The Effect of “Clean and Cold” EGR on the Improvement of Low Temperature Combustion Performance in a Single Cylinder Research Diesel Engine

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1. ABSTRACT
In the present paper, the effect of the clean and cold EGR flow on the performance of a diesel engine running under Low Temperature Combustion conditions is investigated by means of experimental tests on a single-cylinder research engine. The engine layout was “ad hoc” designed to isolate the effect of the clean and cold recirculated gas flow on the combustion quality. The results have shown the possibility to increase the EGR rate by EGR flow temperature reduction, with a decrement of both NOx and PM emissions, at the same fuel consumption, highlighting that the intake manifold temperature is the main factor affecting the engine performances.

2. INTRODUCTION
The next European legislation concerning passenger cars emission standards (EURO6) represents for the diesel engine a real challenge. As well known, the diesel engine has to guarantee a further simultaneous reduction of NOx and PM emissions, keeping low unburned gaseous emissions (HCs and CO). The Low Temperature Combustion (LTC) mode seems a suitable solution for a reduction of NOx and PM emissions, but its application is still limited in the low load and speed range of engine working map, due to the inadequate control of EGR-air-fuel premixing levels that influence the pressure rise, the particulate emissions and fuel consumption at high loads. At the same time, in order to have smokeless engines for any running condition, all future diesel engines will be equipped with Diesel Particulate Filters (DPF).

Starting from this scenario, new EGR layout concepts (named “long-route” or “low pressure”) were put under development in order to exploit the effect of the cleaner and colder flow at the exhaust of the DPF in the whole NEDC operating range. The combined use of the low pressure EGR layout (LP-EGR) characterized by clean and cold EGR flow and the conventional high pressure EGR layout (HP-EGR), could improve the potentiality of LTC in terms of pollutant emissions and fuel consumption, as already observed in [1]. From this point of view, it appears very interesting to analyze the effect on engine combustion of the two factors characterizing the LP-EGR flow: the cleanliness from particulate and unburned compounds and the lower temperature with respect to HP-EGR flow. To isolate the effect of both factors, it was necessary to use a research engine laboratory plant, in which all operating parameters are independently controlled. In the present paper, the effect of the clean and cold EGR flow on the performance of a diesel engine running under conventional and Low Temperature Combustion conditions is studied by means of experimental tests on a single-cylinder research diesel engine. The results evidence the stronger influence of the EGR temperature compared to the chemical composition of the recirculated flow, whose effect is, on the contrary, very negligible.
3. EXPERIMENTAL APPARATUS

The layout of the single cylinder engine was designed in order to control each operating parameters independently from the others [2]. Cylinder head is derived from the 4-cylinder Fiat 1.9 16V Multi-Jet production engine; it has been modified to work in single-cylinder mode. The engine configuration is illustrated in Figure 1 where the main engine characteristics are also reported.

![Engine Layout Diagram](image)

**Fig. 1 Intake-Exhaust engine layout and main engine characteristics.**

The above picture shows the EGR layout with the sampling line downstream the DOC+DPF system. Upstream the DOC+DPF element there is a by-pass line controlled by a three way valve in order to perform the tests with and without the catalyst filter, at the same pressure and temperature conditions. In this way, it is possible to isolate the effect of the two characteristics of the LP-EGR system with respect to HP-EGR one. The engine was fully instrumented for the measurement of typical indicated signals (cylinder pressure, energizing current, injection line pressure), while exhaust flow composition was characterized by means of a gas analysis bench and an AVL 415S smoke meter for particulate.

4. TEST METHODOLOGY AND SELECTED OPERATING POINTS

According to the aim of the paper, the tests were performed with three different layout configurations as listed in the following:

- Simulation of the “clean” and “cold” EGR flow of the Low Pressure EGR system, sampling the recirculating flow downstream the DPF and reducing its temperature by means of an EGR cooler (see Fig. 1). This arrangement of layout is indicated as CC-EGR (CleanCold-EGR);
- Recirculation of exhaust gas without cleaning and cooling the flow, adopting the DPF by-pass at the same exhaust pressure condition of the above simulation. This operating condition is indicated as DH-EGR (DirtyHot-EGR);
- Recirculation of exhaust gas without the flow cleaning using the DPF by-pass, but cooling the flow using the EGR cooler at the same temperature of CC-EGR case. This operating condition is indicated as DC-EGR (DirtyCold-EGR).

