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Research Article

Emissions Characteristics and Engine Performance from the Interaction Effect of EGR and Diesel-Ethanol Blends in Diesel Engine

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Abstract. Recently, most of the researchers focused on provide lower greenhouse gas emissions that emitted from diesel engines by using renewable fuels to be good alternative to the conventional diesel fuel. Ethanol can be derived from renewable sources such as sugar cane, corn, timber and dates. In the current study, the ethanol fuel used in the tests was derived from the dates. The effects of using exhaust gas recirculation (EGR) diesel-ethanol blend (E10) with on engine performance and emissions characteristics have been studied in diesel engine under various engine loads. This study focused the use of oxygen in the bio-ethanol composition to compensate for the decrease occurred by the addition of EGR, which improves the engine performance and reduces its emissions. In this experiment, the ratios of EGR were 10%, 20% and 30% as well as 10% ratio of ethanol was blended into the diesel fuel blend under fixed engine speed. A traditional (without additional systems to reduce emissions) four cylinders direct injection (DI) diesel engine was used for all tests. The brake specific fuel consumption (BSFC) increased with increasing the EGR ratio by 10%, 20% and 30% by 18.7%, 22.4% and 37.4%, respectively. The thermal efficiency decreased under variable conditions of engine load for different ethanol blends. Furthermore, the emissions of NO_X decreased when fuelled B10 into the engine in comparison with diesel under low engine load. Significant reduction in the NO_x emissions were found when applied EGR in the tests than to the absence EGR for E10 blend and diesel. The NO_x reduction rate was 12.3%, 30.6% and 43.4% when EGR rate was 10%, 20% and 30%, respectively. In addition, the concentrations of HC and CO emissions decreased more by 8.23% and 6.4%, respectively, when using E10 in comparison with the diesel for various engine loads. It is indicated that the oxygen reduction by EGR effect was compensated from ethanol blend combustion. The results showed that the combination use of E10 and EGR leads to significant reduction in engine emissions accompanied with partial reduction in the engine performance.

Keywords: Engine performance, Diesel engine, EGR, Ethanol, Engine load, NO_X emissions.

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1. Introduction

In many countries, the focus of studies were on the energy crisis due to increase the demand on energy and increase the population in recent years. The high demand on energy is coming from increasing standards of living in our lives and on-going economic growth. In different sectors, the energy is normally generated from the combustion of fossil fuels to meet the requirements of industrial sectors and transportation. The use of fossil fuels is beneficial on the environment and health as well as global warming and climate change (Dhahad *et al.*, 2021; Charlson *et al.*, 2022; Al-Ghezi *et al.*, 2022; Dhahad and Chaichan, 2020). The adverse impact of fossil fuels and reduction in fossil fuel supplies leads to accelerated research to find a new sources of renewable energy and environmental-friendly sources (Chaichan *et al.*, 2018; Al-Ghezi and Mahmoud *et al.*, 2022; Kim and Choi, 2010; Al-Ghezi *et al.*, 2021). The increasing demand on fossil fuels in internal combustion engines can be considered as one of the main reasons encourages authors to search and find clean fuels or renewable fuels such as bioethanol and biodiesel. Many studies have used biofuels as an additive to diesel in a compression combustion engine, and the researchers in this filed have agreed that this type of mixture is an effective technique in reducing pollutants emitted (Abdullah and Ariyanti, 2012; Al-Ghezi, 2019; Hoang and Van, 2017).

Several papers have examined the effect of reducing diesel engine exhaust pollutants by using mixtures of crop-

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grown fluids (biodiesels) into the diesel fuel (Pauline *et al.*, 2021; Venkatesh *et al.*, 2021). These additives are characterized by the fact that they carry in their chemical composition a high percentage of oxygen, so they are called the oxygenated additives. However, the most common and long-studied are using alcohol and biodiesel for combustion in the diesel engine. Alcohols have attracted the attention of researchers and manufacturers in recent years because they can be blended into the diesel fuel as they have a high oxygen content in their chemical composition (Restiawaty *et al.*, 2020; Fayad, 2021; Hadiyanto *et al.*, 2020).

