Galindo, J.; Dolz, V.; Monsalve-Serrano, J.; Bernal-Maldonado, MA.; Odillard, L. (2021). Advantages of using a cooler bypass in the low-pressure exhaust gas recirculation line of a compression ignition diesel engine operating at cold conditions. International Journal of Engine Research. 22(5):1624-1635. https://doi.org/10.1177/1468087420914725

Advantages of using a low-pressure EGR cooler bypass in a compression ignition diesel engine operating at cold conditions

J. Galindo, V. Dolz[1], J. Monsalve-Serrano, M.A. Bernal

CMT – Motores Térmicos, Universitat Politècnica de València, Spain

L. Odillard

Valeo – Systèmes Thermiques

Abstract

The low efficiency of the after-treatment systems during the cold start period of the internal combustion engines leads to excessive pollutant emissions levels. To reduce the NOx emissions at these conditions, it could be necessary to use the high and low pressure exhaust gas recirculation (EGR) strategies, even operating at low temperatures. This paper evaluates the impact of using a low-pressure EGR cooler bypass on a Euro 6 turbocharged diesel engine running under cold conditions (-7ºC). A new compact line fitted with a bypass system for the cooler is used with the aim of accelerating the engine warm-up process as compared to the original low-pressure EGR line. The system is evaluated following two strategies, first performing EGR without bypass and then performing EGR bypassing the cooler. The results show that activating the low-pressure EGR from the engine cold start leads a significant NOx emissions reduction. Moreover, the bypass activation leads to increase the engine intake temperature, reducing the engine warm-up time and the CO emissions due to a better combustion

---

[1] V. Dolz. CMT-Motores Térmicos, Universitat Politècnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain. Phone: +34 963877650 Fax: +34 963877659 e-mail: vidolrui@mot.upv.es

efficiency. However, the activation of the low-pressure EGR at low temperatures could produce condensation and fouling deposits on the engine components affecting their life span. These phenomena are visualized by means of endoscope cameras in order to identify the condensation time and the final conditions of the elements. In addition, a chemical analysis of some condensates collected during the experiments and a comparison versus other species found in the literature is presented.

Keywords

Bypass, Fouling, Visualization, LP EGR, Cold Conditions, NOx Reduction

NOMENCLATURE

Acronyms

EGR	Exhaust Gas Recirculation
HP	High Pressure
LP	Low Pressure
MR	Mid-Route
ICE	Internal Combustion Engine
NOx	Nitrogen Oxides
CO_2	Carbon Dioxides
HC	Hydrocarbons
PM	Particulate Matter
ECU	Electronic Control Unit
DPF	Diesel Particulate Filter
DOC	Diesel Oxidation Catalyst
TGA	Thermal Gravimetric Analysis
GC-MS	Gas Chromatography – Mass Spectroscopy
VOC	Volatile Organic Compound

Notation

Latin

$\dot{m}$	Mass flow	kg/s

Greek letters

η	Combustion Efficiency	--

Subscripts

exh	Exhaust gases
int	Intake
$comb$	Combustion
$fuel$	Fuel
air	Air
amb	Ambient

1. Introduction

The exhaust gas recirculation (EGR) is a widely used technique to reduce the nitrogen oxides (NOx) from internal combustion engines (ICE), especially in diesel engines [1]. Many engine manufacturers have invested time and resources trying to optimize this technique due to its effectivity to reduce these kind of emissions [2]. A recent solution implemented by the manufacturers of current diesel engines was the use of two independent EGR circuits. Although making complex the engine architecture, this was found to be an effective solution to reduce the NOx levels in different engine operating points [3] [4]. The first circuit, is the conventional EGR circuit, known as high pressure (HP) EGR, where the EGR rates are limited by the pressure difference among the inlet and outlet manifolds. The second circuit, is an innovative solution known as low pressure (LP) EGR, which has been introduced as a cleaner EGR, with higher values of EGR rates and the same effectivity to reduce NOx emissions [5].

The use of the LP EGR concept could be mandatory to fulfill the future approval regulations applied to vehicles equipped with IC engines, which are becoming more stringent with the years. It is expected that this kind of approval procedures will take into account the engine cold start period, when the pollutant emissions are largely critical [6] [7]. For this reason, the LP EGR is presented as an alternative to reduce NOx emissions even under these expected regulations.

The benefits of the LP EGR system in the engine behavior are the lower temperature of the exhaust gas, the higher amount of energy available to the turbine and the smaller pressure difference needed to move the gas [8]. Nevertheless, the use of EGR presents some issues, as per example the condensation phenomenon at low temperatures. At these conditions, the condensates can produce fouling deposits inside the EGR line components [9]. Condensation is produced due to the fact that the exhaust gas coming from the combustion has important water content as well as other products like acids and hydrocarbon (HC) species [10]. When the temperature decreases in this gas with high humidity ratios, the condensation phenomenon appears. The condensate liquids contribute to the fouling processes on these elements, which reduces their useful life [11]. On the other hand, the important rates of HC species in the exhaust gas during the engine warm-up could affect the actuation of these elements due to the accumulation of deposits on the elements of the EGR line (i.e. valves and coolers) [12].

Many works presented in the literature highlight the importance of the EGR to fulfill the current and future emissions regulations and many researchers have studied how to continue taking advantage of this system. For example, Lapuerta et al. [13] presented a comparison of the effectiveness of both exhaust gas recirculation systems on the improvement of the NOx particulate matter emission on an Euro 6 turbocharged diesel engine. In this work, different combinations of engine speed and torque, at transient and steady conditions with different coolant temperature strategies were performed, finding that the LP is more efficient than the HP EGR to reduce the NOx emissions due to the higher recirculation potential and the lower temperature of the recirculated gas. In addition, during the engine warm-up, switching from HP to LP EGR at an intermediate coolant temperature is also beneficial for the emissions. Dimitriou et al. [14] evaluated the potential of introducing an alternative EGR route in a two stage boosted engine. The authors proposed a Mid-route (MR) EGR system to combine the benefits of the HP and LP EGR systems in order to increase the EGR rates and reduce the transportation delay of the exhaust gases. Besides, the performance of different components (i.e. compressor, turbine and cooler) with this proposed configuration was examined. The study demonstrated that MR EGR could provide high EGR rates, particularly at high and low engine speeds. The reduction in the EGR response time was found to be around 50% and the study related to the sizing of the cooler revealed that a LP EGR cooler is unnecessary whereas the MR EGR cooler can also be omitted from the system.

Few studies have been carried out regarding the condensation and deposits phenomena. In this sense, Furukawa et al. [15] presented a chemical analysis of the hydrocarbons deposits that produce the sticking of the EGR valves and a method to avoid this issue when the EGR operating range in a diesel engine is expanded. The analysis revealed that the type of hydrocarbons collected, and their dew points, are the major factors in the sticking process of these valves. Furthermore, a control method to maintain the temperature of the EGR valve walls above the critical temperature necessary to produce these deposits was proposed.

According to the previous paragraphs, in this work, the impact of using a LP EGR cooler bypass in a 4-cylinder diesel engine during the engine warm-up process under cold conditions is evaluated. The effect of using LP EGR during the engine cold start on the regulated diesel emissions, NOx and soot, as well as on the thermal engine efficiency is assessed. An analysis of the condensation and fouling phenomena observed on the LP EGR line components is also presented in this paper. This analysis includes a chemical analysis of samples of some species collected from the engine 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 engine points. The injected fuel mass flow and the intake air mass flow are also measured.

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 HP EGR circuit, in which the exhaust gas is directly cooled in the cylinder head and mixed with the fresh air coming from the intake line. However, for this particular study, this circuit is not activated. The second circuit is the LP EGR. In this case, the exhaust gas passes through the catalyzer and the particulate filter, and then is redirected into the turbo compressor. Fig. 1 shows the LP EGR line and its instrumentation. This circuit introduces the exhaust gas coming from the turbine into the after treatment systems. First, using a diesel oxidation catalyst (DOC), the CO and HC emissions are reduced. Then, using a diesel particulate filter (DPF), the particulate matter (PM) coming from the combustion process is also reduced. When the exhaust gas is treated by these systems, a LP EGR cooler is used to reduce its temperature and a LP EGR valve controlled by the electronic control unit (ECU) of the engine sets the LP EGR rate. The LP EGR cooler is cooled by the own engine coolant circuit. Finally, the exhaust gas is driven and distributed to the engine intake line and mixed with the air at the compressor inlet. This gas mixture is compressed and directed to the engine intake manifold where is introduced into the four cylinders. The WCAC is not activated (0 flow inside) during cold start operation.