It must be pointed out that Low Pressure EGR system means an EGR flow sampling at low pressure conditions downstream the turbine, while in the present simulation all tests were performed at high pressure condition typical of exhaust manifold upstream turbine (see Fig. 1). Therefore the authors preferred to choose the acronym CC-EGR to avoid any confusion.
with the practical Low Pressure EGR systems. The three layout configurations described above were studied in two engine operating points:

- 1500 rpm @ 3.7 bar of IMEP;
- 2000 rpm @ 7 bar of IMEP.

The LTC tests were performed, for each configuration, approaching the maximum reachable EGR value within the following fixed limits on maximum cylinder pressure rise (combustion noise), fuel consumption and smoke upstream DPF:

- Maximum cylinder pressure rise of 80 bar/ms;
- Maximum fuel consumption increment of 5% with respect to EURO 4 standards;
- Maximum smoke level upstream DPF of 1.5 FSN.

LTC conditions were carried out with one injection per cycle; all other parameters were set equal to EURO 4 calibration values, except for the injection timing that was optimized in order to give the best compromise between the above described fixed limits. At light load, it is possible to realize LTC mode setting a very early injection, avoiding excessive combustion pressure rise [3]. At medium load, the injection management generally switches towards late injection (SOE close to the TDC), taking advantage of the in-cylinder gas cooling in the expansion stroke, to increase the ignition delay time and so the premixing level [4].

In the Table 2 the values of the parameters kept constant for each EGR layout, in both test conditions, are reported.

<table>
<thead>
<tr>
<th>Test point</th>
<th>Intake pressure [barG]</th>
<th>Exhaust pressure [barG]</th>
<th>Inject. pressure [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500@3.7</td>
<td>0.03</td>
<td>0.15</td>
<td>480</td>
</tr>
<tr>
<td>2000@7</td>
<td>0.21</td>
<td>0.43</td>
<td>974</td>
</tr>
</tbody>
</table>

Tab. 2   Engine operating parameters for all test conditions

5. COMPARISON AMONG CC-EGR, DH-EGR AND DC-EGR UNDER LTC MODE

Generally, differently from conventional diesel combustion mode, under LTC condition with one injection shot per cycle, the intake temperature reduction increases the ignition delay time and so a re-timing of the injection is required. In this case, differences in engine operating parameters and emissions are expected. For this reason, in the Figure 2, all engine operating parameters for the three EGR layouts are displayed. The corresponding cylinder pressure, injector energizing current and apparent rate of heat release for the three test configurations are plotted in the left diagram of Figure 3, while in the right diagram of the same figure the relative emission indexes are displayed.

The injection timing was properly chosen in order to reach a good premixing level without penalties in fuel consumption. The heat release curves for all three tests (Fig. 3, diagram on the left), confirm the premixed behavior of the combustion. This is highlighted by a start of combustion after the end of injection event and by the presence of cool flame phenomena that masks the timing of the high temperature combustion start [5]. Following the test methodology for LTC experiments, the reduction of EGR flow temperature by means of LP-EGR system, permits only a little increase of maximum attainable EGR rate within the prefixed limits on maximum pressure rise, fuel consumption increment and smoke level (see Fig. 2 for CC-EGR and DC-EGR layouts). At the two EGR layouts correspond, in turns, reduced EGR flow temperatures. In any case no further increment of injection timing was possible in order to improve the engine efficiency, but it must be considered that the combustion timing was already set very near to the TDC, so it is very difficult to gain further efficiency improvement from the injection timing optimization (see Fig. 3, left side).
The emissions measured at the engine exhaust, upstream DPF for the CC-EGR layout, are reported in the histograms of the right diagram of Fig. 3. As confirmed by a lot of past experiences, NOx values follow the EGR rate that remains the main driver for them [5].

