

The exhaust gas temperature control through an adequate thermal management of the engine

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Abstract. In general, the efficiency of the currently used aftertreatment solutions is strongly conditioned by the temperature of the exhaust gases. The regeneration capability of the aftertreatment equipment can be improved by intentionally rising the temperature of the exhaust gases. When using technologies like hybrid transmission, engine Start/Stop and cylinder deactivation, the temperature must be also intentionally increased in order to assure a high conversion rate. This paper presents the experimental research regarding to the effects of changing some engine parameters on exhaust gases temperature and performances of a compression ignition engine. The values of these parameters were modified as follows: the coolant temperature was modified 4 times (60, 70, 80 and 90 °C), the injection timing was modified 5 times (25, 20, 15, 10 and 5 °CA before top dead center), the injection strategy was changed 3 times (main injection, one and two pre-injection) and engine speed was modified in the range 1800-2800 rpm. The number of injections and the thermal regime modify the least temperature of the exhaust gases, with values of up to 44 °C. Yet, by the modification of the load, speed and of the injection advance greater temperature of the exhaust gases variations with values of up to 95°C.

1. Introduction

The temperature that the exhaust gases have when they come out of the engine is especially important in current vehicles. In recent years, the number of the auxiliary systems of the engine has dramatically increased. The working efficiency of some of this equipment / these technologies depends greatly on the temperature of the exhaust gases (T_{gas}) [1]. Others can influence T_{gas} . Among the equipment on whose efficiency depends T_{gas} can be enumerated: aftertreatment technologies and turbochargers. Among the technologies that influence T_{gas} can be enumerated: hybrid transmission, Start/Stop engine, cylinder deactivation, injection strategy and exhaust gases recirculation. Some of these last technologies improve the ecologic and economical performances of the engines, but they affect the efficient functioning of exhaust gas aftertreatment equipment and sometimes even of the turbocharging equipment [2], [3], [4], [5], [6].

In this context, it is imperiously necessary to maintain the high T_{gas} by an adequate thermal management. The T_{gas} depends on the heat distribution in the cylinder that has not been converted to mechanical work. A number of engine operating parameters influence T_{gas} . In this paper, is present the extent to which T_{gas} is influenced by: the coolant temperature, the engine speed, the number of fuel injections per cycle and the value injection timing. The experimental research was carried out on a CI engine, taking into account the following aspects: in a CI engine T_{gas} is lower than in a SI engine; the



time when the CI engine warms up (the length of time when the optimum heat is reached) is longer than for the SI engine; exhaust gases aftertreatment technologies are intensely applied in the CI engine, especially in the Euro 5 and Euro 6 engines.

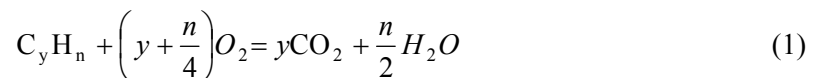
2. The importance of the temperature of exhaust gases

2.1. Exhaust gases aftertreatment technologies

The observance of the pollution standards by vehicles is also due to exhaust gases aftertreatment equipment. For vehicles to comply with Euro 6 pollution standard, it was necessary, among others, to use more intensively the exhaust gases aftertreatment technologies. With the increase in pollution restrictions, the complexity of exhaust gases aftertreatment systems has excessively increased. The temperature with which the exhaust gases are discharged from the engine cylinders has become a particularly important parameter. The efficiency of most aftertreatment solutions is conditioned by T_{gas} . In addition, the regeneration of this equipment can be done thermally, by applying the intentional increase methods of T_{gas} [1], [2], [3].

By using exhaust gases aftertreatment equipment, the concentration of hazardous pollutant emissions is diminished. Actually, this equipment modifies the chemical composition of the exhaust gases. Carbon monoxide, hydrocarbon, oxides of nitrogen (NO_x) and particulate matter are among the chemical compounds that are particularly harmful to human health and to environment and that are transformed into other less hazardous chemical compounds.