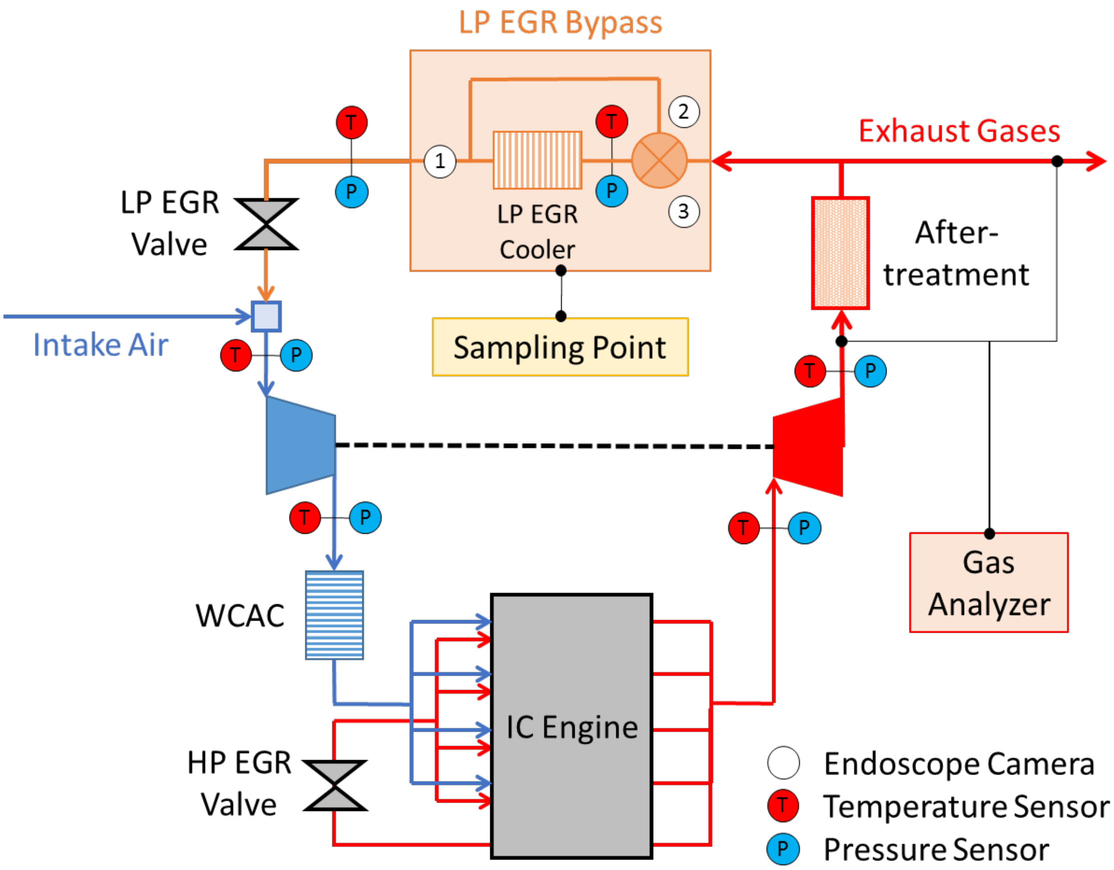

Fig. 1. LP EGR circuit fitted with Bypass

The LP EGR cooler bypass prototype tested in this experimental work can be observed in Fig. 1 and Fig. 2. This is a compact concept of the whole LP EGR line of the engine. This bypass has an electronically controlled flap valve in order to guide the exhaust gas through the cooler and then to the mixer, or directly to the mixer through a parallel circuit with the aim of increasing the engine intake temperature during the cold start operation. In addition, this compact bypass has been instrumented with three endoscope cameras and two light sources in order to locally observe the condensation phenomenon inside the circuit and a sampling point coupled to a beaker in order to collect part of the condensates produced during the experiments.

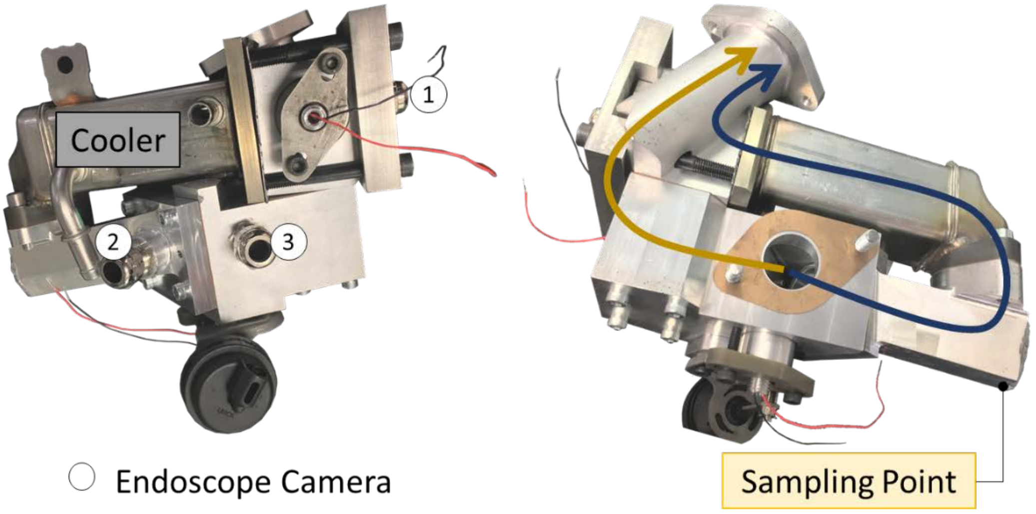

Fig. 2. LP EGR Bypass Prototype

Fig. 3 shows the locations of the prototype and the cameras on the engine experimental set-up as well as the field of view that is observed and recorded during the experiments. These endoscope cameras allow to record videos and pictures with a quality of 30 fps and 96 dpi.

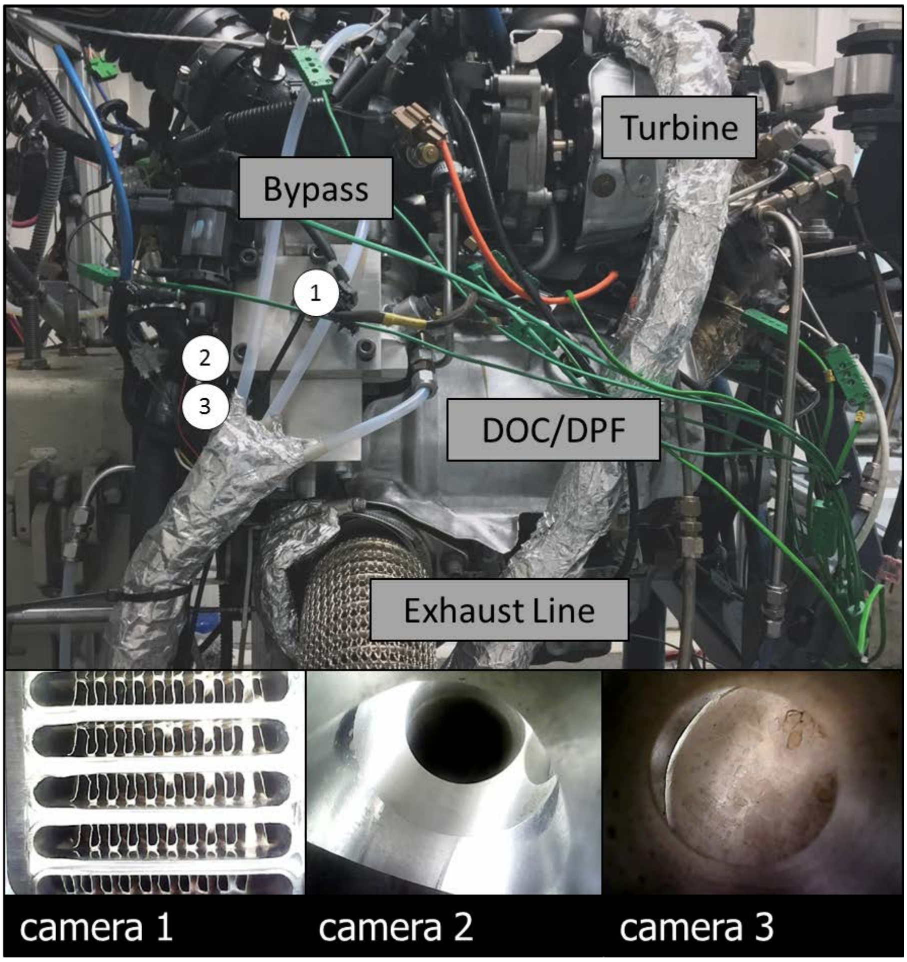

Fig. 3. Engine Set-up, Cameras Configuration and Field of View

Several engine parameters were measured to assess the engine performance and 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 ambient temperature inside the climatic chamber was set at -7ºC, 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 O_2, CO_2, CO emissions using a non-dispersive infrared analyzer, and unburned hydrocarbons with a chemiluminescent detector. The error of the gas analyzer is in the range of 2%. Two measurement points are located upstream and downstream of the after-treatment system.

The EGR rate has been obtained experimentally from CO_2 measurement in exhaust and intake manifolds using the following expression:

$$EGR_{rate} = \frac{[CO_2]_{Int} - [CO_2]_{Amb}}{[CO_2]_{Exh} - [CO_2]_{Amb}} \tag{1}$$

2.2. Methodology and Strategies

A transient engine cycle with special characteristics in terms of NOx generation and soot formation inside the EGR components of a diesel engine running at cold conditions was tested. Fig. 4 shows the profile of the cycle performed for these experiments. This cycle is characterized by low-middle load points with important EGR rates and sudden accelerations. For this experimental work, a total of 30 tests have been performed at -7ºC and activating the LP EGR during the whole cycle. 20 of these tests were performed with the bypass system activated in order to check the repeatability of the experiments and to check the engine response under this new configuration. The remaining 10 cycles were performed with the bypass deactivated.

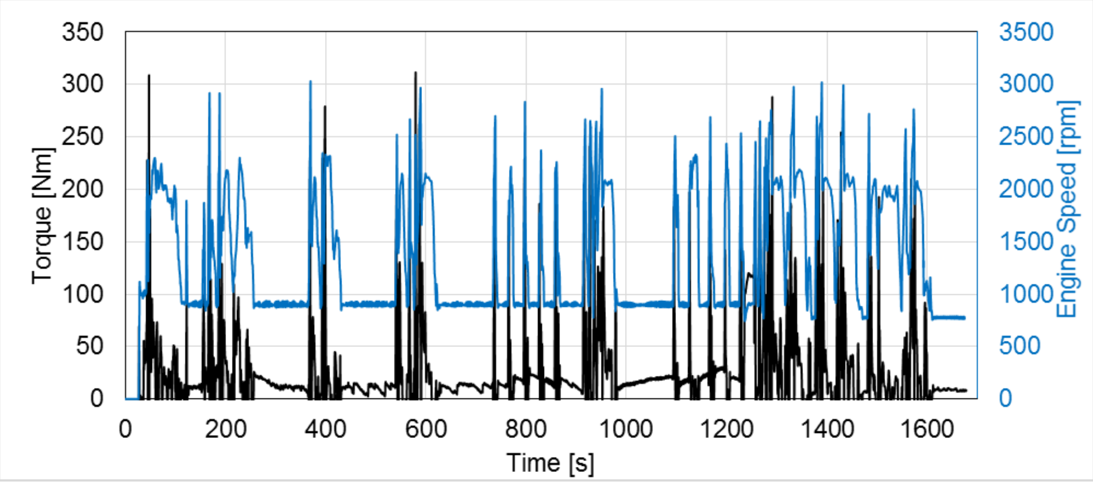

Fig. 4. Profile of the cycle performed

In addition, it was necessary to modify the standard engine calibration (ECU) in order to activate the LP EGR and deactivate the HP EGR during the complete cycle because the ECU is not configured to perform LP EGR under these particular conditions. In order to perform realistic EGR rates during the warm-up process, the ECU was modified to introduce similar EGR rates to those of the engine running after the completion of the warm-up process. Fig. 5 shows the LP EGR rate along the entire cycle measured with the Horiba system.

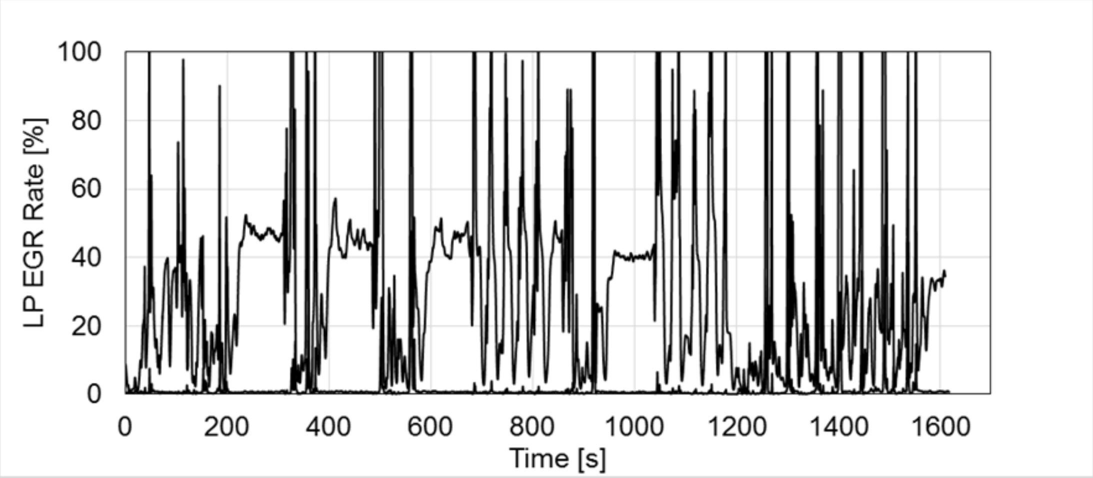

Fig. 5. LP EGR rate since engine cold start

3. Results and Discussions

In order to present how the implementation of a bypass in the LP EGR line could improve 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 intake and exhaust temperatures, pollutant emissions and fuel consumption is presented. In the second subsection, the condensation and the chemical composition of the deposits is analyzed and the fouling phenomena evolution inside the engine components is presented.

3.1 Impact of the LP EGR bypass on the engine behavior

The use of a bypass system in the LP EGR line avoids the passage of the gas through the LP EGR cooler. This strategy leads to a higher temperature at the engine intake line as expected. In order to show the main results of this work in terms of repeatability and dispersion between tests, a group of five tests is selected. First, a reference test performed at -7ºC without activating the LP EGR and without using the bypass system. Later, two tests are performing using LP EGR and without bypass. Finally, two tests are performed using LP EGR with the bypass system activated. Fig. 6 shows the compressor outlet temperature and the engine intake temperature measured in the intake manifold. Comparing the reference test to the two tests performing only LP EGR, it can be observed how the compressor outlet temperature increases approximately by 15ºC. Furthermore, an additional increment of approximately 15ºC is observed when the bypass system is activated in combination with the LP EGR, that is, when the exhaust gas is driven directly to the intake line without passing through the LP EGR cooler. Due to the WCAC deactivation during cold start operation, it can be observe in the bottom of the figure how the engine intake temperature increase progressively with regard to the reference test. These higher temperatures could increase the in-cylinder temperature and accelerate the warm-up processes of the engine, improving the engine combustion efficiency.

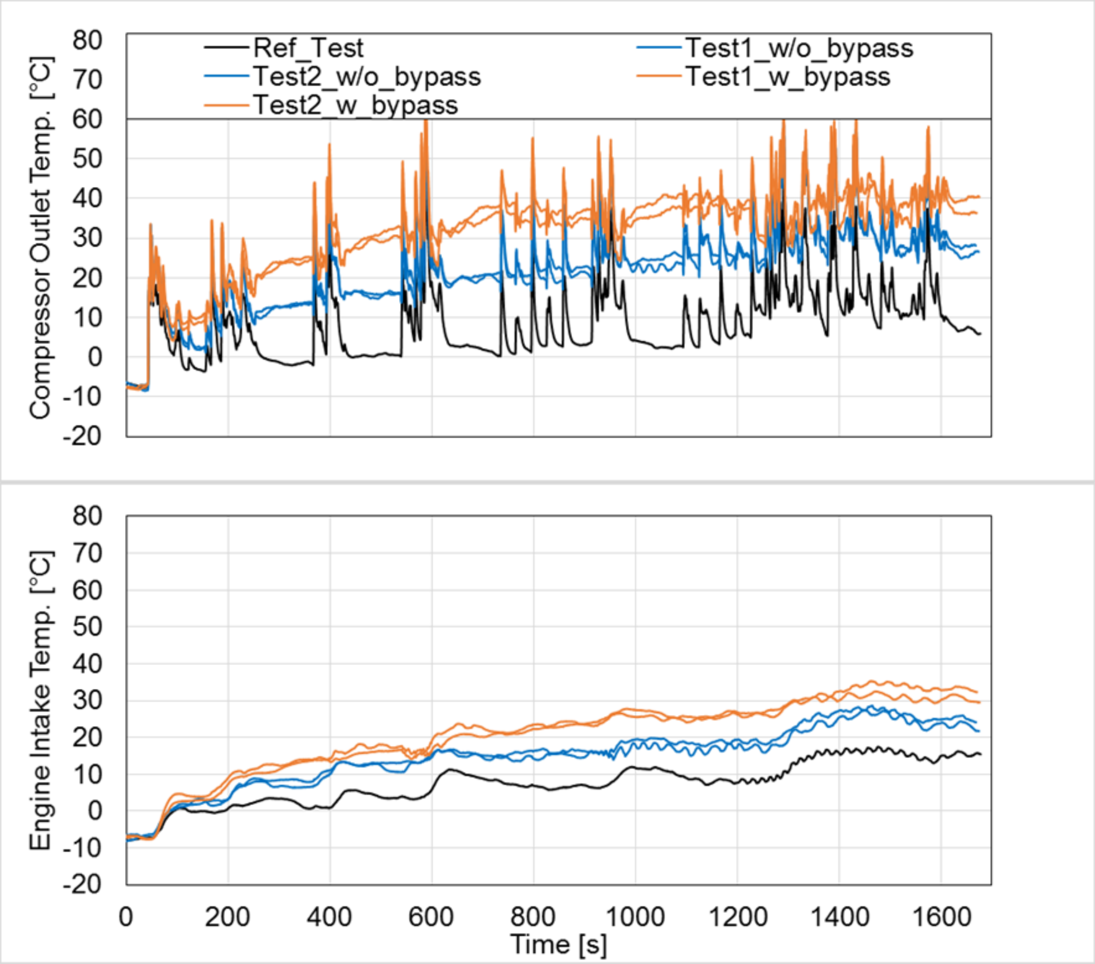

Fig. 6. Compressor Outlet Temperature and Engine Intake Temperature

As in the case of the intake temperature, Fig. 7 shows how the exhaust temperature increases also progressively when performing LP EGR in combination with the bypass activation. From literature, it is known that an increase of 15ºC in the intake temperature leads to a proportional increase in the exhaust temperature, affecting the combustion process and as a consequence, the engine pollutant emissions [16][17].