As regard smoke emissions, authors think that the trend among all configurations is mainly dependent on the total oxygen mass trapped in the cylinder (consequence of lower intake temperature), notwithstanding the increase of EGR rate. Raw unburned compound emissions seem influenced by the presence of DOC in the CC-EGR layout, because they show a difference between the catalyzed layout with respect to the two others. This result should indicate that the recirculated fraction of HC and CO are only partially oxidized during combustion. However, this result is contrary to other results performed on real low pressure EGR system, where its adoption generally tends to increase the raw unburned emissions [1].

The results of the tests performed at 2000 rpm at 7 bar of IMEP are shown in the Figures 4 and 5, respectively. In the present test case, the adoption of LP-EGR layout has a more evident effect than at low load-low speed because the temperature drop inside the turbine is higher, also with the CC-EGR layout.
Fig. 4  Engine performance under LTC mode for all EGR layouts and for the test case 2000 rpm at 7 bar of IMEP.

In this case, since the engine cycle is characterized by a “retarded” combustion timing with respect to the TDC, the engine behavior was sensible to the intake manifold temperature reduction, so permitting an increase of maximum attainable EGR rate. This last is followed by a decrease of maximum pressure rise that allowed to a re-tuning of the injection timing with combustion timing closer to the TDC with respect to the DH-EGR layout test case (see both Fig. 4 and Fig. 5).

Fig. 5  Test case 2000 rpm at 7 bar of IMEP. On the left: cylinder pressure, injector energizing current and apparent rate of heat release. On the right: emission indexes for all EGR layouts.

The benefit of combustion advanced timing on thermodynamic efficiency was balanced by the negative effect of EGR on combustion efficiency, so any reduction of the indicated fuel consumption was measured (Fig. 4) changing the layout from DH-EGR to CC-EGR. In terms of engine parameters, the two EGR layouts with reduced EGR temperature, CC-EGR and DC-EGR, have shown the same results. Contrary to the fuel consumption values, the NOx and PM emissions were sensible to EGR temperature but not to the cleaner EGR flow, while
unburned compounds, especially CO, were affected by the presence of DOC upstream the EGR probe, confirming the trends observed in the previous test point.

As regard to the results carried out under LTC mode in both engine operating points, it is important to point out that the reached benefits on NOx emission together with the invariance of fuel consumption, depend on the adopted test methodology that is based on the maximization of the EGR rate under stable engine operating conditions. Therefore, for the same EGR temperature variation, it could be possible to manage the engine in order to keep the same EGR rate and so NOx emission, minimizing the fuel consumption by means of an appropriate injection re-tuning.

6. CONCLUSION

The present paper investigates the effect of the characteristics of the new “Low Pressure” EGR system, as the lower temperature and the greater cleanliness of the recirculated stream, on the improvement of engine performance under “Low Temperature Combustion” conditions. Three different EGR layouts were arranged in order to put in evidence the effect of the low EGR flow temperature and of the reduced amount of PM and HC/CO in the recirculated gas.

The experimental activity shows that the lower EGR temperature, typical of LP-EGR systems, leads to an increased density of the intake charge and to a consequent increment of the in-cylinder oxygen trapped mass. At the same time the results reveal that the EGR flow temperature reduction permits to increase the EGR rate. As a consequence, a decrement of both NOx and PM emissions, at the same fuel consumption was observed.

With a different engine management, the EGR flow temperature drop could be exploited in terms of fuel consumption reduction at same NOx/PM emissions or a compromise among all. To sum up, it appears that, in the adoption of LP-EGR systems, the most effective feature is the EGR flow temperature drop and the LP-EGR technology, characterized by cold and clean recirculating gas, proves to be very useful for the development of the future EURO 6 diesel engines.

7. References

Conference proceedings: