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Effects of exhaust gas recirculation (EGR) rates on emission characteristics of ethanol and methanol diesel blended fuels

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Abstract. The introduction of ever more stringent diesel emission standards is associated with a reduction in greenhouse gases. These limitations push many researchers working in this field to look for alternative solutions with the aim of lower greenhouse gas emissions. One of the alternatives is the use of alternative fuels and additives in order to reduce the consumption of fossil fuels. The use of alternative fuels such as ethanol, methanol and others in combination with traditionally used technologies such as exhaust gas recirculation (EGR) is one of the solutions that would lead to the limitation of diesel engines emissions. The aim of the present study is to investigate the performance of a diesel engine with ethanol and methanol additives combined with different degrees of recirculation on engine emissions. For this purpose, a model of a diesel engine with EGR with the possibility of working with ethanol and methanol additives has been developed.

1 Introduction

Depletion of fossil fuel reserves, global warming and environmental protection worldwide encourage the search for alternatives to traditional fuels (diesel fuel and gasoline). As a consequence of the three global problems, the search and development of new technologies or the improvement and implementation of the old technologies known to us are stimulated in order to reduce the consumption of fuels and thereby the emissions released by internal combustion engines (ICE). Despite the strict measures that are imposed in connection with the protection of the environment, the demand for fossil fuels continues to grow provided that it is well known that alternative fuels can be an alternative to fossil fuels. Some sources report that more than 84% of CO2 emissions released into the atmosphere are from fossil fuels [1].

Despite the great restrictions imposed in recent years on the use of diesel engines, they are still widely used in various fields of industry such as shipbuilding, agriculture, transport (land, sea and rail), electric generators, construction equipment and tools. The reason for this wide application is due to their high reliability, fuel economy, adaptability and thermal efficiency. Due to the large number of vehicles and wide application, the share of greenhouse gas emissions emitted by diesel engines is also increasing. The pollution in big

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cities is especially great, causing acid rain, numerous respiratory and cardiovascular diseases and photochemical smog [2].

In order to reduce harmful emissions emitted by diesel engines, combinations of different technologies are used to control the combustion process in combination with the use of different alternative fuels. Exhaust gas recirculation (EGR) technology has been widely and successfully applied to both diesel and gasoline engines to reduce NO_X emissions. Many scientists are of the opinion that applying up to 15% of the EGR NO_X concentration can be reduced up to 80%. EGR can also be successfully used in diesel engines running on various alternative fuels such as biodiesel, various alcohol fuels, natural gas, hydrogen and others without deteriorating their thermal efficiency, and without a significant increase in fuel consumption. In one of the studies [3] con-ducted with a diesel engine and 10% EGR, a reduction in NOx and a slight increase in the PM and soot emission were found. In another study [4] conducted with a direct injection diesel engine using biofuel blends applied up to 20% of EGR was found to reduce NOx emissions and improve combustion characteristics.

1.1 Properties of Methanol and Ethanol

Methanol (methyl alcohol) and ethanol (ethyl alcohol) can be directly used without any engine modifications as a single-fuel and mixed with both diesel fuel and gasoline. They also have similar chemical properties (Table 1). Both alcohols have a simple chemical structure and are liquid and homogeneous [5]. They belong to the group of light alcohols [6].

Table 1. Comparison of fuel properties.

Properties	Euro Diesel	Methanol	Ethanol
Chemical formula	$C_{14}H_{28}$	CH_3OH	C_2H_5OH
Molecular weight (kg/kmol)	196	32	46
Flame speed rate (cm/s)	33	35	39
Boiling temperature (℃)	190–280	64.7	78.1
Density (kg/m3, at 20℃)	840	796	789
Flash point (℃)	52	11	13
Autoignition temperature (℃)	254	464	423
Lower heating value (MJ/kg)	42.74	20.27	28.40
Cetane number	56.5	4	6
Carbon content (wt.%)	86	37.5	52.2
Oxygen content (wt.%)	0	50	34.8
Heat of vaporization (MJ/kg)	0.27	1.11	0.92

Table 2 show diesel-methanol with 10% CH_3OH (M10) and diesel-ethanol 10% C_2H_5OH (E10) blends used for the analysis.

Table 2. Composition of diesel-methanol and diesel-ethanol blends.