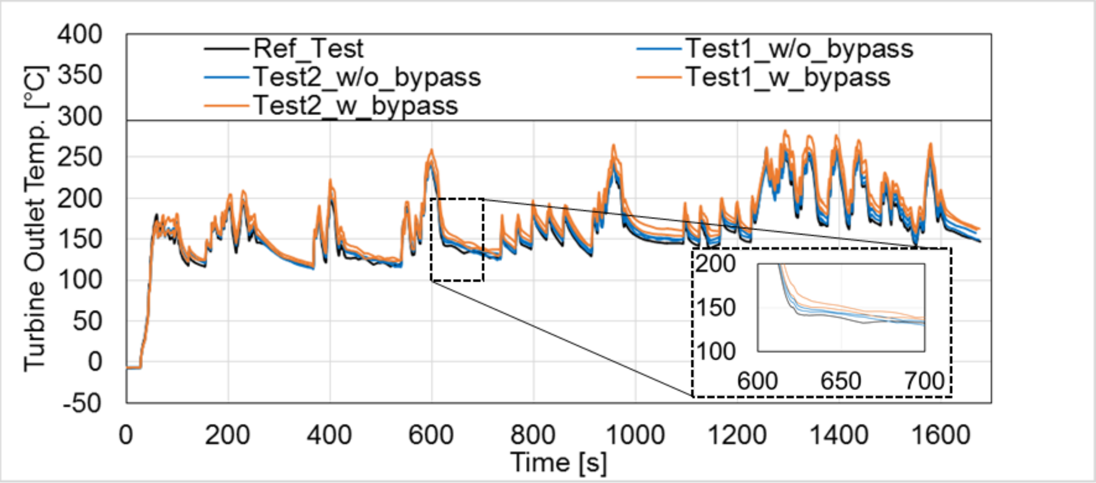

Fig. 7. Exhaust Temperature with Zoom

As is usual in the IC engines calibration, the engine coolant temperature is used as a reference parameter in order to set different control strategies as per example the injection timing, the EGR activation and the engine cooling. Fig. 8 shows this temperature and how the time to heat-up the engine coolant is reduced due to the abovementioned increase of the intake and exhaust temperatures. For this experimental work, the coolant temperature where the ECU changes the EGR calibration strategy for an engine cold start is set at 60ºC. During the experiments, it has been observed that the tests performed with LP EGR and without bypass reach earlier a higher temperature reducing the time for heating the coolant, while tests performed with LP EGR and bypass work better than the reference test, but have a delay for the coolant temperature of thirty seconds approximately with respect to the previous case. This effect is expected to be due to the cooling engine configuration, where the coolant inside the engine circuit is recirculated to the LP EGR cooler in order to cool down the exhaust gas coming from the after-treatment. By this reason, the tests performed with LP EGR and passing the exhaust gas through the cooler (without bypass) allow to cool down the EGR gas and at the same time to heat the coolant inside the cooling circuit contributing to improve the global engine warm-up. This is something relevant in terms of engine calibration in order to know the effects that the implementation of a bypass system could produce in the abovementioned engine control strategies and also could be used a reference parameter to follow the engine warm-up process.

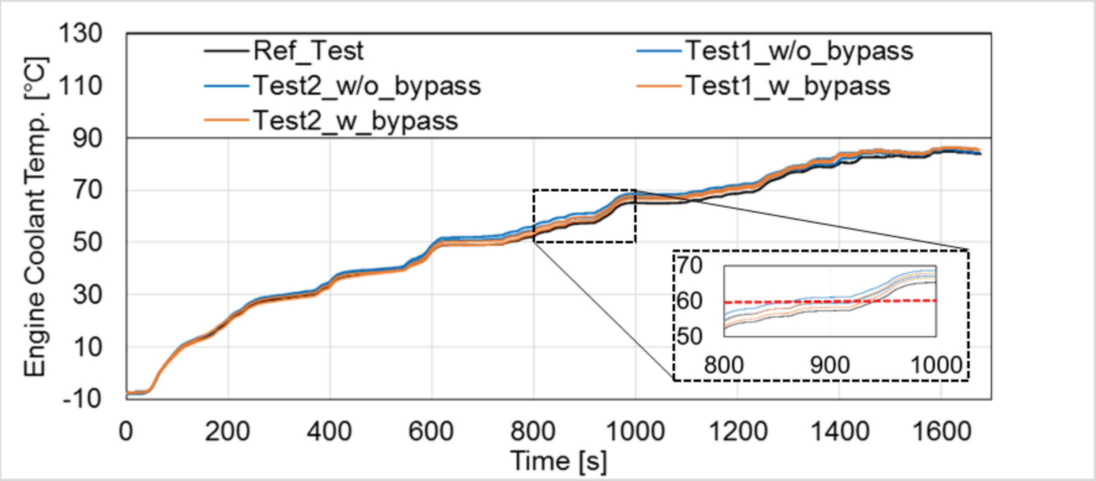

Fig. 8. Engine Coolant Temperature with Zoom

Pollutant Emissions

Accumulated values of NOx, HC and CO emissions measured upstream (continuous lines) and downstream (dashed lines) the after-treatment system are presented in Fig. 9. These values are calculated using aggregated data of each variable during the whole experimental cycle. The aim of performing EGR is to obtain a significant NOx emissions reduction to both during the warm-up in cold operating conditions and after the warm-up process. Nevertheless, one disadvantage of this strategy is the combustion degradation, increasing the unburned HCs and PMs. The top graph of Fig. 9 shows the accumulated value of NOx emissions. The accumulated value at the end of the cycle for this polluting emission is reduced from 11 g, in the case of reference test, to approximately 4.5

g, by activating the LP EGR from the beginning of the cycle for both configurations (with and without bypass). This reduction represents approximately a reduction of 60%. In terms of HC and CO emissions, a slight increase is observed during the first part of the cycle, when the engine is working in cold conditions. The increment in these emissions is due to the combustion degradation caused by the EGR gas introduced into the cylinders. However, this increase in HC and CO, during the first part of the test, disappears in the second part of the test, due to the reduction of the engine warm-up duration when EGR is performed during the test. This positive phenomenon (reduction of the warm- up process period) compensates the negative phenomenon (exhaust gas introduced into cylinders) and at the end of the cycle, the accumulated emissions are practically the same in the two cases, with and without EGR.

When comparing the raw emissions (Continuous curve) to the final emissions (Dashed curve), by using the engine after-treatment system, the total HC emissions are reduced approximately 30% during the whole cycle (accumulated reduction at the end of the cycle). Regarding CO emissions, the reduction in accumulated emissions is practically a 50% at the end of the cycle.

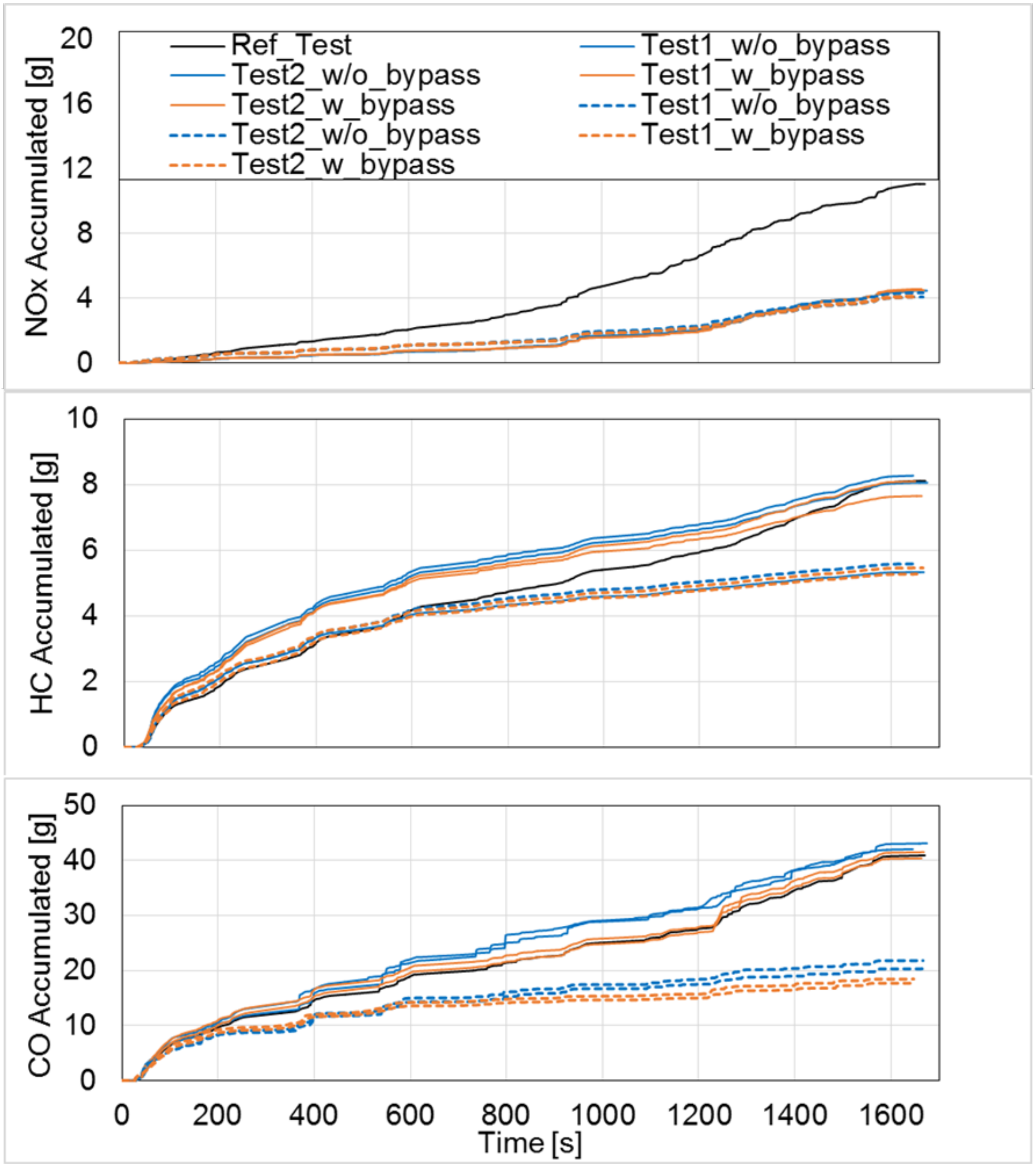

Fig. 9. Accumulated Pollutant Emissions. Continuous line: Raw emissions. Dashed line: Final emissions

In addition, the higher intake temperature reached when activating the LP EGR cooler bypass could help to slightly reduce the CO emissions, as it can be observed by comparing the CO accumulated in these two cases with and without bypass. At the end of the cycle, comparing the accumulated CO emissions after the catalyst in these two cases, it is possible to estimate an approximate reduction of 12% when the LP EGR is performed with the bypass activated.

Combustion Efficiency and Fuel Consumption

Fig. 10 shows the combustion efficiency and the accumulated fuel consumption for the whole cycle. Using the air mass flow, the fuel mass flow and the CO and HCs emissions measured with the gas analyzer, the combustion efficiency is estimated as is shown in the following equation.

$$\eta_{Comb} = 1 - \frac{\dot{m}_{HC}\left(\dot{m}_{air} + \dot{m}_{fuel}\right)}{\dot{m}_{fuel}} - \frac{\dot{m}_{CO}\left(\dot{m}_{air} + \dot{m}_{fuel}\right)}{\dot{m}_{fuel}} \tag{2}$$

As mentioned above, during the first minutes of an engine cold start there are instabilities and degradations in the combustion. In Figure 10, it can be observed how the lowest values of efficiency are present until the 600 seconds approximately. In addition, performing LP EGR from the beginning of the engine cold start could affect the combustion process due to the combustion degradation. By this reason, it can be observed how the reference test without EGR presents a bit higher efficiency. Following the coolant temperature in order to take a reference of when the engine warm-up finishes, approximately at 60ºC and after the second 800, the combustion is stable and the temperature in the cylinder is better for the engine operation, besides, during the end of the cycle, it can be observed how performing LP EGR and activating the bypass could improve the combustion efficiency due to the internal higher temperatures reached [18]. Nevertheless, the variations observed in the combustion efficiency and the fuel consumption are in the order of 5%. In general, the engine torque and the fuel consumption are similar comparing the different experiments.

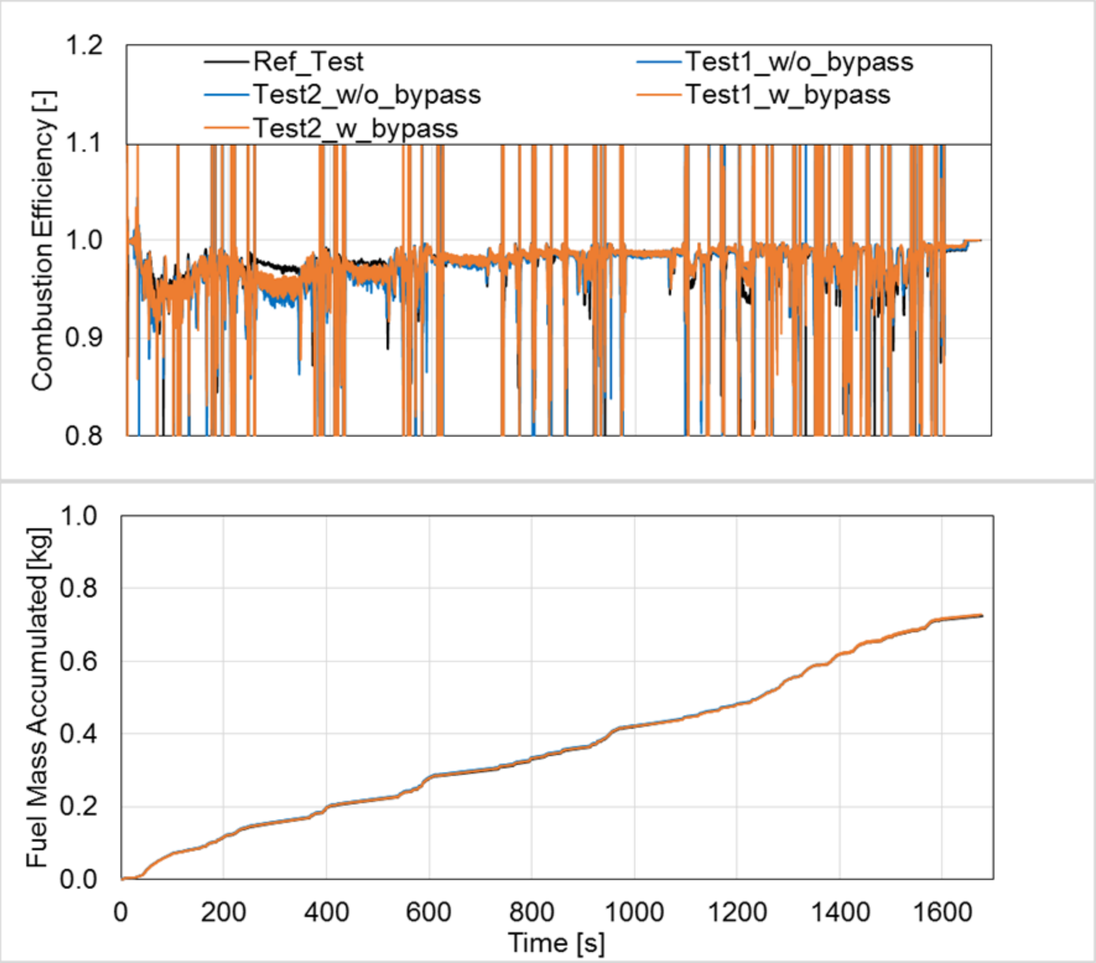

Fig. 10. Combustion Efficiency and Fuel Consumption

A small advantage could be observed performing the bypass activation in terms of combustion efficiency when the engine warm-up process finishes, this behavior could benefit the fuel consumption that should be affected by the combustion degradation during the engine cold start period.

3.2 Condensation and Fouling Analysis

The second aim of this experimental work is the analysis of two events presented when an IC engine is operating at very low ambient temperatures. First, the condensation due to the hot gas coming from the fuel combustion, which has an important liquid content. The high humidity ratio in the exhaust gas produces condensation if the gas temperature is reduced below the dew point, and the fouling deposits, which could affect the EGR systems due to HC depositions on its principal components (i.e. EGR valve, EGR cooler).

Visualization of Condensates

In order to visualize the condensation phenomena inside the LP EGR cooler bypass, different frame rates from the videos and pictures recorded with the endoscope cameras are presented. The Fig. 11 shows a sequence of frames of two tests performed in order to visualize the condensation phenomena inside the LP EGR bypass through the endoscope cameras. The frames at the left of the figure correspond to a test performing LP EGR and without activating the bypass system. The frames at the right of the figure correspond to a test performing LP EGR and activating the bypass system. The first frame (top of the figure) corresponds to a frame of the first seconds of the experiment, showing the initial conditions before that the cycle begins. The second frame of the figure shows the images of the cooler and the bypass flap at 100 seconds. At this point in time, a severe fog appears on the images and the first drops precipitate on the bypass surface, as shown by the bright spots on the surface of the camera 3. The third frame shows the images at the second 200 of the cycle. As Fig. 11 shows, at this time the temperature in the exhaust gas has increased enough to avoid condensation conditions. However, close to the surfaces, the temperature is lower and condensation conditions appear. As the bypass activation allows to increase the exhaust gas temperature, it is possible to observe a reduction in the fog in the frames at the right of the figure, while at the left of the figure, the fog is constant due to the lower exhaust gas temperature reached in the LP EGR cooler. The fourth and fifth frames show the images at 300 and 400 seconds of the cycle. At these moments, the fog practically disappears using the bypass activation. As Fig. 11 shows, although the temperature of the gas has increased considerably at these moments and no fog is formed in the exhaust gases, the temperature in the bypass surfaces continue warming-up and drops of condensates can be observed. With the bypass deactivated, it is still possible to observe fog and condensation conditions at the cooler outlet at this time.

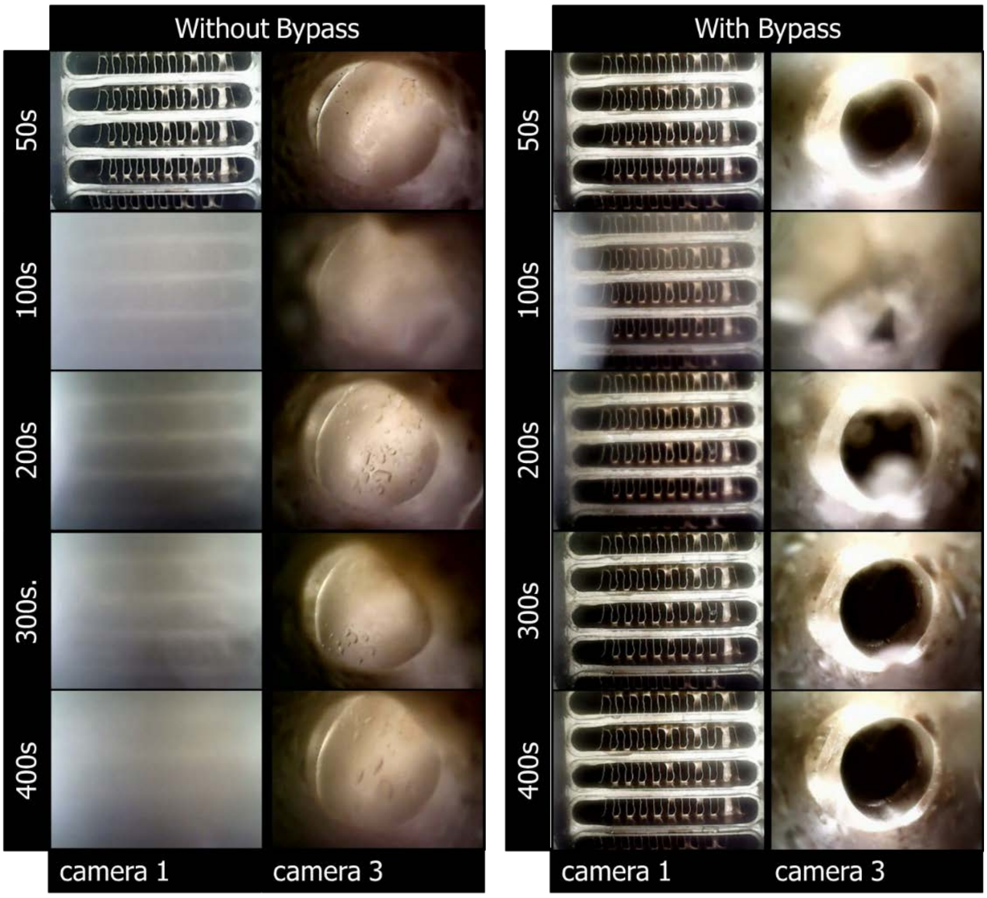

Fig. 11. Video frames comparing two tests performed without (left) and with (right) bypass activation in the second 100, 200, 300 and 400.