2.1.1. Three-Way Catalyst (TWC). In this aftertreatment equipment destined to SI engines chemical reactions to reduce NO_x emissions and oxidizing chemical reactions of carbon monoxide and hydrocarbon emissions take place simultaneously. The increase of the rate of reduction and oxidation reactions is achieved by means of precious metals such as: platinum, rhodium, and palladium. Some of the chemical reactions that occur in TWC are [7]:



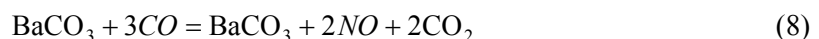
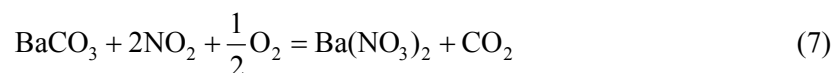
It has been observed that in the presence of metals with catalytic properties, carbon monoxide and hydrocarbon emissions oxidized in the presence of molecular oxygen resulting in water vapor and carbon dioxide. Similarly, carbon monoxide reacts with water vapor and carbon dioxide and molecular hydrogen result. The latter in the presence of oxygen transforms into water vapor. In the case of NO_x emission, it can be noticed that nitrogen dioxide is dissociated into nitrogen monoxide and molecular nitrogen. The speed of this chemical reaction inside TWC increases simultaneously with T_{gas} . Nitrogen oxide reacts with carbon monoxide and is transformed into molecular nitrogen and carbon dioxide.

The efficiency of the conversion of TWC depends on the exhaust gases temperature. Generally, the efficiency of the conversion is maximal when T_{gas} is greater than 400 °C. For this reason, some converters are equipped with an electrical resistance that heats T_{gas} , when is lower than 400 °C [8].

2.1.2. Diesel Particulate Filter (DPF). This has the role of physically restraining particulate matter emissions from exhaust gases. For particulate matter to oxidize (to become carbon dioxide), the exhaust gases must have a high temperature and a sufficient amount of oxygen. If these conditions are not met during engine operation, particulate matter are stored in the DPF. With the accumulation of these particles there is a considerable pressure drop of the exhaust gas in the filter, which affects the functioning of the engine. For this reason, filters that have the ability to regenerate are used, which means that the soot is oxidized and discharged from the filter. Usually, regeneration is done either thermally or chemically. The first method involves increasing T_{gas} by a thermal management of the engine (using the split injection and/or increasing the injection rate, so that part of the fuel will burn during the power process) or the additional fuel injection in the exhaust system using an auxiliary injector. By using this injector, T_{gas} may go up to 1000 °C near the filter [7]. The decision referring to the moment when the filter is regenerated is taken by the engine control unit (ECU) on the basis of the values received from the sensors (for example, from the two pressure sensors mounted on both sides of the filter). The second method may presuppose that by using the catalytic conversion the temperature at which particulate matter is oxidized will reduce. This can be done by replacing the presence of oxygen with that of nitrogen oxide. In the presence of this emission, the carbon particles can be oxidized at low T_{gas} .

2.1.3. Diesel Oxidation Catalyst (DOC). With CI engines besides DPF there is also a DOC, by which are oxidized, as in the case of TWC, the carbon monoxide and hydrocarbons emissions. This catalyst has also the role of forming the nitrogen oxide according to the following chemical reaction (5). Nitrogen oxide emissions are more harmful than nitrogen oxide emissions, but it contributes to DPF regeneration at lower temperatures than in the presence of molecular oxygen alone. The conversion of nitrogen oxide emission, according to the chemical reaction (5), is achieved with maximum efficiency at a temperature of around 300 °C [10].

2.1.4. Lean NO_x Trap (LNT). For CI Euro 6 engines, NO_x emissions were limited from 0.18 g/km to 0.08 g/km. This value cannot be met simply by using the exhaust gases recirculation system. For this reason, in these engines, besides DPF and DOC, an LNT is also used. Practically, this filter fulfils the functions of a DOC and additionally, it stores and reduces NO_x emissions. LNT usually contains active materials such as barium, platinum and rhodium. Generally, the (5), (7) and (8) chemical reactions occur in the storage phase [9], [10].



Thus, nitrogen oxide is oxidized and becomes nitrogen dioxide, at its turn reacting with barium carbonate to form barium nitrate. The storage phase is performed with an excess of air-factor $\lambda > 1$ and a T_{gas} of up to 500 °C, given that barium carbonate to form barium nitrate is unstable above this temperature value. The purge phase is carried out at a mixture with $\lambda < 1$ and the temperature can be increased up to 650 °C. The enrichment or the impoverishment of the mixture is made by the injection system, by using several injections per cycle and by a large post-injection advance [7], [9].

2.1.5. Selective Catalytic Reduction (SCR). For high-capacity CI engines, NO_x emissions are reduced by using the SCR technology. This technology contains: DPF, DOC, SCR catalyst and oxidizing

catalyst of the residual ammonia. In the exhaust gases exiting DOC is injected a solution which contains a mixture of water and urea. By injecting urea into the exhaust gases, it decomposes into ammonia and carbon dioxide. The SCR catalyst contains copper and iron. In SCR there are chemical reactions which have as final results molecular nitrogen and water vapor. Since there may be a concentration of ammonia that did not oxidize in SCR, an oxidation catalyst is also used. The oxidizing reactions of the NO_x by using SCR technology are not significantly influenced by T_{gas} , but the thermal conditions are maintained for DPF and DOC, which are part of SCR technology [9].

2.2. Turbocharging engines

The efficiency of SI and CI engines may significantly increase if they are supercharged with turbocharger or pressure wave compressor [11], [12]. These devices compress the intake air using the exhaust gas energy. The temperature with which the exhaust gases enter in this devices is important, or in other words, the enthalpy of the exhaust gases is important [13]. For this reason, the devices are mounted as close as possible to the engine exhaust outlet. At the same time, for example, T_{gas} that enter the turbine of the turbocharger must not exceed 1050°C , due to the limited thermal resistance of the rotor's material [7]. If this gas temperature limit is exceeded then turbines or liquid-cooled manifolds are made. After the exhaust gases come out of the devices, they enter, depending on the type and norm of the engine pollution, the equipment: TWC, DPF, DOC, LNT and SCR (figure 1). The exhaust gas temperature at the device outlet is lower than at the inlet. The decrease of T_{gas} is due to the energy delivered to the compressor to create the boost pressure.

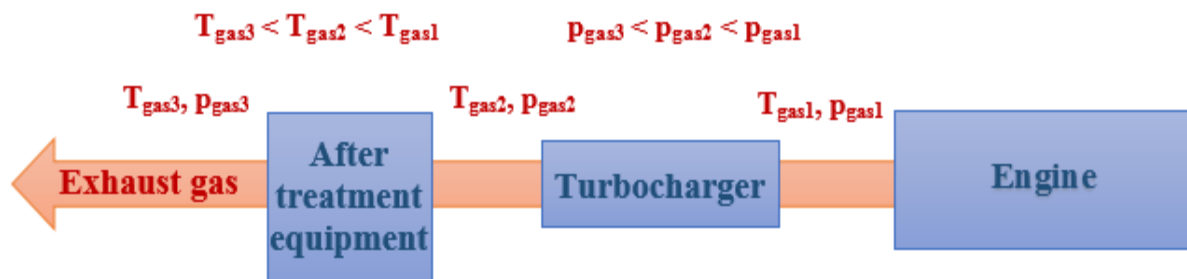


Figure 1. Turbocharger and aftertreatment equipment position – general version.

3. The control and influences on the exhaust gases temperature

According to the energy balance equation (9), the heat released in the engine cylinders (Q_{cyl}) is equal to the sum between the energy at the crankshaft (Q_{crank}), the cooling system heat loss (Q_c), the exhaust gas heat loss (Q_{gas}) and the residual heat evacuated by radiation (Q_r) [7].

$$Q_{\text{cyl}} = Q_{\text{crank}} + Q_c + Q_{\text{gas}} + Q_r \quad (9)$$

Through the combustion of the injected fuel per cycle, the heat created (Q_{cyl}) must be as big as possible. This means a minimum amount of incompletely burned fuel. Also for the engine efficiency to be higher, an important part of Q_{cyl} must be transformed into Q_{crank} . The exhaust gas temperature depends on their energy (Q_{gas}). But, the energy of the exhaust gas is considered to be energy loss according to the energy balance. As it could be seen in the previous paragraph, the efficiency of the exhaust aftertreatment equipment depends on the thermal energy of the exhaust gases. For this reason, the engine's performance is deliberately diminished to increase the environmental performance by means of the aftertreatment equipment. In other words, in order to achieve a satisfactory conversion of harmful pollutant emissions, it deliberately reduces Q_{crank} for Q_{gas} to increase. Taking into account the fact that turbochargers and pressure wave compressors recover a part of Q_{gas} .

A number of engine functioning parameters influence the T_{gas} . For example, a low engine speed increases the time when the heat transfer between *exhaust gases-engine parts-coolant-oil*. At the same time, a low speed implies a reduced number of cycles per time unit, which means a reduced Q_{cyl} value.

For example, according to some research conducted with a gasoline direct injection engine (GDI) functioning at a torque of 20 Nm, the following T_{gas} values were obtained: 318 °C at 1500 rpm and 478 °C at 2500 rpm [14]. In the case of direct injection engines, by the fuel injection strategy per cycle, T_{gas} can be controlled. A great injection rate and the use of split injection favor the burning of a part of the fuel during the power process, which increases the exhaust gas temperature, but with penalties on energy performance and economy (Q_{gas} increases and Q_{crank} decreases).

Exhaust gases recirculation system reduces NO_x emissions. The reduction occurs by reintroducing in the engine cylinders of a part of the exhaust gases. Thus, the amount of molecular oxygen in the cylinders reduces, which, by changing the combustion rate of the fuel, reduces the temperature per cycle. All these aspects (molecular oxygen reduction and the temperature at which the burning takes place) reduce the NO_x concentration.

The systems Start/Stop technology, cylinder deactivation systems and hybrid transmission, share a common feature which leads to the decrease of T_{gas} . All three systems interrupt the functioning of one or all of the cylinders in various situations during vehicle operation. During the interruption of the operation, no heat builds up inside the cylinder(s) so that the cooling of the engine parts increases. To resume the normal engine functioning takes place at a lower temperature regime which reduces T_{gas} and implicitly it affects the efficiency of gas aftertreatment equipment. In the case of power split hybrids vehicles T_{gas} can be considerably influenced. For this type of transmission, the vehicle can be propelled by both the engine and the electric motor. If the vehicle is propelled by the electric motor, then the internal combustion engine is switched off. For this reason, the internal combustion engine of such a vehicle functions for a longer period of time at low thermal conditions [2].

4. Experimental results and discussions

The experimental research was made at Transilvania University of Brasov, ICDT - Research & Development Institute. The CI engine used for experimental researches is an AVL single cylinder research engine (figure 2).



Figure 2. Compression ignition single cylinder engine mounted on single cylinder engine test bed.

During the research, the evolution of the T_{gas} was monitored with the engine running at the same speed and load, but at different values of the thermal regime (figure 3).

The test bed includes a temperature control equipment for cooling. With this equipment it was been possible that the thermal regime to be changed independently of the operating time of the engine. Thus in figure 3 it can be noticed that T_{gas} increased at the same time with the coolant temperature.

When the temperature of the coolant increases to 30 °C (from 60 °C to 90 °C) T_{gas} increased by 44 °C (from 435 °C to 79 °C).

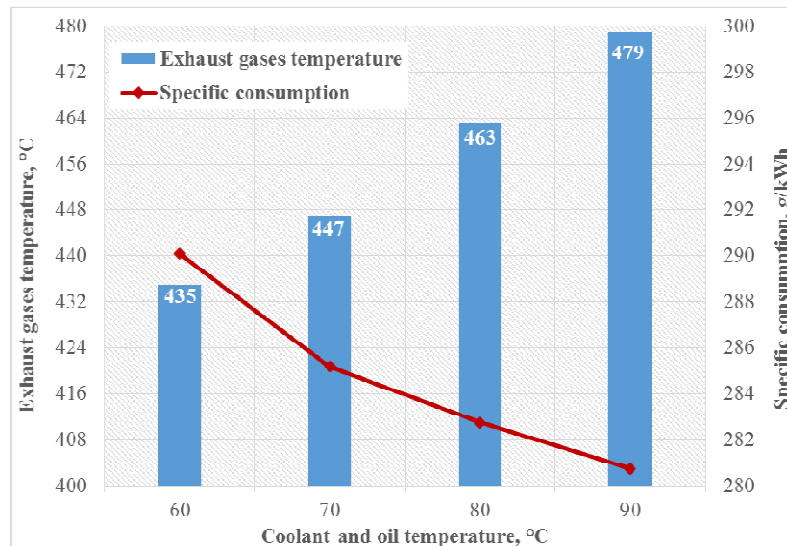


Figure 3. Engine thermal regime influence at 50 % load and 1800 rpm.

Also during the experimental research, the influence of the injection advance on T_{gas} and of some engine performance was analysed. The fuel injection is divided into three periods. Figure 4 shows T_{gas} evolution at various injection timing values. The injection strategy used at this stage involved a one-time injection of fuel per cycle. The advances of the injection, as it can be seen in the figure, were 25, 20, 15, 10 and 5 °CA before top dead center (TDC).

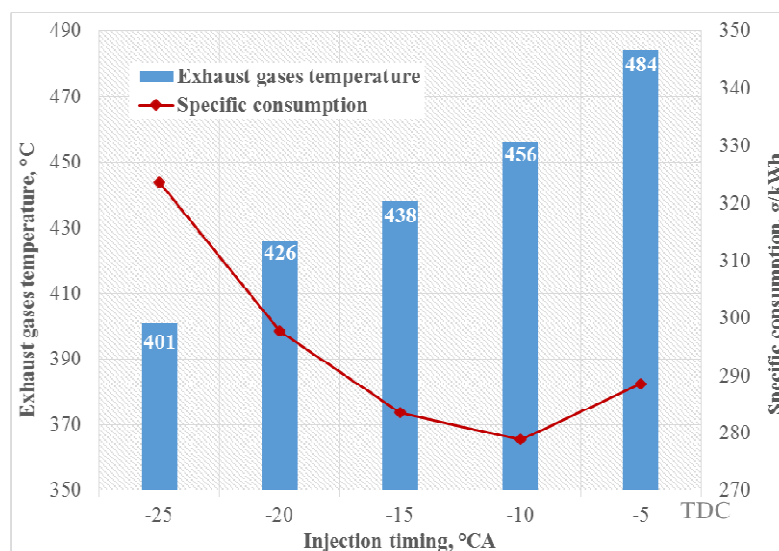


Figure 4. Injection timing influence at 50 % engine load and 2000 rpm.

It is noticed that by modifying the injection rate from 25 to 5 °CA maintaining the same engine regime (speed 2000 rpm and load 50%), T_{gas} changed by more than 80 °C.

