Compression ignition engine – solutions for reducing pollutant emissions

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Abstract. Due to the specific type of combustion in the compression ignition engines, the exhaust gases raise specific pollution problems, which implies the identification of specially adapted solutions for these types of engines. The increasingly stringent pollution standards worldwide have forced manufacturers to find more ingenious solutions for efficiently reducing the harmful impact of these pollutant emissions on the environment. The solutions for reducing pollutant emissions can be grouped into three broad categories, depending on the methods of action: a) solutions that use active methods that consist in optimizing the combustion process or engine construction; b) solutions that use passive methods that consist of retaining and neutralizing pollutant emissions along the exhaust pipe; c) solutions that seek to improve the composition of fuels to result fewer pollutant emissions. Regardless of the method used, the effect of the solutions for reducing pollutant emissions depends on the engine operating regime, to which we will pay proper attention.

1. Introduction

Every day, millions of vehicles using compression-ignition engines carry consumer goods and raw materials on highways all around the world. All these vehicles are an important part of the supply chain, thus playing an essential role for local, regional and global trade. At the same time, Diesel engines are widely used in both industrial and mining installations, factories and agriculture.

Despite the fundamental role that they play in the economic development of human societies, Diesel engines are associated with a number of negative effects on the environment and human health.

The objective of this article is to present the solutions adopted by the manufacturers of road vehicles to reduce the pollutant emissions generated by Diesel engines, so that these vehicles comply with the increasingly severe international pollution standards.

There are three sets of standards worldwide: US specific standards, Japan standards and European Union standards. Large Asian countries such as India and China have started to apply standards on pollutant emissions from motor vehicles, derived from European standards, only in the 21st century, as a result of increased vehicle fleets, and serious air quality problems, generated by this development.

Regarding to the European Union, the new pollution standards EURO 5 and EURO 6 impose much stricter restrictions on Diesel engines for particulate matter emissions and nitrogen oxide emissions. Thus, in the case of the EURO 6d-Temp standard (September 2019), compared to the EURO 4 standard, the maximum permissible limits for nitrogen oxides were reduced by 60% while the limits for particulate matter were reduced by more than 80% [1].

These new measures require car manufacturers to find more efficient ways to reduce pollutant emissions from Diesel engines.
2. Methods for reducing pollutant emissions generated by compression ignition engines

In the present article, we will focus on solutions for reducing the pollutant emissions generated by compression ignition engines. Due to the type of combustion that occurs in compression ignition engines (combustion of preformed and diffusive mixtures), the resulting emissions raise specific pollution problems, which implies the identification of solutions specially adapted to these types of engines.

From the point of view of the procedures used, the methods of reducing pollutant emissions in compression ignition engines, also known as Diesel engines, can be divided into the following categories:

a) Active methods aimed at reducing pollutant emissions by optimizing the combustion process and/or by constructive engine optimization;

b) Passive methods aimed at reducing pollutant emissions by neutralizing them on the escape route;

c) Methods to improve the quality of used fuels.

3. Active methods to reduce pollutant emissions

The active methods of reducing the pollutant emissions of Diesel engines mainly aim to prevent the formation of pollutants inside the combustion chamber, respectively to reducing them by optimizing the combustion process. International pollution standards regulate the maximum limits of four types of pollutants (HC - hydrocarbons, CO - carbon monoxide, NOx - nitrogen oxides, PM - particulate matter).

Experimental researches have shown contradictory influences of the different factors on these four types of pollutants, which is necessary to find compromise solutions that will ensure an efficient reduction of all 4 groups of pollutants.

3.1. Modification of fuel injection parameters

Injection parameters with direct influence on pollutant emissions are:

a) injection law (the amount of fuel injected, as a function of the rotation angle of the crankshaft);

b) the injection advance.

