated between the second 500 and 1800 and finally, two tests where the DPF reached saturated conditions under similar working conditions. Fig. 3 shows the engine intake temperature measured in the intake manifold. Comparing the reference test with the tests performing HP EGR together with regeneration mode, it can be observed how the intake temperature increases approximately by 30ºC. Thanks to keeping the same WCAC regulation between tests, in the figure it can be observed how the engine intake temperature increases progressively above the reference test due to the HP EGR activation. These higher temperatures could increase the in-cylinder temperature improving the engine combustion efficiency.

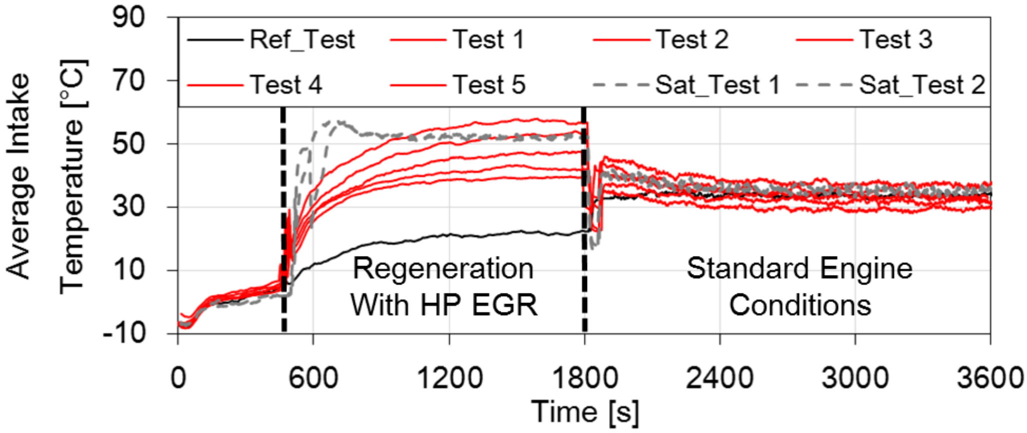

Fig. 3. Engine intake temperature

Fig. 4 shows the HP EGR rate estimated through the Eq. 3. The HP EGR rate performed together with the regeneration mode is a similar rate than the used by the ECU in standard engine conditions. The EGR rate remains approximately constant at 20%. However, the saturated tests present an EGR rate higher than

20% due to a possible DPF saturation or soot accumulation in the HP EGR line, which increases the backpressure in the exhaust line.

