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EFFECTIVE REDUCTION OF NO_X EMISSIONS OF MODERN MEDIUM SPEED DIESEL ENGINES

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Abstract

Good economy and high thermal efficiency of medium-speed diesel engines with direct fuel injection are very favourable characteristics in terms of energy conservation and combating global warming. Despite favourable fuel consumption and high efficiency, high emissions of nitrogen oxides (NO_X) and particulate matter (PM) are a major problem researchers working on diesel engine development must address. Certainly the biggest challenge today is to make a compromise between optimal nitrogen oxide (NO_X) and particulate matter (PM) emissions. Today, nitrogen oxide (NO_X) reduction techniques are widely accepted and based on a combination of diluting in-cylinder air charge with a certain amount of exhaust gas, known as exhaust gas recirculation (EGR), and exhaust gas after-treatment using various sophisticated techniques. Results of the influence of the exhaust gas recirculation (EGR) on the emission of nitrogen oxides (NO_X), obtained by experimental research on a medium-speed diesel engine are presented in this paper.

Keywords: diesel engine; NO_x emission; exhaust gas recirculation (EGR); particulate matter (PM); Euro standards.

1. Introduction

Development of modern motor vehicles is entering a phase that inevitably leads to the development of propulsion systems that, from an environmental point of view, offer a far better characteristics then conventional internal combustion engines. Today, great emphasis is placed on hybrid drives and fully electric drives, which are propulsion systems with very low or zero pollutants emissions locally (at the place of exhaust gases emission) [1]. However, the infrastructure network that would enable unlimited use of vehicles with such drives, primarily the electric ones, is not developed even close enough to compete with conventional drives that use liquid and gaseous hydrocarbon fuels. This is especially evident in the road transport of goods over long distances [2]. On the other hand, gasoline engines with modern systems of fuel supply, ignition and after-treatment of exhaust gases show a great potential in terms of reducing hydrocarbon fuels consumption and pollutants emissions in exhaust gases [3].

The use of diesel engines in road vehicles in urban areas has a declining trend, primarily due to increasingly stringent requirements with regard to the permitted concentration of NO_X and particulate matter (PM) in the air.

Effective diesel engine performance and low fuel consumption still keep the diesel engine at the forefront as power unit for trucks and other commercial vehicles.

The combustion process in diesel engines is not "ideal" thus in addition to the products of complete combustion (carbon dioxide CO_2 and water vapour H_2O) in the exhaust gases there are also other toxic components that are released into the atmosphere. Harmful products are carbon monoxide (CO), unburned hydrocarbons (CH), nitrogen oxides (NO_X) and particulate matters (PM) [4], [5]. In higher concentration particulate matters form a visible smoke. All these harmful substances have strong impact on the local environment and the health of the population. According to the World Health Organization (WHO), air pollution poses a major risk to human health [6]. Therefore, standards have been introduced that limit the allowable amounts of individual components in exhaust gases. Reducing the emission of pollutants in a modern diesel engine is very complicated and is performed by targeted corrections of the combustion process in the engine cylinder and by the use of complicated equipment for subsequent exhaust gas after-treatment outside the engine cylinder. Exhaust gas after-treatment equipment, in addition to the price, also has a negative effect on the effective performance of the engine due to difficulties in working fluids exchange processes and constant changes in the control parameters of the engine in order to maintain the required operating conditions.

In this paper, emphasis will be placed on reduction of NO_X emissions in diesel engines, by applying exhaust gas recirculation (EGR). The reason why NO_X was chosen is that NO_X is a very problematic toxic component of diesel engine exhaust emissions. Therefore the engine designers pay great attention to this component in terms of its greater reductions in exhaust gases.

2. Formation of nitrogen oxides in diesel engines and ways of their reduction

From the moment it was established that a significant level of atmospheric pollution by engine exhaust originated from NO_X emissions, a very intensive study of the formation of nitrogen oxides in the engine has begun. The aim of these researches has been to consider the mechanisms of formation of these components, in order to find out about the possibility of influencing this mechanism and consequently reducing the corresponding component and reduce the total NO_X (NO and NO_2) emissions. There are three general mechanisms of NO_X formation: as a consequence of rapid reactions in the combustion process, as a consequence of the presence of nitrogen in the fuel and as a consequence of heat. Considering the amount of NO_X emitted, the most interesting mechanism is thermal, which occurs as a consequence of high temperatures in the engine cylinder during the combustion process. Chemical reactions take place according to the known Zeldovich mechanism of chain chemical reactions [1], [3].

In addition to the peak temperature in the engine cylinder, other thermodynamic parameters, combustion rate, and retention time of gases at high temperatures are of great importance. The composition of the air/fuel mixture, expressed through the coefficient of excess air, significantly affects the value of NO_X emissions. The highest NO_X generation takes place in the zones of values of the coefficient of excess air 1.1 to 1.2. Smaller or higher values of the excess air coefficient lead to a reduction in NO_X emissions. Accordingly, it can be concluded that temperatures and the amount of oxygen (O_2) are two key parameters for creating high NOx emissions. Both parameters are present in diesel engines, which inevitably classifies them as major environmental pollutants in relation to NO_X emissions [7].

European Union legislation defines the permitted emission of NO_X for diesel engines and it is very strict. The permitted values for NOx emission pose major problems for engine manufacturers in terms of achieving those values. The trend of decreasing permissible NO_X values emitted by diesel engines (when operating in standardized driving conditions) in the period from the introduction of these regulations to the present day is shown in Figure 1.

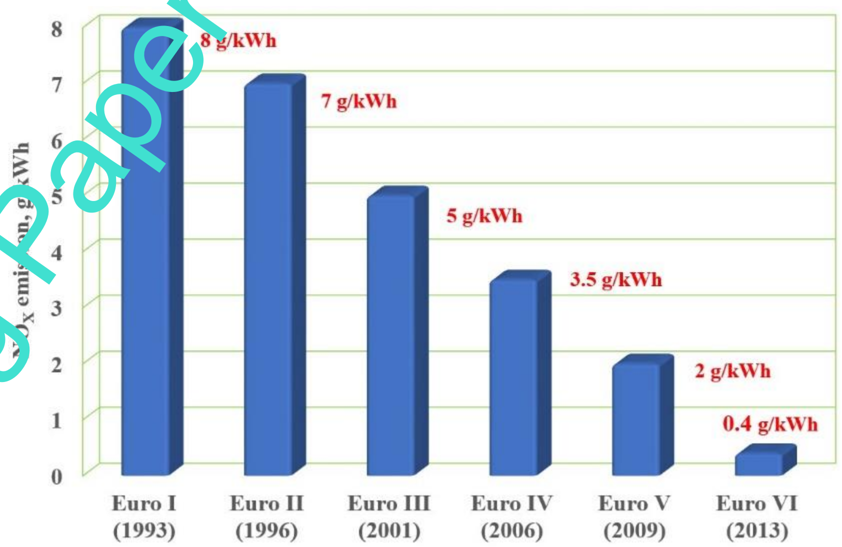

Fig. 1. Euro standards of NO_X emission for heavy-duty vehicles

Figure 1 shows that from the period of the Euro III standard (2001) until the introduction of the Euro VI standard (2013), the permitted values of NO_X emission were reduced by 92%. This led to large investments in diesel engine research with the aim of achieving the legal limit of NO_X emissions.

By analysing the effects of formation of NO_X in diesel engines, it can be concluded that there are a large number of ways to influence the combustion process itself to reduce NO_X emissions. However, it should always be kept in mind that certain measures could have negative effect on other pollutants emission, primarily particulate matters (PM). Consequently, the following approaches are most often used today in order to reduce NO_X emissions in modern diesel engines:

- One approach involves acting on the combustion process itself. This approach is made possible primarily due to the development of fuel supply systems, engine supercharging systems and engine control systems. In this part, high pressure multi-stage injection, controlled ignition of the mixture by varying the pre-injection angle, control of turbocharging system according to the engine operation mode and exhaust gas recirculation (EGR) are applied today. Of course, the use of alternative fuels as options to reduce NO_X emissions should be mentioned here [1], [3], [8].
- Another approach involves acting on the exhaust gases coming out of the engine cylinder. This approach involves installation of the additional devices that reduce the emission of combustion products by appropriate chemical transformations. The biggest problem is that not all harmful combustion products are treated in the same way, which requires a larger number of components for the subsequent treatment of exhaust gases. Absorption catalysts and selective catalysts are used to reduce NO_X emissions. Selective catalysts can be passive or active. Today, active selective catalysts show a dominant presence, primarily due to efficiency and service life.

No matter which approach is chosen, due to the specific engine operating conditions and the number of harmful combustion products, no approach alone meets the objectives in terms of environmentally acceptable exhaust emission. Vehicle engine operation is a combination of stationary and transient operating modes. Transient operating modes are very common in engine operation and very unfavourable in terms of exhaust emissions. Consequently, a combination of both approaches is used today to meet the NO_X emission requirements. In this paper, attention will be paid to exhaust gas recirculation (EGR), which can independently reduce NO_X by up to 50%, while in combination with exhaust gas after-treatment it meets very strict requirements set by current standards [1], [5]. The scheme of exhaust gas recirculation (EGR) system implemented in modern supercharged diesel engines is shown in Figure 2. This system assumes that the exhaust gases are taken before entering the turbine and conducted through the valve into the intake system after the compressor. For better results, the exhaust gases are cooled in the exhaust gas cooler before entering the intake system.

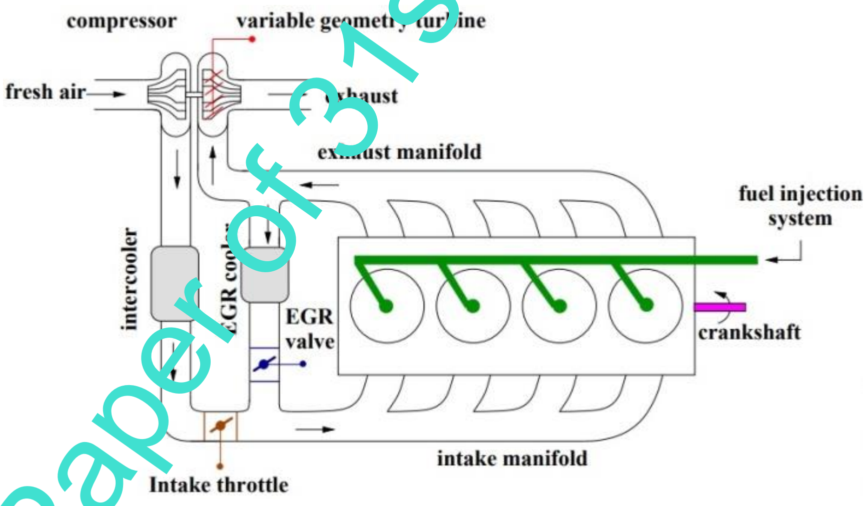

Fig. 2. Scheme of IC engine with high pressure EGR circuit [9]

If exhaust gases are added to the working cycle by the recirculation system as in Figure 2, a certain amount of fresh air is pushed out of the intake and replaced by an equivalent amount of exhaust gases. The consequence of this is a “dilution" of the fresh air in terms of O_2 content, and ultimately a reduction of the amount of available active oxygen that could be used in combustion process. Since the amount of fuel injected into the cylinder must remain constant, for a given power and torque, the reduced mass of air available for combustion reduces the O_2 concentration leading to a reduction in combustion rate and lower mean temperature of working cycle [1]. It is this reduction in available O_2 that can significantly reduce the level of NO_X emissions in diesel engines. On the other hand, the exhaust gases that participate in the combustion process absorb part of the heat, thus reducing the temperatures in the combustion process and consequently reduce NO_X emissions.

The analysis of NO_X emission, obtained by experimental measurement on a particular medium speed diesel engine operating at stationary modes, will be presented below. Of course, this effect is very difficult to isolate and to observe only the impact on NO_X emissions without compromising the emissions of other pollutants.

3. Experimental research and results analysis

The results used in this paper are obtained by testing one supercharged medium-speed diesel engine on the engine testing bed. Engine testing was carried out in accordance with the European Stationary Cycle 13-Mode Emissions Test (ESC). Only the results that are of interest for the purpose of this paper was used. All the results were obtained in accordance with the control criteria defined by the engine manufacturer, using original engine control unit (ECU). The basic data of experimental engine are given in Table 1.

Engine	6 cylinder, 4 stroke diesel engine
Maximum power	362 kW
Maximum torque	2237 Nm
Injection system	Cummins HPI
Turbocharging system	Variable Geometry Turbocharger
Exhaust Gas Recirculation (EGR)	High-Pressure Loop

Table 1. Experimental engine data

Characteristics of the engine torque and power as a function of the engine load, recorded during the engine operation in stationary modes, are shown in Figure 3. The full throttle engine power and torque is represented by a 100% load line. Other values of engine loads were selected to cover normal engine operating range.

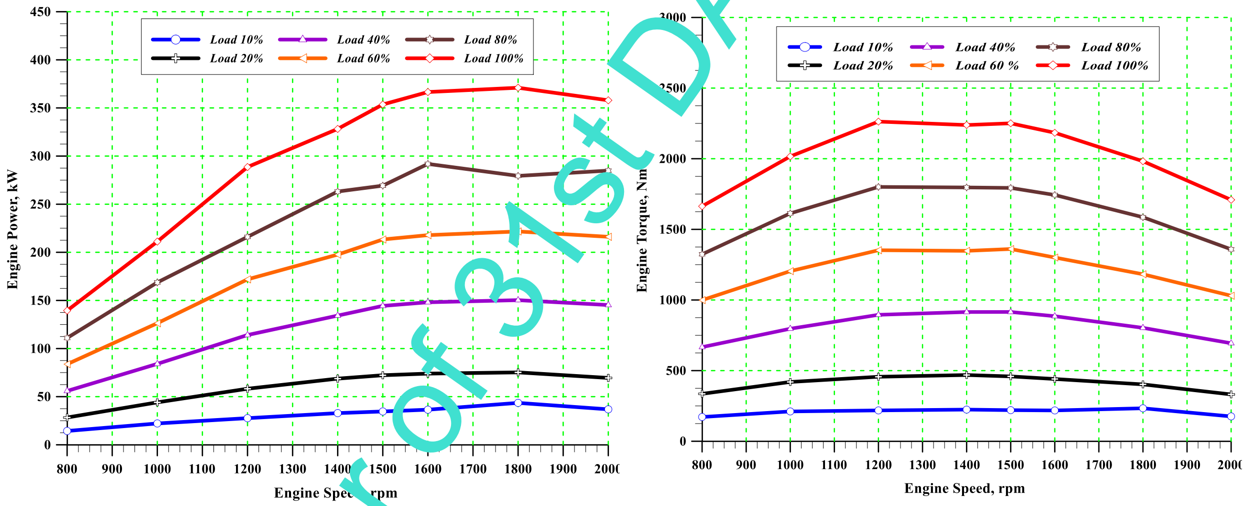

Fig. 3. Engine power (left) and torque (right) characteristic as a function of engine load

Engine load is defined as [10]:

$$Engine\ LOAD\ (\%) = \left(\frac{current\ fuel\ flow}{peak\ fuel\ flow\ as\ a\ function\ of\ rpm}\right)\left(\frac{1}{\frac{BARO}{29{,}92}\cdot\sqrt{\frac{298}{T_{amb}+273}}}\right)\cdot 100\ \% \quad (1)$$

where BARO is barometric pressure (inHg) and T_{amb} is ambient temperature (°C).