The Fig. 12 shows a sequence of frames of the following seconds of the two tests above mentioned. The first frame (top of the figure) corresponds to a frame at 400 seconds. Although at this time there are no condensation conditions on the exhaust gas using the bypass activation, dew conditions are produced in all the bypass walls and water drops appear in the bypass surface. The second frame of the figure shows the images of the cooler outlet and the bypass flap at the 500 seconds. At this time, the warm-up process reduces the relative humidity and dew conditions start to disappear. At the left of the figure, it is possible to observe a reduction in the fog and in the quantity of liquid in the bypass wall, especially in Camera 1. The last three frames, third, fourth and fifth, show the images at the 600, 700 and 800 seconds respectively. These images show a progressive reduction of the liquid drops on the bypass surface. This reduction is clear in the cooler outlet and in the bypass flap for both configurations, where the relative humidity decreases and condensation conditions disappear. It can be observed that the condensation time is lower by activating the bypass strategy. A reduction in time, of approximately 250 seconds could be reached due to the higher temperatures in the engine.

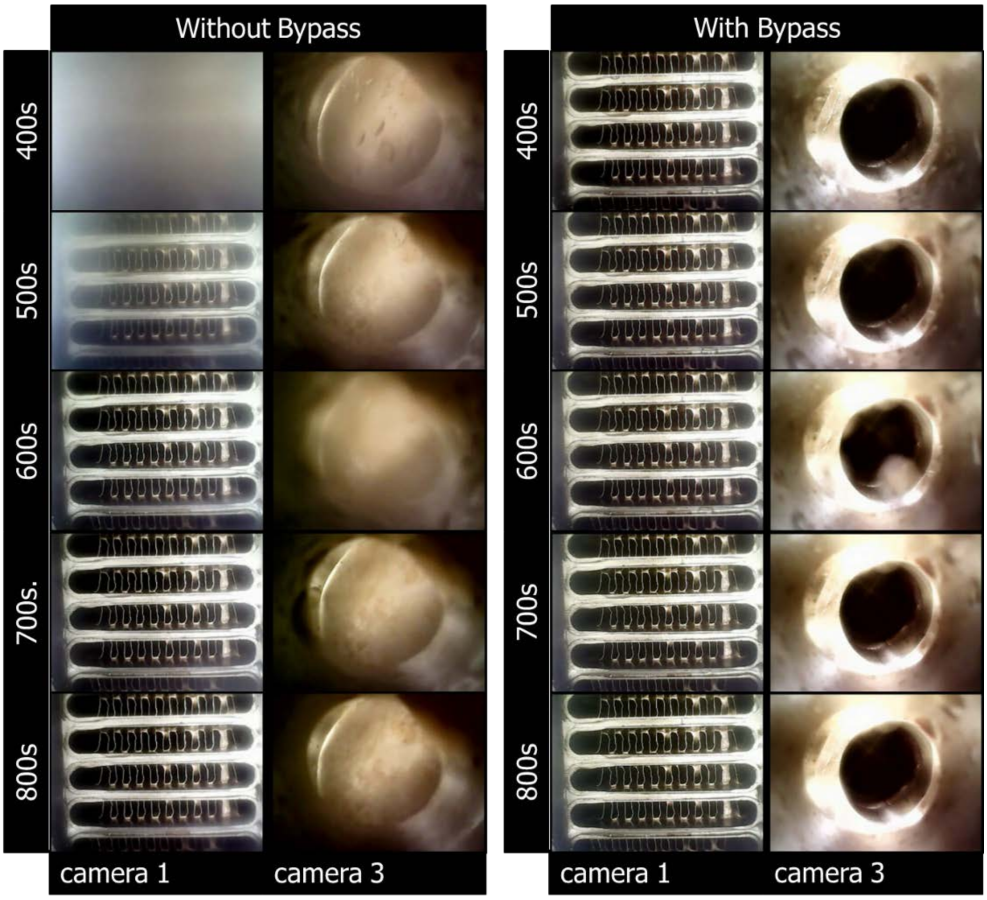

Fig. 12. Video frames comparing two tests performed without (left) and with (right) bypass activation in the second 500, 600, 700 and 800.

This reduction could be explained by analyzing the exhaust gas temperature at the LP EGR cooler outlet. Fig. 13 shows an increase of approximately 50ºC activating the bypass (with bypass) with respect to perform LP EGR in the standard configuration, that is, using the EGR cooler (without bypass). Besides this temperature increment, it can be observed how a reduction in exhaust gas heating time is noticed, temperatures beyond 50ºC are reached close to 200 seconds with the bypass configuration and after 600 seconds without the bypass configuration. This could explain the condensation reduction observed thorough the endoscopes cameras and also could justify how local temperatures beyond 40-50ºC contribute to leave the dew point and consequently avoid condensation conditions as could be observed in previous studies [19].

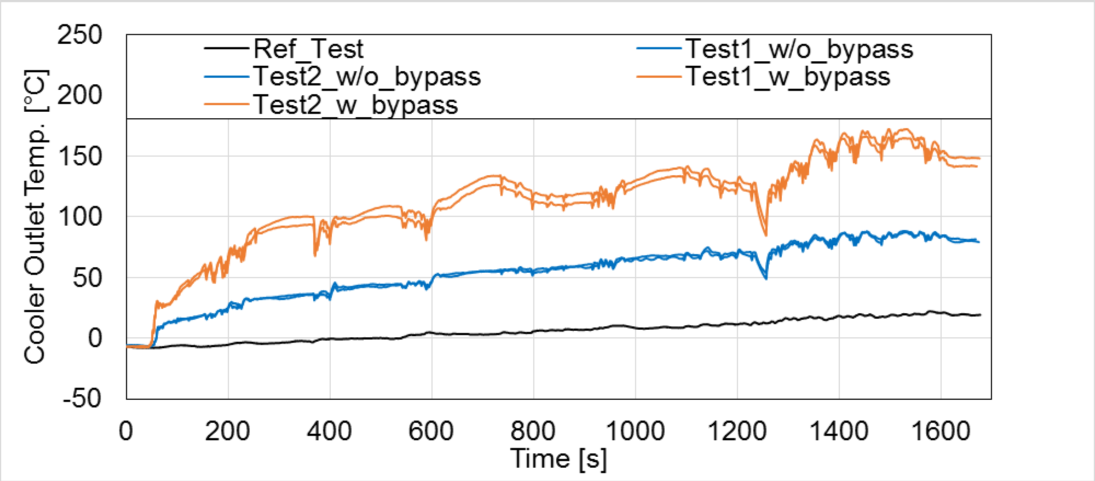

Fig. 13. LP EGR Cooler Outlet Temperature (Gas Temperature)

Chemical analysis of condensates

Apart from visualizing the condensation phenomenon inside the LP EGR cooler bypass by means of the endoscope cameras, a sample of approximately 15 milliliters of condensates was collected through the sampling point mentioned in the experimental setup and shown in Fig. 1 and 2.

A Thermal Gravimetric Analysis (TGA) and a Gas Chromatography – Mass Spectroscopy (GC – MS) analysis of the condensates collected during the experiments were performed. These analysis have the purpose of identifying which HC species are present in the condensates when the LP EGR is activated at cold conditions.

The TGA analysis evaluates the mass loss when a substance is heated at a given heating rate. For this experimental work, the characterization of absorbed species and mineral fraction is assessed. Fig. 14 shows the TGA analysis profile and its interpretation. Samples could be analyzed in an inert atmosphere (nitrogen) increasing the temperature until 800ºC and in an oxidative atmosphere (synthetic air) increasing the temperature until 1000ºC. The weight loss up to about 150°C is attributable to the water evaporation-desorption, the weight loss between 200 and 400°C is related to hydrocarbon desorption or decomposition of unstable functional groups (hydroxyls, carboxylic, carbonylic,…), the weight loss between 400 and 800ºC is related to decomposition of stable functional groups and the weight loss from 800 to 1000°C is related to the oxidation of the carbonaceous core [20].

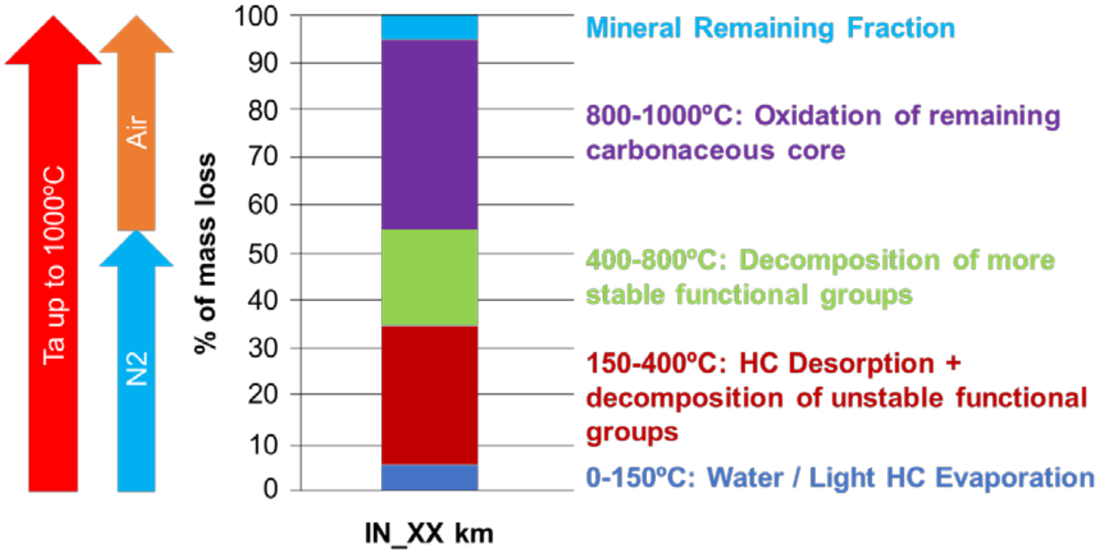

Fig. 14. Thermal Gravimetric Analysis (TGA) Profile

The TGA analysis performed in the condensates sample shows that approximately 98% of the weight loss is associated to water and light HC evaporation, and only the remaining 2% is related to decomposition of functional groups. That could explain the drops observed in Fig. 11 and Fig.12 which are similar to water drops but what after several working hours can produce deposits accumulations related with the remaining HC species identified.