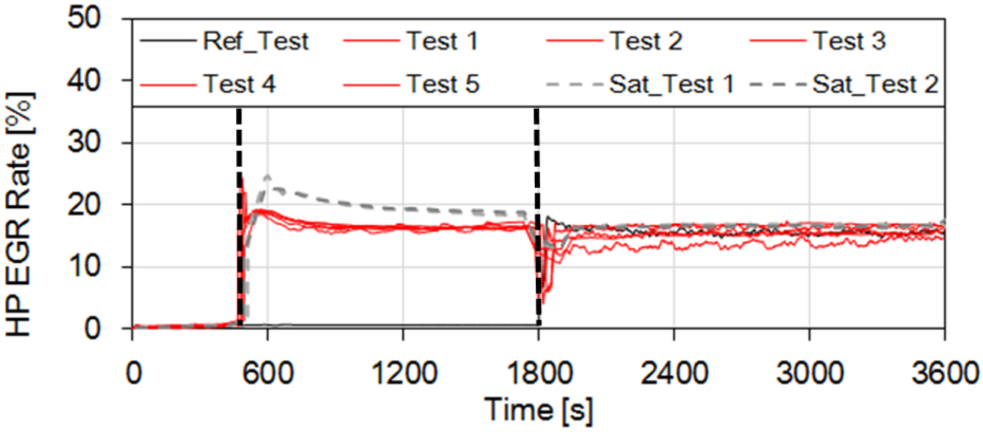

Fig. 4. HP EGR rate performed

The higher backpressure could lead to variations in the turbocharger speed and pressure ratios. Fig. 5 presents the VGT position (top of the graph) and the turbocharger speed (bottom of the graph). Due to the low engine operating point selected for this experimental study, there is no evidence of representative variations on the VGT position. Pressure ratios on the turbocharger change with respect to the air mass flow and the HP EGR rate performed. In addition, following the turbocharger speed in the reference test, it can be observed how the higher air mass flow and fuel mass flow under regeneration process lead to higher speeds on the turbocharger. Tests with lower air mass flow due to the HP EGR activation present lower speeds.

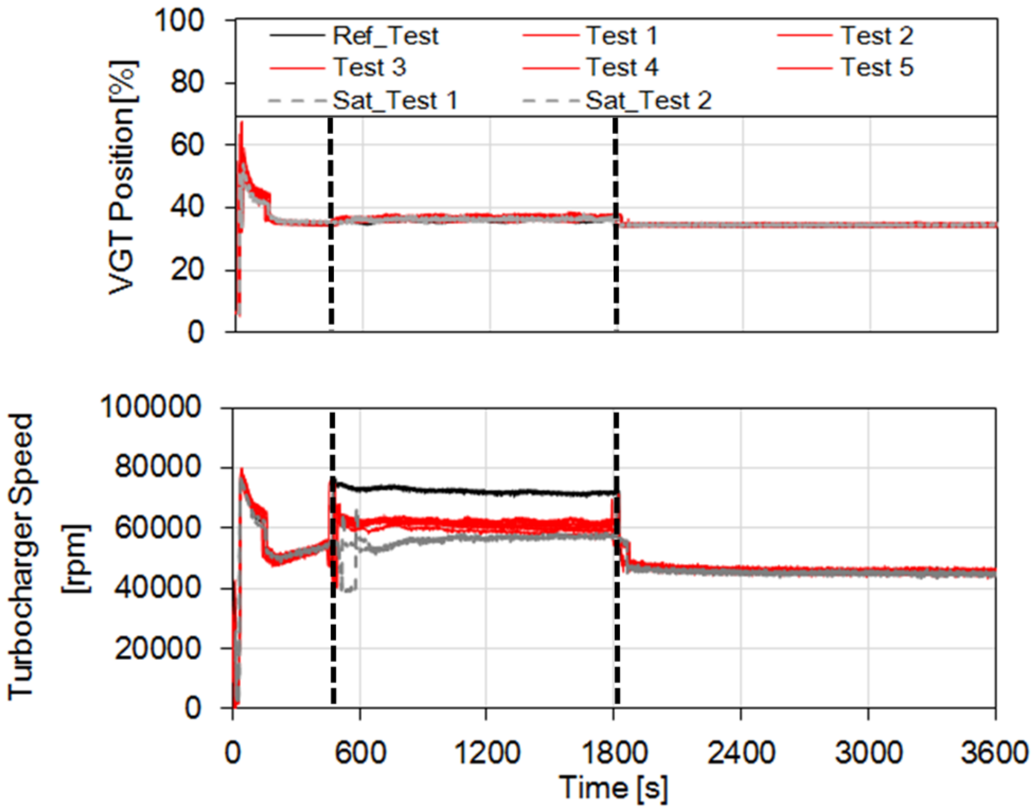

Fig. 5. Turbocharger behavior

3.1.1 DPF regeneration analysis

Experimentally, the DPF saturation can be followed through the differential pressure sensor measurement (ΔP ECU) at the filter inlet and outlet and the soot mass estimation performed by the ECU. Fig. 6 shows the DPF ΔP as a reference to identify if there are clogging conditions on the DPF. It can be observed how performing HP EGR while the DPF is under active regeneration allows to reduce the pressure difference below the reference test, indicating that the regeneration process is efficient. The soot mass variable recorded from the ECU confirmed this statement. Nevertheless, under standard engine calibration (right of the figure), performing HP EGR and operating under cold ambient conditions could produce a DPF saturation condition increasing this ΔP value. It is important to highlight that the exhaust gases carried through the high pressure circuit are not cleaned in the engine after treatment system and could affect the combustion process considerably. For this reason, the EGR rate control, the EGR line temperatures and the engine intake temperature is a key factor to ensure a reliable DPF regeneration process.