NO_X emissions were measured using a heated chemo-luminescence detector. The results of NO_X emission measurements with engine running in stationary modes are shown in Figure 4. It should be noted that, for the sake of comprehensibility, only a part of measured data was used in the analysis. The data was selected to cover the area of low, medium and high speed engine operational regimes.

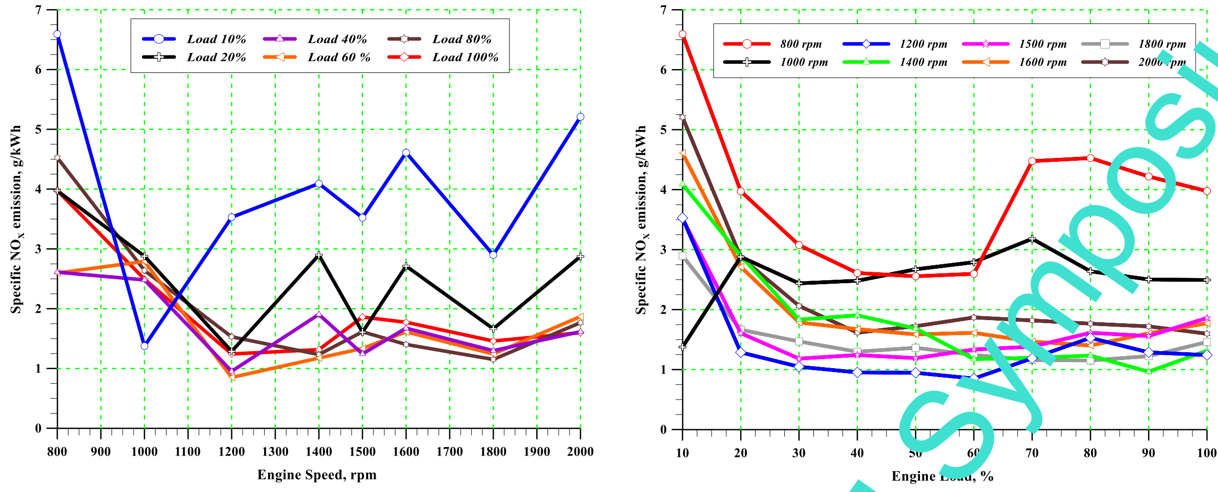

Fig. 4. NO_X emission as a function of engine rpm (left) and emission NO_X as a function of engine load (right)

Calculation of instantaneous exhaust gas recirculation rate is done using measured value of CO_2 emission, by following equation [1]:

$$EGR\ Rate\ (\%) = \left(\frac{CO_{2,Intake} - CO_{2,Background}}{CO_{2,Exhaust} - CO_{2,Background}}\right) \cdot 100\ \% \tag{2}$$

The results of the achieved exhaust gas recirculation rate are shown in Figure 5.