Countries of Brazil, Canada and the United States consider alcohol (ethanol) as a primary fuel in spark-ignition engines, because of it has a high octane number. This make it is one of the most popular liquid biofuels. New and efficient technologies for ethanol production have begun to emerge, the most common of these technologies are the fermentation method of agricultural waste, fruit waste, and municipal and industrial waste (Khoshkho *et al.*, 2022). Recently, many studies have been reported that the use of bioethanol in diesel engine is better solution to decrease the pollution emissions produced from the combustion of conventional fuel. Furthermore, bioethanol blended with diesel fuel can be used directly in diesel engine without any modification. It is reported in the literature that the amount of bioethanol blended into the diesel fuel in the range between 5% to 10% (Fayad, 2019). Bioethanol helps in increasing the oxygen content in the fuel blend which in turn reduces the air pollution, hydrocarbon HC, nitrogen oxides (NO_X), and carbon monoxide (CO) emissions (Charlson *et al.*, 2022; Abdullah and Ariyanti, 2012, Dhahad et al., 2021). The first-generation of bioethanol produced from the sugar cane, corn, barley sugar, and cassava (Ekaab *et al.*, 2019; Ağbulut and Sarıdemir, 2021). The researchers focused on produce the bioethanol from lignocellulosic materials which contribute in decrease the growing concern over food shortages, and environmental-friendly, which known as second-generation fuel of bioethanol. Fayad et al., 2021 reported that the combustion of bioethanol blend has the ability to burn more fuel at the same stoichiometry and faster burn. They found that the NO_X, CO and particulate matter (PM) decreased from the combustion of ethanol blend. In addition, the parameters of specific power output and thermal efficiency of diesel engine enhanced from the ethanol blend combustion. The prior work by Chaichan, (2018) stated that the mixture of 15% of ethanol into the diesel fuel can be decrease the PM and improve cetane number. Besides, the blends of ethanol blend result in modify the emission characteristics for both light and heavy duty diesel engines. Previous studies (Liang *et al.*, 2021; Vallapudi *et al.*, 2018) indicated that the NO_X, CO emissions and smoke opacity decreased from the different blends of ethanol-diesel due to improve cetane number and quality ignition characteristics. Higher brake specific fuel consumption (BSFC) and lower exhaust emissions produced from the waste cooking biodiesel when compared with diesel fuel. Different alcohol blends were used in compression ignition (CI) diesel engine to decrease emissions of NO_X and PM over range of engine operating conditions.

Despite all the advantages that mentioned previously of use ethanol blends, there are still some obstacles that must be taken into consideration when mixing ethanol with diesel. For example, the flash point of ethanol is lower than that of diesel, which take strict precautions for preparing mixtures of bioethanol with diesel. The evaporation temperature of diesel is higher by two to three times than ethanol, therefore, ethanol mixes with diesel early at the beginning of fuel evaporation (Manigandan *et al.*, 2021). This causes a rapid brewing of the air/fuel mixture at diesel/ethanol mixtures (with ethanol addition at 5%, 10%, and 15%).

The technology of exhaust gas recirculation (EGR) has been widely used to decrease the NO_X emissions in diesel engine that located in the exhaust pipe of the engine (Fayad *et al.*, 2021). This is because of the decrease oxygen concentration during the process of combustion which results in lower level of NO_X emissions (Wei *et al.*, 2022; Vellandi *et al.*, 2022). The EGR technology is carried out by returning about 10% to 30% of the exhaust gases emitted by the engine to the inlet manifold (Abdullah and Ariyanti, 2012) to mix with the inlet air, resulting in a decrease the amount of oxygen concentration entering to the combustion. This process is called diluting the incoming air charge. In addition, the circulating exhaust gas draws part of the heat into the combustion chamber, which leading to decrease the maximum combustion temperature. The low temperature of the combustion chamber significantly limit the formation of NO_X during the combustion. Many researchers have been suggested that up to 80% of NO_X concentrations will be reduce by applying up to 15% of EGR to the exhaust gas. Therefore, EGR is considered one of the best methods for controlling NO_x emissions. EGR technology can be applied to CI engines that run on multiple types of fuels such as diesel, biodiesel, LPG, hydrogen and others without causing deterioration in thermal efficiency or a significant increase in the BSFC.

Saravanan *et al.* (2013) stated that the use of EGR is the good way to decrease NO_X formation during combustion process, while slightly increase in the emissions of PM and soot emission. Sen *et al.* (2011) studied different rates of EGR from 0% to 5%, 10%, 15%, and 20% in diesel engine. Another work observed that the in-cylinder NO_X formation reduced when adding EGR to the inlet mixture (Ibrahim, and Bari, 2007). The shape of heat release rate during premixed combustion is changed due to the increasing the EGR ratio which enhance the inhibition formation of NO_X emissions. Moreover, the emissions of CO, HC and PM increased with increasing the ratio of EGR as well as slightly increase was noticed in the BSFC during combustion (Restiawaty *et al.*, 2020). High ratio of EGR leads to reduce the performance and durability of the engine because of piston-cylinder liner wearing and corrosive and abrasive components. To high decrease in NO_X emissions, EGR technology was used in diesel engine with ratio less than 30%. Previous study (Koder *et al.*, 2018) indicated that the charge dilation occurred and increased combustion instability when adding EGR inside cylinder. Over many technologies used to control NO_X emissions, EGR is most important technology helps in reducing NO_X and PM emissions (Anandan *et al.*, 2014; Fayad, 2020).