The highest temperature rise, of 28 °C, occurred by changing the rate from 10 to 5 °CA. At a high injection timing, specific fuel consumption increases because the injection takes place when the

pressure cylinder is lower (figure 5), which worsens the combustion (Q_{cyl} reduces) and implicitly reduces T_{gas} (Q_{gas} reduces).

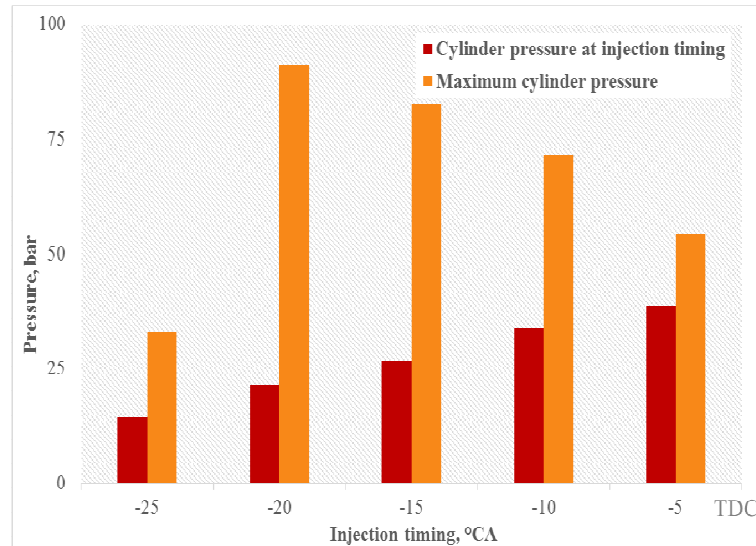


Figure 5. Cylinder pressure in relation with injection timing, at 50 % engine load and 2000 rpm.

Also, by injecting fuel well before the TDC, the maximum values of the pressure and the values of the cylinder temperature increase considerably (figure 5). Furthermore, the combustion being initiated earlier, the time and the surface through which the heat is transferred increases. Thus, T_{gas} reduction is due to the fact that there is a high temperature gradient and higher heat losses occur through the engine's parts (Q_c and Q_r increase). At 25 °CA the combustion process is strongly affected by the high value injection timing.

At low fuel injection advances the combustion process takes place mainly during the power process, at low pressures and temperatures. In such regimes, the soot oxidizing rate is reduced resulting in increased smoke emission. As can be seen in figure 6, at the injection timing of 10 °CA, a minimum fuel consumption and maximum power is obtained, but with high smoke emissions.

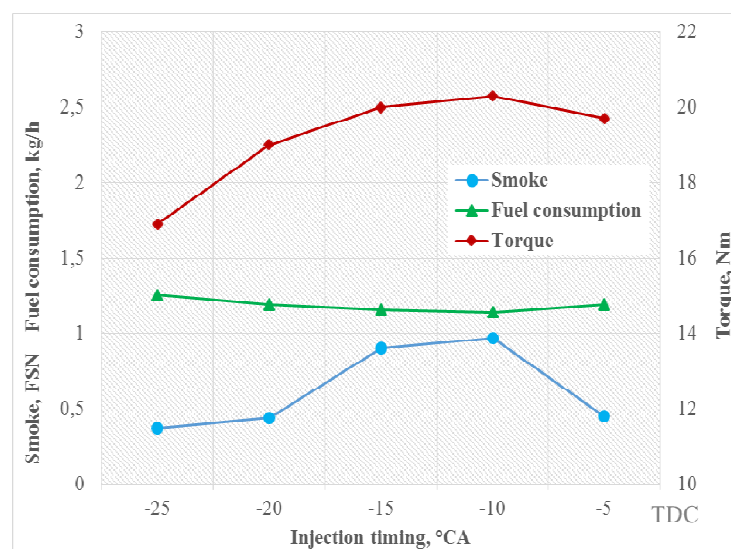


Figure 6. Engine performance evolution in function of injection timing, at 50 % load and 2000 rpm.