Properties	**Diesel**	**M10**	**E10**
Diesel Fuel (%)	100	90	90
CH_3OH fuel (%)	0	10	10
C_2H_5OH fuel (%)	0	10	10
Density (kg/m^3)	840	836	835
Lower heating value (MJ/kg)	42.74	40.2	40.8
Heat of evaporation (KJ/kg)	270	357	334
Oxygen content (%)	0	5	3.1

C_2H_5OH and CH_3OH have a lower viscosity compared to diesel fuel (Table 1). This results in easier atomisation and evaporation and therefore better air-fuel mixing. These two alcohols do not contain sulphur unlike diesel fuel, their use as fuels in internal combustion engines contributes to the reduction of sulphur dioxide (SO_2) and to reduce acid rain, as SO and NOx emissions lead to acidic acid deposition. Due to the higher latent heat of evaporation of C_2H_5OH and CH_3OH compared to diesel fuel, it is associated with lower combustion temperatures, which in turn leads to lower NOx emissions. The content of oxygen in the molecules of C_2H_5OH and CH_3OH leads to a reduction in the formation of soot and particulate matter during combustion. This has a beneficial effect on the combustion process, which also improves. The combustion process of these two alcohols is associated with a high laminar flame propagation speed, which leads to an earlier completion of the combustion process and improves the thermal efficiency of the engine. High evaporative cooling leads to cooling of the combustion chamber during the intake and compression stroke and to an increase in engine volumetric efficiency, thus reducing the necessary work in the compression stroke. This cooling effect can also reduce NO_X concentration in the combustion chamber.

As some of the disadvantages of C_2H_5OH and CH_3OH are:

The cetane number of C_2H_5OH is low, and when mixtures between methane, C_2H_5OH and diesel fuel are used, it is necessary to add a cetane number improver to improve the properties of the mixture. In addition to the cetane number improver, an emulsifier is also added. This further increases the price of the mixture [7].

C_2H_5OH and CH_3OH have limited solubility in diesel fuel, which leads to phase separation of mixtures with these alcohols. The dynamic viscosity of C_2H_5OH is much lower than that of diesel fuel, which impairs the lubricating properties of the mixture. This is a problem because the lubricating properties of diesel fuel are used to lubricate the combustion system [8].

Both alcohols have low self-ignitability due to their high latent heat of vaporization, low cetane number, and high ignition temperature [9].

Thanks to the specific properties of C_2H_5OH and CH_3OH, they can be used in the form of mixtures in diesel engines without requiring structural changes to the fuel system, but the ratio of alcohols to diesel fuel must be low. In order for them to be used in their pure form, it is necessary to make structural changes to the fuel system.

Various studies have been done with mixtures of C_2H_5OH and CH_3OH. A study [10] involving a diesel engine and blends of biodiesel, C_2H_5OH, CH_3OH, and vegetable oil with diesel fuel, where each blend contained 15% alternative fuel by volume, discovered that the use of C_2H_5OH and CH_3OH blends led to decreased brake power, increased fuel consumption, and reduced CO emissions. In a separate study [11], an automotive common-rail diesel engine was utilized, fuelled by a blend of diesel and C_2H_5OH with a 20% C_2H_5OH content. The engine was operated under various working conditions, and the results demonstrated a reduction in soot emissions across all operating conditions. However, the thermodynamic efficiency was found to decrease with increasing C_2H_5OH content at low load conditions, while it showed a slight improvement at medium-high load conditions. Furthermore, in another investigation [12], the impact of different mixtures containing C_2H_5OH and diesel fuel (5%, 10%, and 15% C_2H_5OH) on the performance and emissions of a diesel generator was examined. The generator was subjected to a load range of 5 to 37.5 kW. It is characteristic of the experiment is that the fuel mixtures are directly injected into the combustion chamber of the engine. The obtained results show that in C_2H_5OH mixtures at low loads the in-cylinder peak pressure and heat release rate decreased and at high loads they increased. Increasing the C_2H_5OH content in the mixture results in increased ignition delay and reduced combustion duration. The temperature of the exhaust gases has also decreased. Increasing the C_2H_5OH content has also led to a reduction in CO_2 emissions by up to 8.6%. CO, HC and NOx emissions vary depending on engine load and C_2H_5OH content of the mixture. Other authors [13] studied diesel-methanol blends and solvents for better mixing of diesel fuel with CH_3OH. The performance and emissions at different fuel injection angles were investigated. The obtained results show that with the increase of the fuel advance angle, the thermal efficiency of the engine increases and the BSFC decreases. It was found that the NOx emissions increase with the increase of the advance angle of the fuel supply, with the increase of the CH_3OH content, the NOx emissions are decreasing. The effect of reducing NOx emissions is more noticeable at high loads. As the fuel advance angle increased, the CO content also decreased and the amount of smoke was reduced for the different blends.