The GC-MS analysis allows to determine different compounds, like aromatic molecules or aliphatic compounds that can be examined in a very precise way. The aim of this analysis is the quantification of C1 – C2 and C3 – C10 aldehydes with an approach to Volatile Organic Compounds (VOC´s).

Table 3 shows the results of the GC-MS analysis with the total amount of each hydrocarbon present in milligrams per liter (mg/l). The main species found in the condensates were aliphatic HCs, specially, C1 – C2 aldehydes (formaldehyde and acetaldehyde) with a 74% of the total hydrocarbons. C3 – C10 aldehydes are present in a 14% of the total hydrocarbons and the remaining 12% correspond to aromatics and other species. Regarding the volatile organic compounds, its presence is minimal and irrelevant in this study. Nevertheless, these results are in agreement with the HC species identified by Furukawa et al. [15], which reacting with other species could produce sticky fouling and deposits that could affect the normal operation of engine components as EGR valves and coolers.

Table 3. Gas Chromatography – Mass Spectroscopy (GC – MS) Results

	Total VOC´s	Total Aliphatic	Total Aromatic
Condensates Sample (mg/l → ppm)	0,4503	54,59	0,21287

Fouling Analysis

After 30 tests performing LP EGR at cold conditions, due to the condensation and the HCs depositions abovementioned, fouling conditions on the LP EGR line components are observed. Fig. 15 shows a sequence of the initial and final conditions of the LP EGR cooler and the bypass flap. It can be observed the fouling depositions on the surface comparing the reference test (without LP EGR) with four different tests performing LP EGR and activating or deactivating the bypass strategy. At the bottom of the figure it can be observed the final conditions of the surfaces, where it is possible to evidence fouling and deposits due to reactions between the chemical components in the exhaust gas. Furthermore, following the highlighted zone in the pictures recorded with the camera 3, it is possible to identify local points on the surface where fouling depositions has increased and accumulated after each test.

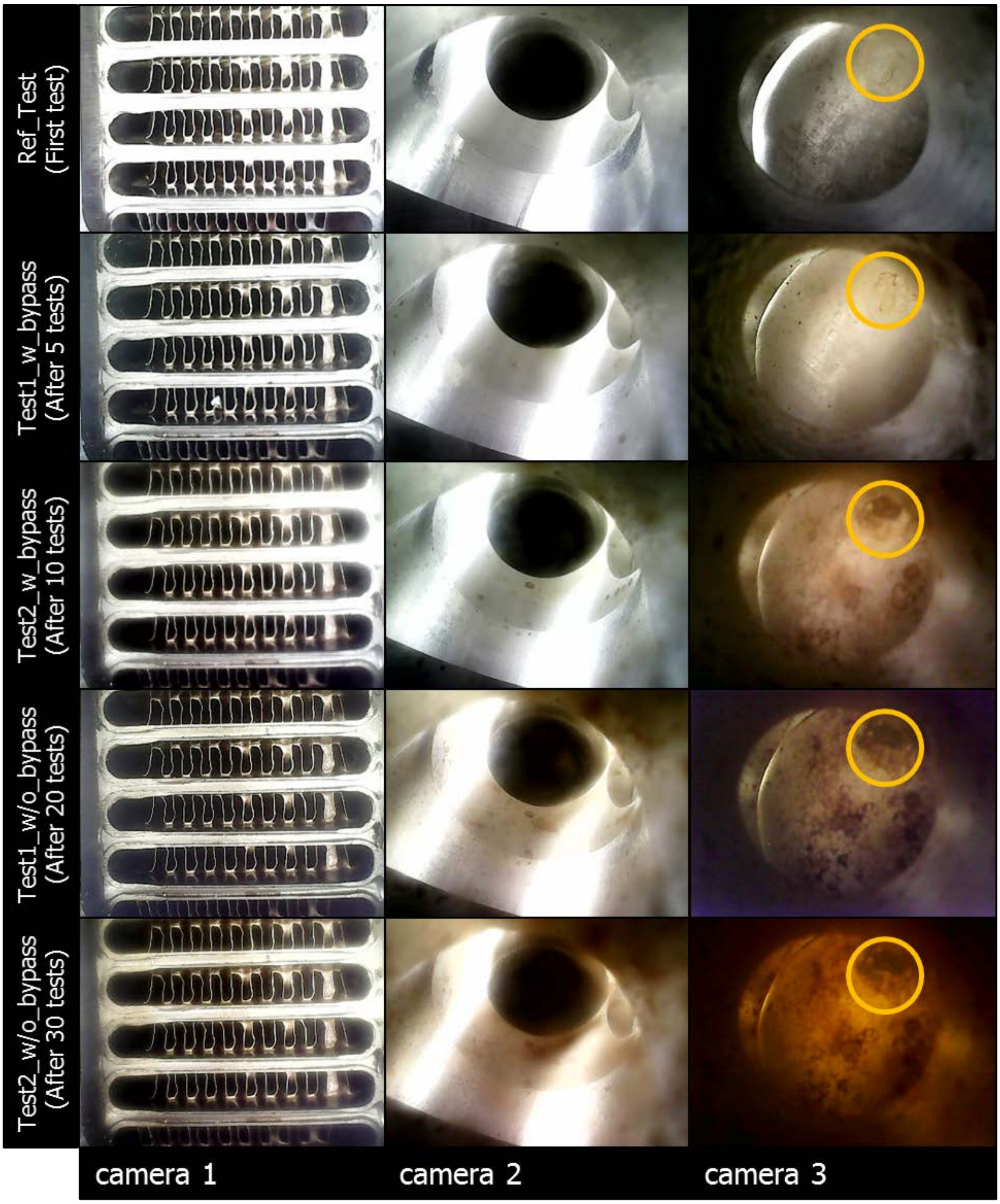

Fig. 15. Pictures of fouling conditions after tests performed with and without bypass activation

Fig. 16 shows a detail of the final conditions of the bypass flap. From the figure, it can be observed a golden layer of fouling, with apparently, burned depositions on its surface, probably from the accumulation of some species as could be observed in Fig. 15.

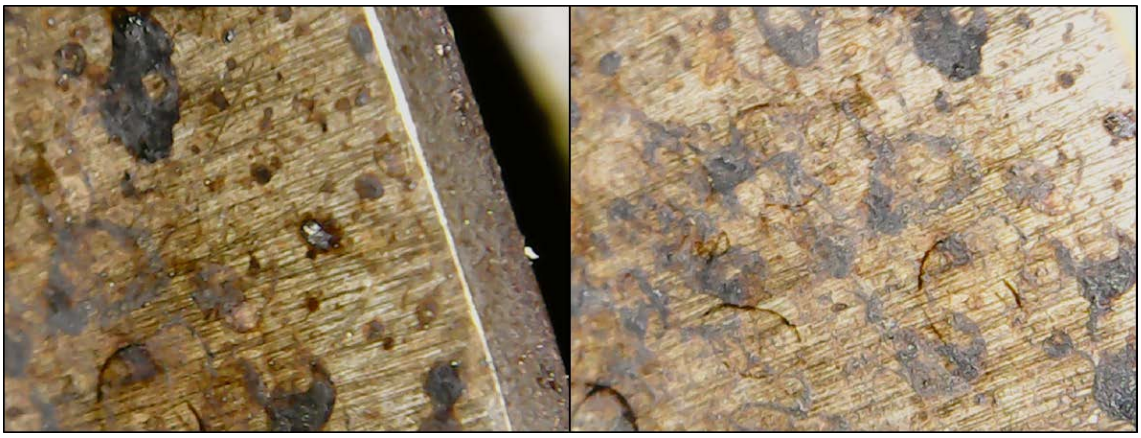

Fig. 16. Detail of fouling observed on the bypass flap

A similar golden layer of fouling at the LP EGR cooler outlet can be observed in Fig. 17. The initial condition of the LP EGR cooler before to start the experiments is presented at the left of the figure. The final conditions of the LP EGR cooler outlet after 30 tests performed at -7ºC and activating the LP EGR during the whole cycle is shown at the right of the figure. It can be appreciated a uniform fouling layer on the internal surface of the cooler that could be related with the condensates observed through the endoscope cameras in the previous section.