Figure 1. The effects of changing the injection law [2].
3.1.1. Modification of the injection law. The modification of the injection law can be obtained both by increasing the pressure at the injection and by using injectors with several holes with smaller diameter. A considerable effect of these changes is the reduction of particulate matter emissions by up to 27% – figure 1 [2]. Also, constructive change of the injectors by reducing the volume of the spray bag and prolonging the needle guide of the sprayer led to a reduction of HC emissions and a reduction of specific fuel consumption, under the conditions of increased power and torque up to 3% [2].

3.1.2. Modification of the injection advance. The injection advance has contradictory influences on nitrogen oxides (NOx), particulate matter (PM) and on hydrocarbon (HC) emissions. By reducing the injection advance, a reduction of NOx emissions, respectively of nitrogen monoxide and nitrogen dioxide emissions, is obtained, with the price of increasing the percentage of nitrogen dioxide from the total nitrogen oxides emissions – figure 2 [3].

Changing the injection advance in the case of Diesel engines has influence on the pollutant emissions even in the case of using alternative fuels, as it results from a study conducted on a single-cylinder CRDI (Common Rail Direct Injection) engine powered by both diesel fuel and two types of biodiesel fuels obtained from cooking oil – figure 3 [4].

As can be seen in figure 3, the level of nitrogen oxide emissions is significantly reduced by reducing the injection advance, while the level of smoke emissions remains almost unchanged.

Figure 2. The influence of the reduction of the injection advance on the emissions of nitrogen oxides [3].

Figure 3. The influence of injection advance reduction on nitrogen oxides emissions and on smoke emissions, for 3 types of fuel [4].
3.2. Exhaust gas recirculation

The Exhaust Gas Recirculation (EGR) system allows the re-entry of a part of the exhaust gases into the intake manifold. In this way, some of the oxygen required for combustion is replaced by combustion gases, which leads to the reduction of excess oxygen and the combustion temperature in the cylinder, and ultimately to the reduction of NOx emissions.

The main challenge facing EGR technology is to overcome the problem of exhaust gas flow repression and to optimize the flow of recirculated exhaust gases. Currently, the recirculation of the exhaust gases is carried out using a valve and a Venturi tube, mounted after the cooling system (EGR cooling tube) – figure 4.

![Figure 4. Exhaust gas recirculation [5].](image)

Following the studies on the influence of the quantity of recirculated exhaust gas (expressed as a percentage of the total quantity of exhaust gases), it was found that with the increase of the quantity of exhaust gas recirculated, the level of nitrogen oxide emissions decreases proportionally, the effect being more pronounced at the high loads – figure 5 [5].

![Figure 5. The effect of the quantity of exhaust gases recirculated on NOx emission [5].](image)

(a) 900 rpm; (b) 1500 rpm.
Figure 6. The effect of the quantity of exhaust gases recirculated on smoke emission [5].
(a) 900 rpm; (b) 1500 rpm.

As can be seen from figure 5, at high loads (75%) and high speeds (1500 rpm), with the increase in the quantity of exhaust gases recirculated from 0.6 to 10.1%, the reduction of NOx emissions is about 30% [5].

Contrary to the evolution of NOx emissions, smoke emissions increase significantly as the amount of recirculated exhaust gas increases – figure 6. The increase of these emissions is more pronounced at higher loads when the air/fuel ratio is lower and more sensitive to the influence of the quantity of recirculated exhaust gases. Therefore, it is advisable to avoid increasing the amount of recirculated exhaust gases at high loads [5].

3.3. Modifying the compression ratio
The study on a single-cylinder diesel engine, powered by a mixture of diesel and ethanol, showed that by increasing the compression ratio, an increase in the level of nitrogen oxides emission is achieved as a result of the temperature increase inside the cylinder, while the level of smoke emissions decrease more pronounced at lower loads [6] – figure 7.