Regarding the saturated tests (dashed lines), the higher EGR rate due to a higher pressure difference, it is an evidence of the soot accumulation on the DPF and the consequence of a higher intake temperature. This fact can improve the combustion efficiency under controlled conditions , but out of control, it could affect the thermal efficiency of the components (i.e. EGR valve and EGR cooler), thus affecting their normal operation.

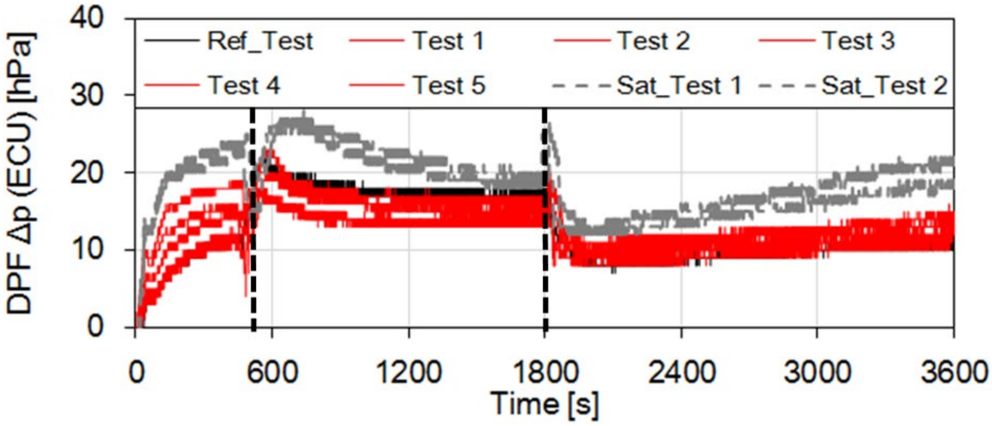

Fig. 6. DPF difference pressure

In addition to the abovementioned ECU variables, other important variable that allows to follow the regeneration process efficiency is the DPF inlet temperature [20]. Fig. 7 shows that, even activating the HP EGR together with the regeneration mode, the DPF inlet temperature remains constant around 470ºC for this engine configuration. This high temperature allows to clean the soot particles accumulated in the DPF and to keep an optimal operation condition for the diesel oxidation catalyst.