Figure 7 shows the influence of the number of injections on T_{gas} , with the engine functioning at full load (100 %). The fuel injection strategy per cycle was modified three times, as follows: main injection, one and two pre-injections.

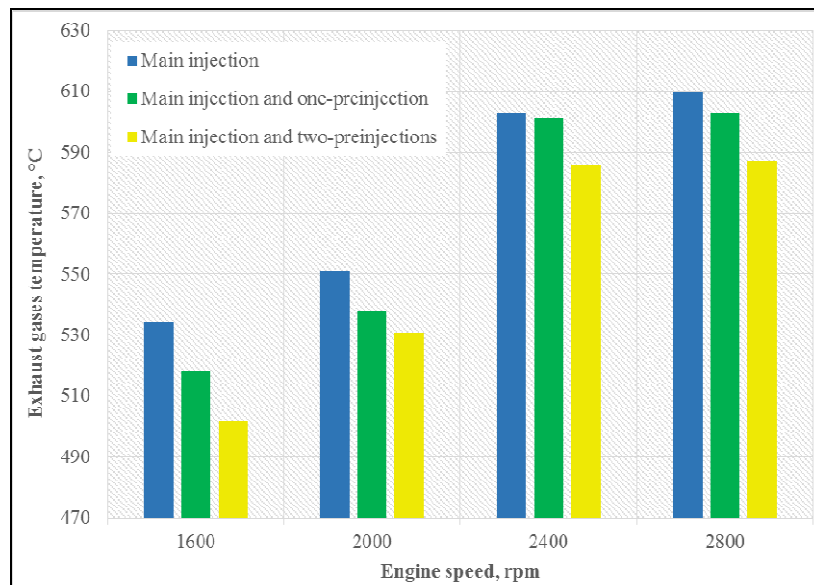


Figure 7. Exhaust gases temperature evolution at different fuel injection strategies (at engine full load – 100 %).

As it can be seen at each revolution, temperature of the exhaust gases decreased as the number of injections increased. The effects of preinjections produce effects similar to those of a big injection advance. It is noticed that, keeping constant the engine speed, temperature of the exhaust gases T_{gas} varies according to the number of injections by up to 32 °C. At the same time, it is noticed that by increasing the speed from 1600 rpm to 2800 rpm, T_{gas} increases by 76 °C (in the case of main injection cycles only) and 85 °C (for one / two pre-injections cycles).

5. Conclusions

Temperature of the exhaust gases is a parameter that has become especially important in the functioning of engines.

Start/Stop engine, cylinder deactivation and hybrid transmission are technologies that reduce T_{gas} . A reduced value can affect the efficiency of the aftertreatment equipments and turbochargers. Moreover, the regeneration of the aftertreatment equipments can be made thermally by an intentional increase of T_{gas} .

By the experimental research on AVL single cylinder engine a part of the functional parameters that bear an important influence on T_{gas} were identified. The effects of the changes were analyzed: injection advance, injection number, thermal regime, engine speed, and engine load. The number of injections (main injection, one preinjection and two preinjections) and the thermal regime (between 60 °C and 90 °C) modify the least T_{gas} , with maximal values of up to 32 °C, 44 °C, respectively.

Yet, by the modification of the speed (from 1600 rpm to 2800 rpm) and of the injection advance (from -25 to -5 °CA, at a constant speed of the engine) greater T_{gas} variations were obtained at around 80 °C. As for the load of the engine, by being modified from 50 % to 100 %, with the engine running at the speed of 2000 rpm, and the advance being -10 °CA, temperature of the exhaust gases increased by 95 °C.

Thus, it can be asserted that reducing the injection advance and increasing engine speed and load (injection pressure) an important growth of T_{gas} can be obtained, but possibly when diminishing the economic and ecological performance of the engine.

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