2 Engine simulation

2.1 Simulation setup

The primary objective of this research was to develop a 1D model of a direct injection diesel engine. The model was designed to investigate the impact of fuel blends containing C_2H_5OH and CH_3OH with diesel fuel on both emitted emissions and engine specific fuel consumption. The specialized software tool AVL BOOST was utilized to construct the one-dimensional model. The model's accuracy was ensured through calibration, and the engine's configuration is depicted in Figure 1, while the specifications are presented in Table 3.

Table 3. Library with the used elements.

Engine Data	Value
Cylinders	4
Displacement	3666 cc
Engine Bore	100 mm
Engine Stroke	110 mm
Compression ratio	17:1

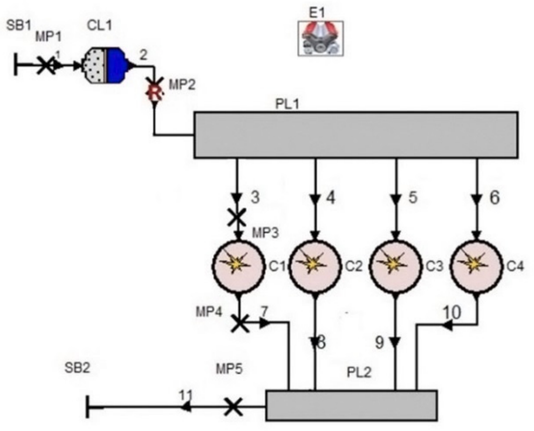

Fig. 1. Layout of a four-cylinder diesel engine.

3 Results

The current study focused on investigating the performance and emission properties of a four-cylinder, four-stroke diesel engine. The engine was operated using various mixtures of CH_3OH, C_2H_5OH, and pure diesel fuel, along with the implementation of exhaust gas recirculation (EGR). The AVL BOOST software was utilized to simulate and analyze the engine behaviour. The experiments were conducted at different engine loads and speeds. Specifically, the following fuel blends were utilized: 10% CH_3OH (or C_2H_5OH) and 90% pure diesel fuel, denoted as M10 (or E10) by volume.

3.1 Performance characteristics

Figure 2 illustrates the outcomes of brake specific fuel consumption (BSFC) achieved through a combination of alcohols and pure diesel fuel, along with exhaust gas recirculation (EGR).

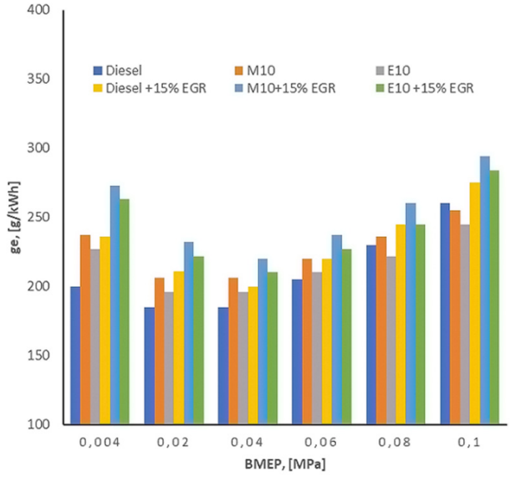

Fig. 2. Influence of E10, M10 and EGR on BSFC under various engine loads.

As can be seen from Figure 2, BSFC increases with increasing C_2H_5OH and CH_3OH content in the fuel mixtures. This can be explained by the lower energy content of CH_3OH (20.27 MJ/kg) and C_2H_5OH (28.40 MJ/kg) compared to diesel fuel (42.74 MJ/kg). In addition, the heat of vaporization of C_2H_5OH (0.92 MJ/kg) and CH_3OH (1.11 MJ/kg) is higher than that of diesel fuel (0.27 MJ/kg). As a consequence, C_2H_5OH and CH_3OH will absorb more heat in their vaporization process compared to diesel fuel, and this will lead to a drop in the temperature in the engine cylinder, which will be especially affected at low loads. This will lead to deterioration of the combustion process and in-crease in fuel consumption. A significant increase in fuel consumption was also observed for the fuel mixtures combined with a 10% recirculation rate. This can be explained by a deterioration of the combustion process due to a lack of oxygen due to the exhaust gases entering the cylinder from the EGR.

3.2 Engine emissions

The CO and HC emissions by blended alcohols and net diesel fuel and EGR are shown on Figure 3 and Figure 4.

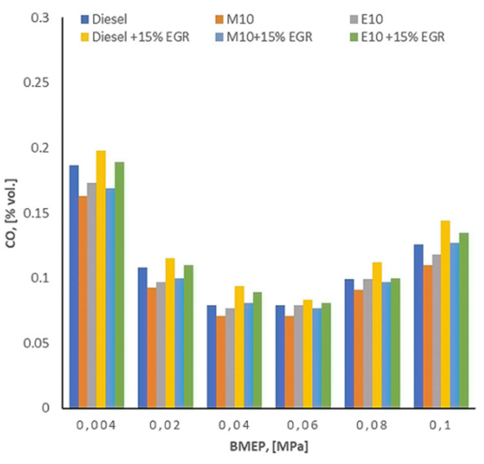

Fig. 3. Influence of E10, M10 and EGR on CO emissions under various engine loads.

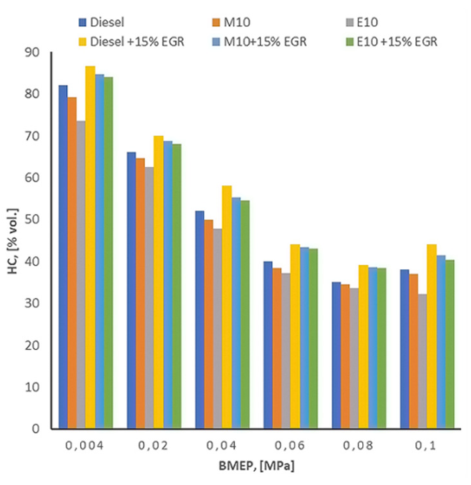

Fig. 4. Influence of E10, M10 and EGR on HC emissions under various engine loads.

The obtained results show that when using EGR technology, an increase in CO and HC emissions is observed for all used fuels and fuel mixtures. The CO content is higher in fuels that do not contain oxygen in their molecular structure. The reason for the obtained results is a deterioration of the combustion process due to dilution with inert gases. The higher oxygen content of alcohols contributes to the lower levels of CO emissions. Some of the reasons for the formation of HC emissions are the properties of the fuel, the presence of oxygen in the composition of the fuel, the combustion temperature, etc. The addition of C_2H_5OH and CH_3OH to diesel fuel results in a higher temperature in the cylinder, resulting in the fuel reacting more easily with oxygen. At the same time, CH_3OH and C_2H_5OH increase the laminar flame speed compared to diesel fuel, leading to a reduction in burn duration but an increase in combustion temperature and more complete combustion and lower HC emissions. The graphs show that this effect is most pronounced with C_2H_5OH - diesel blends. The flame speed of C_2H_5OH is 39 cm/s compared to CH_3OH 35 cm/s and diesel 33 cm/s.

The results for NOx emissions obtained by blended alcohols and net diesel fuel and EGR at different engine speed are shown on Figure 5, Figure 6 and Figure 7.

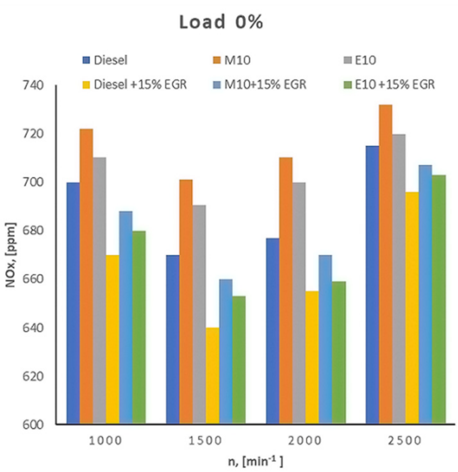

Fig. 5. Influence of E10, M10 and EGR on NOx under various engine speeds with no load.