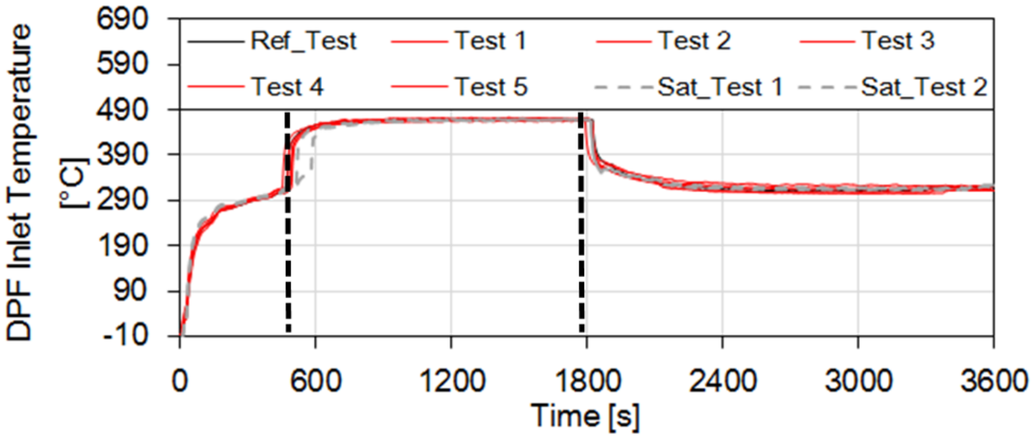

Fig. 7. DPF inlet temperature

Although these variables provide experimental information about the DPF current status, it is possible to perform a mathematical analysis in order to sustain these results. Fig. 8 shows the pressure drop dimensionless coefficient (α) calculated as a theoretical indicator of the flow resistance through the DPF. This coefficient is estimated as a function of the delta pressure (ΔP) and the volumetric flow rate through the DPF, as is shown in the Eq. 4.

$$\Delta P = \alpha \,.\frac{1}{2}.\rho \,. v^2 \tag{4}$$

The gas density (ρ) is calculated as a function of the pressure and temperature (P, T) at the inlet of the DPF and the gas velocity (v) is calculated as a function of the exhaust gasses mass flow, the gas density and the section area of the filter. Taking this into account, an increase in the pressure drop dimensionless coefficient indicates a higher flow resistance through the DPF (saturation) and a decrease in the coefficient indicates a lower flow resistance (cleaning). In Fig. 8, it can be evidenced how, under standard engine calibration (right of the figure), the DPF is saturated due to the HP EGR activation at cold ambient conditions. On the other hand, the regeneration process in combination with the HP EGR activation (left of the figure) presents a slight tendency to decrease, indicating that exists a reduction in the amount of soot clogged on the filter, as could be observed experimentally.

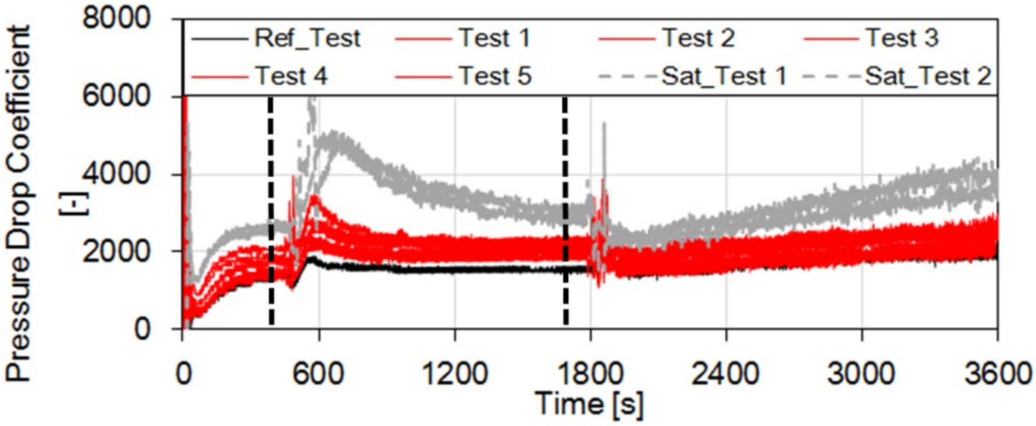

Fig. 8. Pressure drop dimensionless coefficient

3.1.2 Pollutant emissions

Measured values of NO_x, HC and CO emissions collected upstream the after-treatment system are presented in Fig. 9. The aim of performing EGR is to obtain a significant NO_x emissions reduction under cold operating conditions. Nevertheless, one disadvantage of this strategy is the combustion degradation, increasing the unburned HCs and PMs. The top graph of Fig. 9 shows the measured values of NO_x emissions. With the standard calibration at cold conditions, the engine is prepared to perform HP EGR and keep a NO_x values of approximately 2.5 g/kWh. During the DPF regeneration mode in combination with the HP EGR this value is reduced to approximately 1.25 g/kWh. This value represents a reduction of 50%. In terms of HC emissions, a significant increase is observed compared to the standard calibration due to the additional post injected fuel used during the DPF regeneration. However, comparing the DPF regeneration with and without HP EGR, it could be observed that the proposed configuration could help to reduce this issue thanks to a small reduction in the post injected fuel and the higher intake temperatures reached. Furthermore, CO/HC concentrations increase, leading to significant DOC exothermic reactions and as a consequence higher temperatures in the exhaust line.