Figure 7. The influence of the compression ratio on the nitrogen oxides and smoke emissions, for different loads of the diesel engine [6].
4. Passive methods to reduce pollutant emissions
The passive methods for reducing pollutant emissions mean using of devices that act as after-treatment of the exhaust gases. These devices include Diesel Oxidation Catalyst (DOC), Selective Catalytic Reduction (SCR) and particulate filters.

The use of these devices on Diesel engines leads to an increase in the final price of the vehicle, given the complicated technologies and the rare materials used in their construction. However, the efficiency of these devices can reach up to 90%.

4.1. Diesel Oxidation Catalysts
Diesel oxidation catalysts (DOCs) are catalytic converters designed especially for diesel engines and diesel equipment to reduce carbon monoxide (CO), hydrocarbon (HC) and particulate matter (PM) emissions – figure 8. Catalysts are simple, maintenance-free systems and are suitable for all types and applications of Diesel engines.

![Figure 8. The operating principle of the oxidation catalyst for the diesel engine [7].](image)

Modern catalytic converters are made from a honeycomb substrate, which is covered with a platinum catalyst, the whole assembly being packaged in a stainless-steel container.

The honeycomb structure has a high catalytic contact area with the exhaust gases. The pollutants in the exhaust gases are converted into carbon dioxide and water as they come into contact with the catalyst.

The effects of diesel oxidation catalyst (DOC) on diesel engine emissions have been studied by a team of researchers at Tsinghua University in Beijing, China, on a stand, for different loads, for two constant speed regimes using diesel fuel and B20 biodiesel [8].

The catalytic converter has been shown to be effective in reducing hydrocarbon (HC) and carbon monoxide (CO) emissions. Thus, a reduction of approximately 90 - 95% of CO and a reduction of 36 -70% of HC was obtained. Particular attention has been paid to the effects of the catalyst on the elementary fractions of carbon (EC) and fine particles (PM2.5) of organic carbon (OC) emitted by the diesel engine. PM 2.5 mechanical particles were analysed by thermal/ optical reflectance (TOR) method.

The results showed that by using the catalytic converter, the total emissions of carbon (TC), organic carbon (OC) and elementary carbon (EC) fractions were generally reduced. In the case of diesel fuel, emissions (TC) decreased by 22 - 32% after the catalytic converter, depending on the operating modes. The decrease (TC) was attributed to the decrease of (OC) by 35 - 97% and the emission reduction (EC) by 3 - 65%. At low loads, a significant increase of the ratio (OC)/(EC) of PM2.5 was observed after the catalytic converter [8].

Compared to diesel fuel, the effect of the catalytic converter on PM2.5 particulate emissions, in the case of B20 biodiesel, was a different one. At lower loads, a slight increase in the emissions of elementary carbon (EC) fractions was observed, but at the same time a significant decrease of the ratio (OC)/(EC) of PM2.5 after the catalytic converter [8].

4.2. Selective catalytic reduction systems
Comparing with spark ignition engines, Diesel engines cannot use trivalent catalysts to reduce CO, HC and NOx emissions, because NOx emissions cannot be reduced in an oxidizing environment such as diesel exhaust gases. Additionally, due to the fact that the combustion gases from diesel engines contain
mechanical particles (soot), this would clog relatively quickly the trivalent catalyst that has a fine ceramic cell structure.

Catalytic reduction systems (SCRs) allow the reduction of NOx emissions by creating a reducing medium on the escape route by injecting a reducing agent (ammonia, urea solution or alcohol) followed by the passage of the exhaust gas through a reduction catalyst – figure 9.

The SCR system involves the use of an installation that includes a special reservoir for the reducing agent and an injection system on the escape route, as well as two monitoring systems: one for the reducing agent level in the tank and the second for the NOx concentration level – figure 9. The efficiency of this system can reach up to 90%, under the conditions of an exhaust gas temperature between 180° C and 450° C, and in addition it can lead to a reduction of the fuel consumption equivalent to the consumption of reducing agent. In the case of the Euro 4 standard, the reduction agent consumption can be about 3 - 4% of the amount of fuel consumed, while for the Euro 5 standard, the reduction agent consumption can reach up to 5 - 7% [9].

Figure 9. The after-treatment system for combustion gases, with Selective Catalytic Reduction [9].

4.3. Diesel particulate filters
Particulate filters work according to a principle, similar to the vacuum cleaner principle, whereby the particles are trapped in a porous structure. This structure allows the filter to be cleaned later when the gas-dynamic resistance, due to the deposits, exceeds a certain value. The particle filter is mounted downstream of the catalytic reduction system (SCR) and the oxidation catalyst (DOC).

Since the 1990s, several constructive types of particulate filter have been developed, with good capture mechanisms (internal impact, interception and diffusion principle) and have been used different modes of regeneration. Through regeneration, the particulates accumulated in the body of the filter are oxidized with a production of carbon dioxide and water, after which the filter can be reused.

In order to evaluate the emission characteristics of the diesel engine equipped with particulate filter (DPF), a team of researchers from the Engineering College, China University, has studied particulate matter emissions on the test bench (PM) and gaseous emissions from a diesel engine complying with China II standard, equipped with particulate filter [10]. The mass and concentration for PM emission were analysed using a DLS7200 mass collection system.

The NOx, CO and hydrocarbon (HC) emissions with and without DPF were also quantitatively analysed using a MEXA-7100EGR emission chamber. The results showed that a particulate filter can have an efficient mass and concentration impact on PM emission. The mass capture efficiency of particulate matter (PM) was greater than 90%. Regarding the total NOx emissions, these were obviously
influenced by the particulate filter. However, the NO2/ NOx emission ratio was considerable higher with 10 - 30% compared to the situation without a particle filter [10].

5. Methods to improve the quality of used fuels

The composition of the fuel used for Diesel engines has had a permanent evolution, starting with the reduction of the sulphur content, with the purpose of eliminating the sulphur oxides from the exhaust gases and continuing with the use of additives having different functions: dispersant-detergents, anti-detонate, stability thermal or anti-corrosion.

The perspective of depletion of oil resources and the need to supplement these energy sources have led to the search and discovery of alternative fuels. The most known of these are the biofuels produced from bio regenerable sources, which produce less pollutant emissions after combustion and therefore they are more environmentally friendly.

After using several types of biofuels for two operating regimes of a Renault K9K P 732 engine with a cylindrical capacity of 1461 cm³, the following results have been registered – figure 10 [11].

As can be seen in figure 10, the quality of the used fuel has a direct influence on the level of pollutant emissions. Compared to the situation of the use of diesel fuel, in the case of the use of biofuel, in general, a reduction of all pollutant emissions can be observed for the two engine operating regimes (1000 rpm and 1500 rpm). The only exception is the carbon monoxide, which have generally increased by using biofuel for the two engine operating modes.

Contradictory evolutions of the level of NO emissions can be observed also, for certain biofuels under different operating regimes. This is the case of biofuels B20M5 and B20M10, for which higher NOx emissions are recorded, compared to the case of diesel fuel, at low speeds (1000 rpm), while the level of NOx emissions is lower compared to the case of diesel fuel, at the speed of 1500 rpm [11].

6. Conclusions

Realizing a synthesis regarding the current state of research in the field of reducing of pollutant emissions from the compression ignition engines, we can come with the following conclusions:

a. The problem of reducing pollutant emissions in Diesel engines is a complex one, given the composition of the exhaust gases and the contradictory effect of certain methods on the different components of the exhaust gases;
b. The solutions to reduce polluting emissions must constantly keep up with increasingly restrictive pollution standards. This is the reason why the reducing pollutant emissions remains a permanent concern of researchers in the field;

c. Increasingly complex pollution solutions lead to increased vehicle manufacturing costs, so identifying less expensive pollution solutions is one of the great challenges of the future.

7. References

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