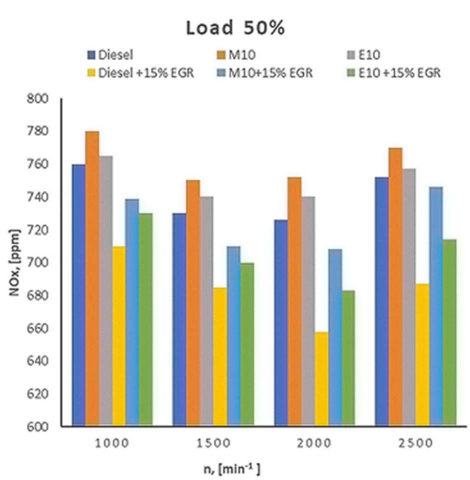

Fig. 6. Influence of E10, M10 and EGR on NOx under various engine speeds with 50% load.

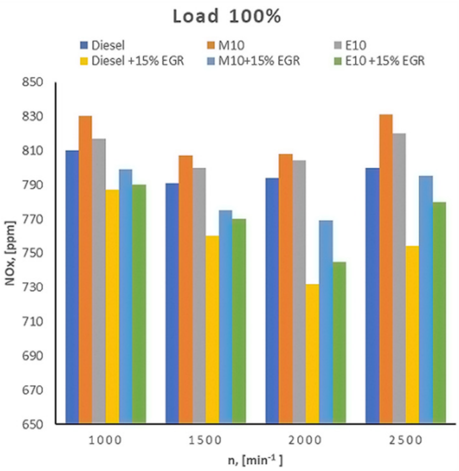

Fig. 7. Influence of E10, M10 and EGR on NOx under various engine speeds with 100% load.

The NOx emissions mainly depend on two factors: the presence of free oxygen and high in-cylinder temperature. The use of alcohols and alcohol additives can lead to two effects. The first is that the oxygen content of alcohols can enhance the formation of NOx. The second, due to their higher latent heating, reduces the combustion temperature in the combustion chamber, as a result of which the formation of NOx is reduced. Consequently, NOx increases with increasing alcohol content in the fuel mixture. It can be seen from the graphs that the increase in NOx is more significant in mixtures with CH_3OH. When the load increases, NOx emissions also increase. NOx reduction with EGR at high loads conditions are greater compared to no load.

The NOx emissions by blended alcohols, diesel fuel and EGR at injection timing change are shown on Figure 8.

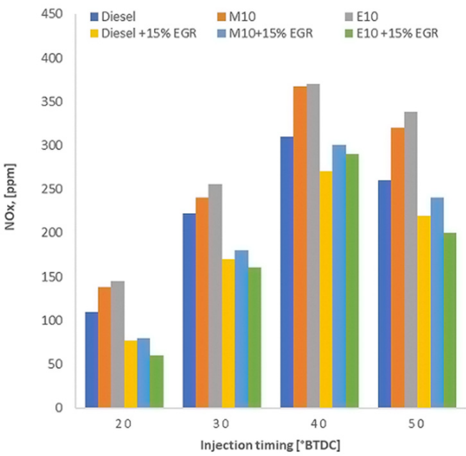

Fig. 8. Influence of E10, M10 and EGR on NOx under various injection timing.

Figure 8 shows that with a decrease in injection timing, the NOx emissions decreases. As a result, the entire combustion process moves along the line of expansion. As a result, fewer combustion products are exposed to the high temperature, resulting in less NOx emissions. Reducing injection timing combined with EGR is a good combination to reduce NOx formation as seen in Figure 8.

4 Conclusions

The effect of diesel/alcohol blends and EGR on engine characteristics were studied. The conclusions can be summarized as follows:

1. BSFC increases with increasing C_2H_5OH and CH_3OH in the fuel mixtures. A significant increase in fuel consumption was also observed for the fuel mixtures combined with a 10% EGR;
2. The obtained results show that when using EGR technology, an increase in HC and CO emissions is observed for all used fuels and fuel mixtures. The CO content is higher in fuels that do not contain oxygen in their molecular structure. Lower HC emissions are observed with alcoholic blends. This effect is most pronounced with C_2H_5OH-diesel blends;
3. NOx emission increases with increasing alcohol content in the fuel mixture. The increase in NOx is more significant in mixtures with CH_3OH. The obtained results show that as the load increases, NOx emissions also increase. NOx reduction with EGR at high loads conditions are greater compared to no load;
4. With a decrease in injection timing, the formation of NOx emissions decreases. Reducing injection timing combined with EGR is a good combination to reduce NOx formation.

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