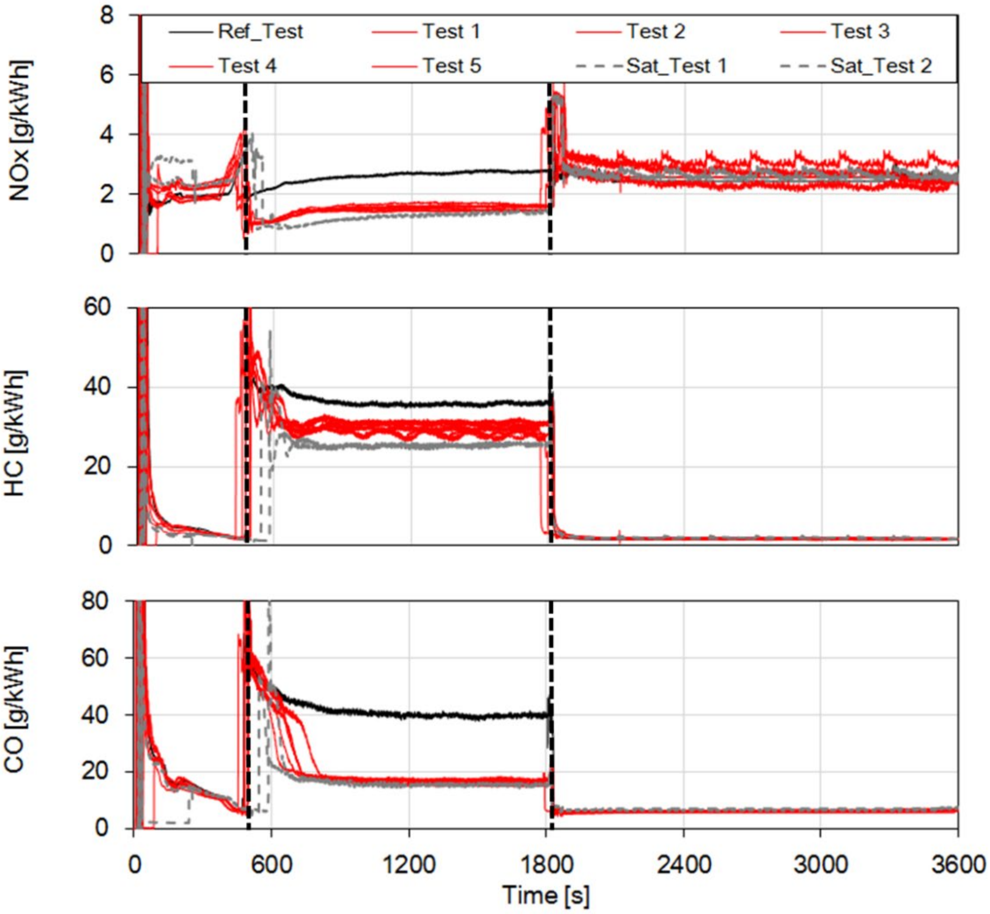

Fig. 9. Raw pollutant emissions measurements

Finally, activating the HP EGR during a regeneration process, keeping an appropriate main injection advance, and thanks to the higher intake temperature reached with this proposed configuration, the CO emissions could be reduced significantly, as it can be observed by comparing the use of the HP EGR or not. It is possible to estimate an approximate reduction of about 60%. This reduction allows to reach close values to the values performed under the standard engine calibration, besides, the aftertreatment system could also reduce significantly these values.