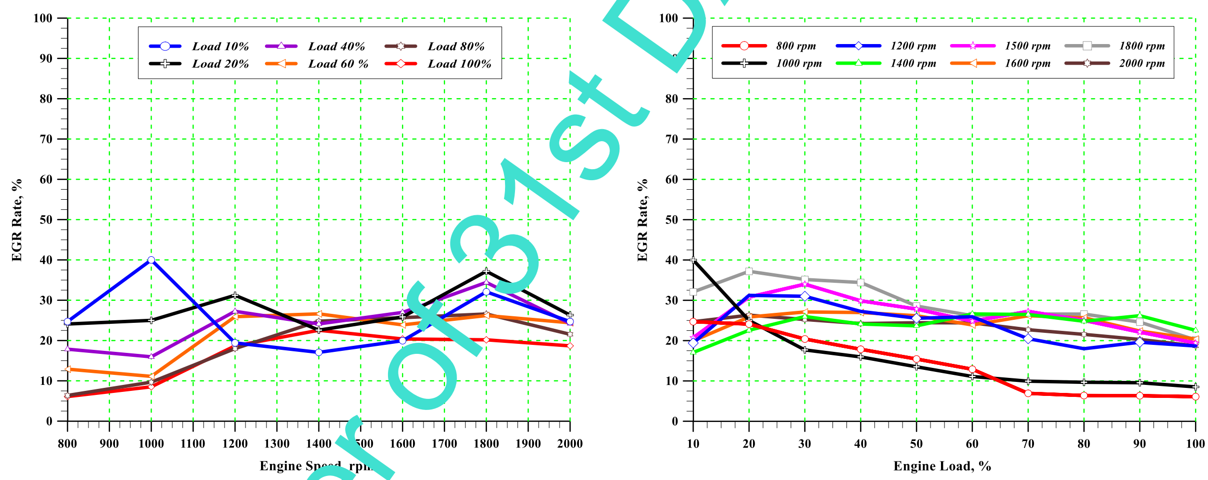

Fig. 5. EGR Rate as a function of engine rpm (left) and EGR rate as a function of engine load (right)

By analysing the results shown in Figure 4, increased NO_X emission can be observed for low engine speeds and loads regime. This is quite problematic due to the fact that this engine operational regime is mainly used in urban areas with heavy traffic condition. Accordingly, a vehicle equipped with this engine would be a significant source of local pollution. In general, lower engine speeds combined with lower loads prolong the duration of the combustion process and result in increased NO_X emissions. Looking at the Figure 5, exhaust gases recirculation rate in this operational regime did not increase significantly, primarily due to the threat of increase of particulate matter emissions, fuel consumption and disruption of combustion process by adding additional exhaust gases. Consequently, an additional increase in the exhaust gas recirculation rate in this engine operational regime is not justified. The medium engine speed operating range (1200 rpm to 1800 rpm) shows a fairly uniform NO_X emission, both in the case of a variation in the engine speed and in the engine load. It can be noticed that NO_X emission is maintained at a fairly uniform exhaust gas recirculation rate, which is considerably different in relation to lower engine speed and load regimes.

At engine speeds above 1800 rpm NO_X emissions begin to increase slightly as the exhaust gas recirculation rate begins to decrease. The reason is increased particulate matter emissions and demands for a more favourable engine power characteristic. It is interesting to note that the trend of changing exhaust gases recirculation rate is divided into two areas: the area of low engine speed (up to 1200 rpm) and the area of medium and high engine speed (above 1200 rpm).

The reason for this phenomenon should be sought in the compromise between NO_X emissions, particulate matter emissions and fuel consumption. Consequently, the analysis of NO_X emissions without comparative monitoring of particulate matter (PM) emissions is very problematic. Therefore, the results of the measurement of particulate matter emission (shown in aggregate form as smoke emission - AVL Smoke) and specific fuel consumption are shown in Figure 6.

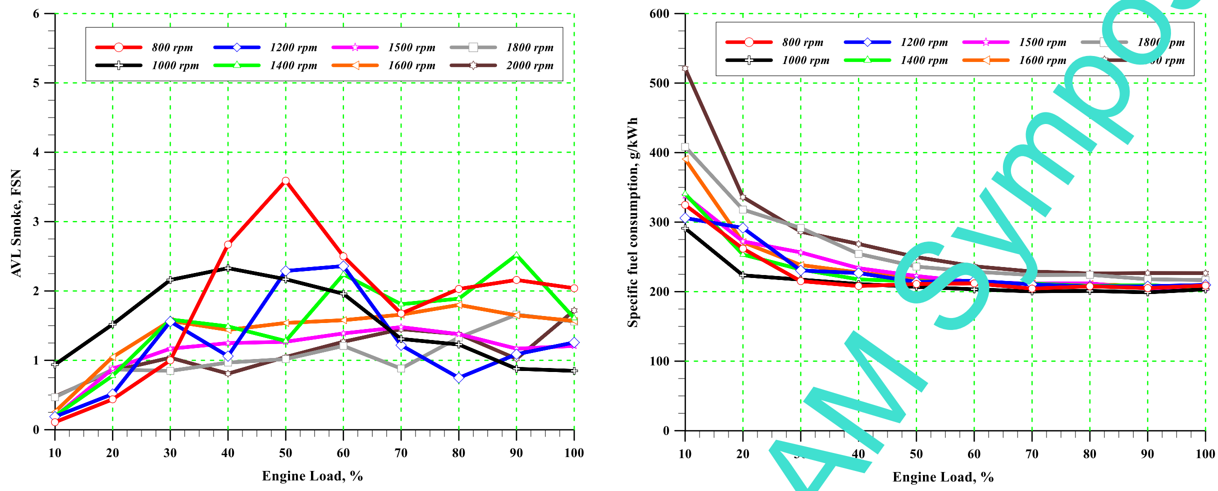

Fig. 6. AVL Smoke emission as a function of engine rpm (left) and Specific fuel consumption as a function of engine load (right)

It has been proven that the exhaust gas recirculation as a method of reducing exhaust gasses emissions allows reducing NO_X emissions up to 50%, even up to 75%, according to some studies [5]. In this example, it can be noted that the exhaust gas recirculation rate must be viewed in the context of other parameters, primarily particulate matter emissions and fuel consumption. Although it is a modern supercharged diesel engine using exhaust gas recirculation only, the strict legal norms regarding NO_X emissions (in force since 2006) cannot be met. Exhaust gas after-treatment must be used in parallel with exhaust gas recirculation.

4. Conclusion

The development of technology inevitably leads to the development of a new concept of motor vehicle propulsion systems based on more environmentally friendly solutions. This primarily refers to electric and hybrid drives. Despite this fact, diesel engines will continue to play a major role in the transport of passengers and goods. It should be emphasized that in the field of transport of goods diesel engines still have no valuable alternatives. An innovative approach in diesel engine development has enabled significantly lower pollutant emissions and fuel consumption compared to older diesel engine designs.

Currently, the two biggest problems in the development of diesel engines are reflected in the way of achieving strict limits in terms of NO_X and particulate matter (PM) emissions, primarily due to the compromise in terms of the combustion process control. The analysis of experimental measurements of one modern supercharged medium -speed diesel engine, with the emphasis on NO_X emission is presented in this paper. Measurement of NO_X emissions was carried out before the exhaust gases after-treatment, with the aim of evaluating the impact of exhaust gas recirculation on NO_X emissions. It can be concluded that the engine meets very demanding Euro IV level norms by using the combustion process control capabilities. When the engine is operating in stationary regimes, the exhaust gas recirculation (EGR) rate ranged from 18% to 30% in almost the entire engine operating range. An attempt was made to solve the problem at lower speed regimes by increasing the exhaust gas recirculation (EGR) rate above 30%, for the low engine load, and below 18% for the higher engine load. These measures resulted in an increase in particulate matter (PM) emissions and specific fuel consumption. Similar problems have occurred in high-speed regimes. Exhaust gas recirculation (EGR) used is a compromise between NO_X emissions, particulate matter, fuel consumption and engine power and torque characteristics.

The use of exhaust gas recirculation (EGR) only did not result in NO_X emissions acceptable for the currently valid legislation limits. The combination of exhaust gas recirculation (EGR) and exhaust gas after-treatment is inevitable if more favourable pollutant emissions are to be achieved. On the other hand, this approach can optimize the combustion process in relation to the pollutant that is the most complicated in context of after-treatment reduction.

Future research should be based on establishing a correlation between NO_X emission, particulate matter (PM) and exhaust gas recirculation (EGR) rate. This would make a clearer understanding of the EGR system control algorithm at modern diesel engines. Also, it is very important to make the same correlation when the engine is operating in transient regimes.

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