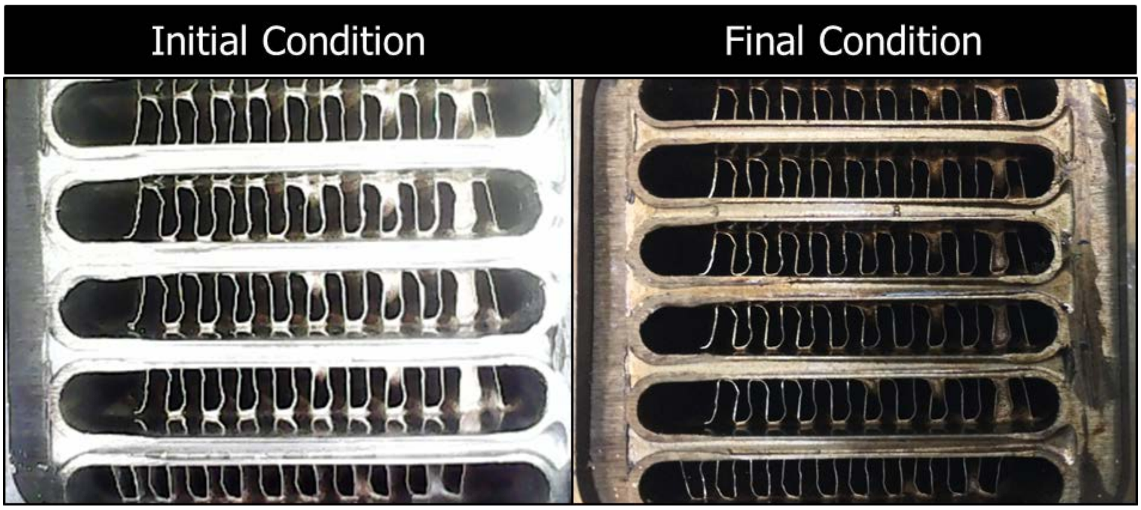

Fig. 17. Initial (left) and final (right) conditions of the LP EGR cooler

The chemical analysis and fouling deposits show the presence of mainly formaldehyde and acetaldehyde in its composition. These species are produced by an incomplete combustion that reacting with acid substances could produce the sticky soot observed in the experiments. The golden color associated to these deposits could be related with the HCs aromatics and other products of the combustion as was founded in the literature.

4. Conclusions

In this paper, the advantages and impacts of using a new concept of a Low-pressure EGR line fitted with a cooler bypass during engine cold operating conditions have been studied and analyzed. The impact in pollutant emissions, fuel consumption and engine warm-up process are presented. Besides, a chemical analysis to identify HC species due to condensation and fouling depositions has been performed.

The main objective of performing LP EGR at cold conditions is to reduce NOx emissions thanks to the oxygen concentration reduction of the working fluid in the combustion chamber. In this work, a noticeable NOx emissions reduction of approximately 60% with respect to a reference case without LP EGR has been achieved. On the other hand, one disadvantage of this strategy is an increment in CO and HC emissions during the first part of the warmup process, due to the combustion degradation. However, the reduction in the warm-up process period, when EGR is performed, could compensate that negative effect and produce a neutral effect in the accumulated values of these pollutant emissions, at the end of the cycle.

The purpose of the bypass implementation is to reach higher temperatures at the engine intake in order to accelerate the warm-up process (from the cold start until optimal working temperature). Activating the bypass system the engine intake temperature has been increased 30ºC, leading a CO emissions reduction of approximately 12%, if it is compared this case with bypass with the case where the bypass is deactivated and the exhaust gas passes through the EGR cooler. Although it is possible to reduce CO emissions by using the bypass strategy, comparing to the reference test, similar values has been reached in both cases. Taking the coolant temperature as a reference of the engine warm-up process, a reduction in time of approximately 60 seconds with the bypass activated and 100 seconds with the bypass deactivated have been achieved.

An additional parameter to take into account in this experimental work is the fuel consumption and the combustion efficiency. Any significant benefit or disadvantage could be observed in terms of fuel consumption. However, analyzing the combustion efficiency it was identified that the bypass strategy could improve the combustion temperature once the warm-up process has finished.

The second aim of this research work is the analysis and visualization of condensation and fouling phenomena produced by the LP EGR activation at cold conditions. It could be stated for this particular work (for an engine warm-up at -7ºC, activating the LP EGR from the engine cold start and using a bypass system for the LP EGR cooler) that the period where condensation is produced, that is, when the relative humidity is above one, could be reduced by activating the bypass in approximately 250 seconds. In addition, using the endoscope cameras was possible to observe how the fouling deposits increased after each test. These deposits have been analyzed chemically concluding that the main species produced in these experiments were aliphatic hydrocarbons, especially C1 – C2 aldehydes (formaldehyde and acetaldehyde). These species in reaction with acids and other HCs could produce sticky soot as the reported in other research works.

5. Acknowledgements

The authors thank to Juan Antonio Lopez for his contribution in the testing process. Authors want to acknowledge the support of “Programa de Ayudas de Investigación y Desarrollo (PAID-01-17) de la Universitat Politècnica de València”.

REFERENCES

[1] F. Millo, P. F. Giacominetto, and M. G. Bernardi, “Analysis of different exhaust gas recirculation architectures for passenger car Diesel engines,” *Appl. Energy*, vol. 98, pp. 79–91, 2012.

[2] J. Thangaraja and C. Kannan, “Effect of exhaust gas recirculation on advanced diesel combustion and alternate fuels - A review,” *Appl. Energy*, vol. 180, pp. 169–184, 2016.

[3] J. M. Desantes, J. M. Luján, B. Pla, and J. A. Soler, “On the combination of high-pressure and low-pressure exhaust gas recirculation loops for improved fuel economy and reduced emissions in high-speed direct-injection engines,” *Int. J. Engine Res.*, vol. 14, no. 1, pp. 3–11, 2013.

[4] J. M. Luján, C. Guardiola, B. Pla, and A. Reig, “Switching strategy between HP (high pressure)- and LPEGR (low pressure exhaust gas recirculation) systems for reduced fuel consumption and emissions,” *Energy*, vol. 90, pp. 1790–1798, 2015.

[5] Y. Park and C. Bae, “Experimental study on the effects of high/low pressure EGR proportion in a passenger car diesel engine,” *Appl. Energy*, vol. 133, pp. 308–316, 2014.

[6] J. M. Luján, H. Climent, S. Ruiz, and A. Moratal, “Influence of ambient temperature on diesel engine raw pollutants and fuel consumption in different driving cycles,” *Int. J. Engine Res.*, 2018.

[7] J. M. Luján, H. Climent, L. M. García-Cuevas, and A. Moratal, “Pollutant

emissions and diesel oxidation catalyst performance at low ambient temperatures in transient load conditions," *Appl. Therm. Eng.*, vol. 129, no. 2, pp. 1527–1537, 2018.

[8] V. Bermúdez, J. M. Lujan, B. Pla, and W. G. Linares, "Effects of low pressure exhaust gas recirculation on regulated and unregulated gaseous emissions during NEDC in a light-duty diesel engine," *Energy*, vol. 36, no. 9, pp. 5655–5665, 2011.

[9] J. R. Serrano, P. Piqueras, E. Angiolini, C. Meano, and J. De La Morena, "On Cooler and Mixing Condensation Phenomena in the Long-Route Exhaust Gas Recirculation Line," 2015.

[10] S. Moroz, G. Bourgoin, J. M. Luján, and B. Pla, "Acidic Condensation in Low Pressure EGR Systems using Diesel and Biodiesel Fuels," *SAE International Journal of Fuels and Lubricants*, vol. 2. SAE International, pp. 305–312, 2010.

[11] A. Warey, A. S. Bika, D. Long, S. Balestrino, and P. Szymkowicz, "Influence of water vapor condensation on exhaust gas recirculation cooler fouling," *Int. J. Heat Mass Transf.*, vol. 65, pp. 807–816, 2013.

[12] M. J. Lance, Z. G. Mills, J. C. Seylar, J. M. E. Storey, and C. S. Sluder, "International Journal of Heat and Mass Transfer The effect of engine operating conditions on exhaust gas recirculation cooler fouling q," *Int. J. Heat Mass Transf.*, vol. 126, pp. 509–520, 2018.

[13] M. Lapuerta, Á. Ramos, D. Fernández-Rodríguez, and I. González-García, "High-pressure versus low-pressure exhaust gas recirculation in a Euro 6

diesel engine with lean-NOx trap: Effectiveness to reduce NOx emissions," *Int. J. Engine Res.*, vol. 20, no. 1, pp. 155–163, 2019.

[14] P. Dimitriou, J. Turner, R. Burke, and C. Copeland, "The benefits of a mid-route exhaust gas recirculation system for two-stage boosted engines," *Int. J. Engine Res.*, vol. 19, no. 5, pp. 553–569, 2018.

[15] N. Furukawa, S. Goto, and M. Sunaoka, "On the mechanism of exhaust gas recirculation valve sticking in diesel engines," *Int. J. Engine Res.*, vol. 15, no. 1, pp. 78–86, 2014.

[16] F. Payri, P. Olmeda, J. Martín, and R. Carreño, "Experimental analysis of the global energy balance in a di diesel engine," *Appl. Therm. Eng.*, vol. 89, no. x, pp. 545–557, 2015.

[17] J. M. Luján, H. Climent, V. Dolz, A. Moratal, J. Borges-Alejo, and Z. Soukeur, "Potential of exhaust heat recovery for intake charge heating in a diesel engine transient operation at cold conditions," *Appl. Therm. Eng.*, vol. 105, pp. 501–508, 2015.

[18] F. Payri, A. Broatch, J. R. Serrano, L. F. Rodríguez, and A. Esmorís, "Study of the potential of intake air heating in automotive DI Diesel engines," *SAE Tech. Pap.*, no. 724, 2006.

[19] J. M. Luján, V. Dolz, J. Monsalve-Serrano, and M. A. Bernal Maldonado, "High-pressure exhaust gas recirculation line condensation model of an internal combustion diesel engine operating at cold conditions," *Int. J. Engine Res.*, 2019.

[20] C. Arnal *et al.*, "Characterization of Different Types of Diesel (EGR Cooler)

Soot Samples," *SAE Int. J. Engines*, vol. 8, no. 4, pp. 2015-01–1690, 2015.