3.1.3 Combustion efficiency and fuel consumption

Fig. 10 shows the combustion efficiency and the brake specific fuel consumption (BSFC) for the different tests. The combustion efficiency estimates the quantity of fuel burned during the combustion process and it is calculated by means of the engine-out emissions measurements, as is shown in the Eq. 5.

$$\eta_{comb} = 1 - \frac{\dot{m}_{HC}(\dot{m}_{air} + \dot{m}_{fuel})}{\dot{m}_{fuel}} - \frac{\dot{m}_{CO}(\dot{m}_{air} + \dot{m}_{fuel})}{4\,\dot{m}_{fuel}} \qquad (5)$$

As mentioned above, operating at very low ambient temperatures cause instabilities and degradations in the combustion process. In Fig. 10, it can be observed how the combustion efficiency increases progressively with the engine warm-up until the 500 s approximately. Performing a DPF regeneration could affect the combustion process due to the additional fuel injected when the post injection is activated. By this reason, it can be observed how the reference test without EGR presents the lower efficiency. Activating the HP EGR together with the regeneration mode results in a slight improvement of the combustion efficiency. This improvement is due to a higher intake temperature and a quite reduction in the post injected fuel during the regeneration mode. Therefore, the consequent higher in-cylinder temperature promotes a better combustion process. In addition, the observed reduction in the brake specific fuel consumption is coherent with this behavior.

Working with the standard engine calibration, both, combustion efficiency and BSFC present optimal values, taking into account that this operation is at low ambient temperature (-7ºC).

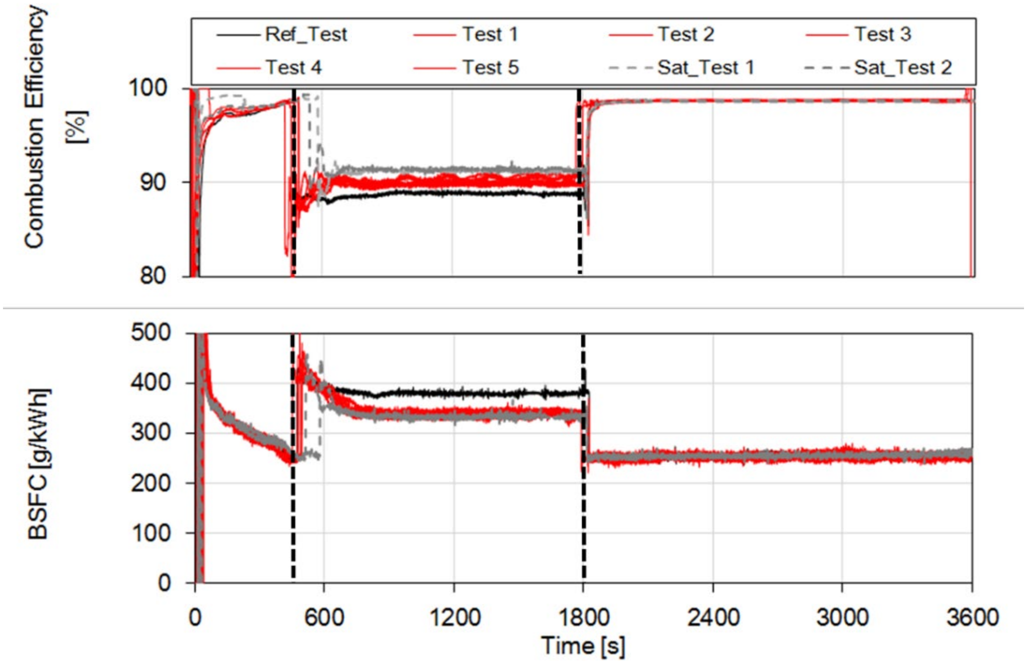

Fig. 10. Combustion efficiency and BSFC

3.2 Impact of the HP EGR combined with the regeneration mode on the engine components

The second aim of this experimental work is to perform a brief analysis of a known event presented when an IC engine is operating with exhaust gas recirculation (EGR) at very low ambient temperatures. These are the fouling deposits, which could affect the EGR systems due to unburned HC and PM depositions on its main components (i.e. EGR valve and EGR cooler).

After 40 hours performing HP EGR at cold conditions, 20 of them with active DPF regeneration, fouling depositions on the HP EGR line components are observed.

Fig. 11 and Fig. 12 shows an images of the initial and final conditions of the HP EGR valve and a section of the HP EGR rail of the circuit. It can be observed a black soot on the actuator surface comparing the reference (initial condition) with the final condition. This is a typical soot as found in EGR circuits of IC engines, with similar features, like matte black color, carbon texture and rough surface.

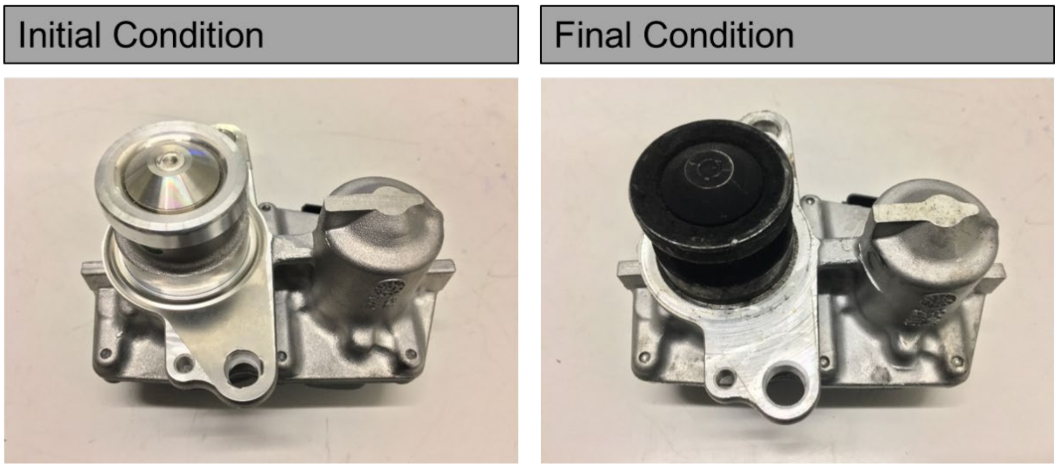

Fig. 11. Fouling observed on the HP EGR valve

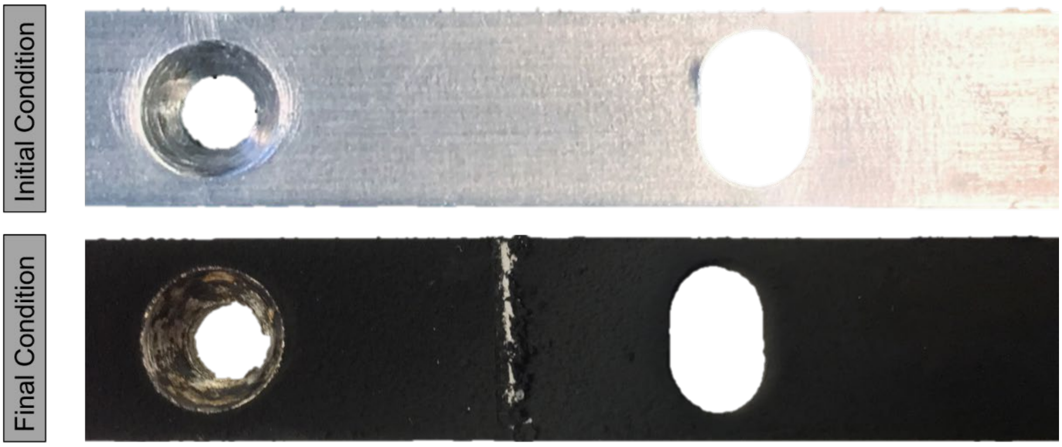

Fig. 12. Fouling observed on the section of the HP EGR rail

In order to obtain a quantitative estimation of the amount of soot produced during this experimental campaign, the layer of soot observed on the surface of the elements is considered as a geometrical area with the same shape of the element. For example, the EGR valve actuator observed in Fig. 11 is considered as a tube with cover. Then, the soot volume is estimated by measuring the thickness of the soot layer. This estimation is performed with the aim of obtaining and order of magnitude represented in a numerical value of the soot produced after this particular experimental campaign. On the other hand, in order to know the mass of soot, approximately 50% of the soot particles has been removed and collected from the HP EGR components (i.e. EGR valve, ducts, rail and intake manifold), the particles collected from each element are weighted in a precision scale and multiplied by two in order to obtain an estimation of the 100% of the mass.

Approximately, the deposition of 30 cm^3 of soot, equivalent to a 6 gr of soot mass, has been estimated after 40 hours performing HP EGR and DPF regeneration at cold conditions. This calculated value can be considered as an acceptable amount of soot produced when exhaust gas recirculation is used. Typical saturation values in diesel engines to conduct DPF regeneration are close to 20 gr of soot.

4. Conclusions

In the present paper, the advantages, disadvantages and impacts of performing HP EGR together with the DPF regeneration mode during engine cold operating conditions have been studied. The impact in regeneration efficiency, pollutant emissions and fuel consumption were presented. Besides, a brief analysis of the impact of fouling depositions on the engine components have been performed.

The main objective of performing HP EGR at cold conditions (-7ºC) is to reduce the NO_x emissions thanks to the oxygen concentration reduction of the working fluid in the combustion chamber. In this work, a noticeable NO_x emissions reduction of approximately 50% with respect to a reference case without HP EGR during a DPF regeneration process has been achieved. Regarding HC and CO emissions, another advantages were found with this proposed configuration. A significant CO emissions reduction of 60% was achieved performing HP EGR and fixing a main injection advance of -10º CAD. In terms of HC emissions, a reduction of 15% was observed due to the improvements in combustion efficiency and fuel consumption. Besides, the after treatment system could also reduce significantly these values. During the DPF regeneration, the additional fuel injected in the post injection affected the combustion efficiency due to the late combustion of this fuel during the exhaust stroke. A quite benefit could be observed due to a slight improvement in the combustion temperature when the HP EGR is activated.

On the other hand, performing HP EGR without the regeneration mode at cold conditions could contribute to the DPF saturation and degradation, the accumulation of soot increases the pressure difference in the DPF and as a consequence an increment in the EGR rate performed and in the EGR temperatures was registered.

In order to avoid the previous conclusion, the regeneration efficiency was evaluated through the DPF pressure difference, the soot mass estimated by the ECU, the HP EGR rate and the flow resistance through the DPF. It was found that the activation of only the HP EGR at cold conditions with EGR rates beyond 20% contributed to increase the soot depositions and to saturate the DPF early. By this reason, if the purpose is to activate the HP EGR to reduce NO_x emissions, the EGR rate and the intake temperatures must be controlled and limited. The LP EGR could be presented as another option to decrease this impact. However, performing a low HP EGR rate in combination with the regeneration mode could reduce the post injected fuel and the exhaust gas temperature, but anyway continue keeping the regeneration efficiency in acceptable values. This was confirmed verifying the DPF status through the ECU variables (DPF ∆P and soot estimation) and the pressure drop dimensionless coefficient estimated. It allowed to obtain the noticeable NO_x emission reduction abovementioned.

The second aim of this research work is the analysis and visualization of fouling phenomena produced by the HP EGR activation at cold conditions. After 40 hours of tests, soot particles were found on the HP EGR line of the engine. These particles match with typical fouling observed in IC engines. A fouling quantity of 30 cm^3 and 6 gr was estimated, observing that the principal components where soot is deposited were the HP EGR rail and the engine intake manifold.

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