The purpose of this experimental study is to evaluate the possibility of adding bio-ethanol (extracted from Iraqi dates) into the diesel to form a blend (B10) and the effect of this addition on engine emissions and performance under specific operating conditions. Furthermore, optimum engine operating conditions have been evaluated that produce lower NO_x emissions and optimum engine performance. This study also focused on find a suitable additive (in terms of local production and appropriate cost) to the diesel in a way that reduces the pollutants emitted.

2. Experimental setup

2.1. Fuels

Diesel fuel used in this study produced by Iraqi refineries has high sulphur content because of the crude oil. High sulphur content of Iraqi diesel fuel (10000 ppm sulphur) with 46.9 of cetane number was tested during the experiments. Ethanol fuel was produced from Iraqi dates with purity of 99.7%. The process of filtration and distillation of bio-ethanol was carried out in a local Iraqi laboratory. In this work, the ethanol fuel was mixed with diesel by 10% of bioethanol by volume and 90% of diesel fuel to produced E10 blend (diesel-ethanol). During experiments, E10 was selected to produce various levels of engine emissions and it was prepared at the same time of the test to ensure the homogeneity of the mixture. All the results of diesel-ethanol blend were evaluated and compared with reference diesel fuel.

Table 1 lists the properties values of all fuels used in this study. These properties were examined in the Dura Refinary laboratories in Baghdad (Iraqi capital). The properties listed in Table 1 show that there are significant differences between diesel and bioethanol. On the one hand, ethanol is characterized by having a high octane number, so its cetane number is low. Hence, it was added to diesel in a small percentage (10%) in order not to affect the cetane number of the prepared blend significantly. The density of bioethanol is somewhat lower than that of diesel; meanwhile its viscosity is much lower than that of diesel. Mixing 10% of bioethanol with diesel will not cause deterioration in the viscosity of the prepared blend or effect on its atomization process. Bioethanol is characterized by its lower calorific value compared to the diesel, which will increase the fuel consumption when it is used 100% as fuel in the engine. However, in this study it was added in an amount of 10% and its expected effect will be limited the specific brake fuel consumption (BSFC). The most important properties that distinguish bio-ethanol is the low carbon content compared to the diesel versus high hydrogen and oxygen contents.

Table 1
Most important properties of tested fuel

Property	Ethanol	Diesel	E10
Chemical formula	C_2H_5OH	$C_{11}H_{19}$	-
Density (kg/m^3 at 20°C)	0.79	0.84	0.835
Boiling point (°C)	76	233	217
Lower heating value (MJ/kg)	28	43	41.5
Viscosity (cP at 20°C)	1.19	2.98	2.8
Lower Calorific Value (MJ/kg)	27.81	42.11	40.7
Heat of evaporation (kJ/kg)	860	277	335
Flash point (°C)	14	78	71.5
Cetane number	7	46.9	43
Auto-ignition (°C)	419	240	258
Carbon content (%)	52	88	84
Oxygen content (%)	11	-	1.1
Sulphur content (%)	-	1	0.9
Hydrogen content	33	9	11.4

Table 2
Tests Engine Specifications

Engine details	Specifications
Engine model	Fiat TD 313
Cylinders number	Four
Injection type	Direct injection
Engine cooling type	Water cooling
Air system	Natural aspirated
No. of valves/cylinder	2
Bore (mm)	100
Compression ratio	17
Fuel injection pump	1
Plunger diameter	26 mm
No. of holies in the nozzle	10
Diameter of the nozzle hole	0.48 mm
Spray angle	160°
Nozzle opening pressure	40 Mpa

The reduction of C to H proportion has significant effect on the resulted emissions. Also, oxygen existence as OH radicals improves the combustion process and makes the oxidation process complete. The proportion of sulphur in diesel used in the study is considered high globally, and it causes dangerous exhaust pollutants and affects public health as well as environment. The addition of ethanol to the mixture will somewhat reduce the sulphur content in the mixture.

2.2. Engine specifications and outline

Four-cylinder, DI FIAT diesel engine was implemented to test the diesel and various of ethanol blends under various engine operating conditions. Table 2 presented the important specifications of diesel engine used in this study. A hydraulic dynamometer was applied and coupled with engine to adjust the torque and these tools are shown in the schematic diagram of Figure 1. This engine was adopted because it is similar to a thousand vehicles working in the streets of Iraq, which is characterized by the absence of emissions treating devices inside and outside the engine.

2.3. Measuring devices

The concentrations of CO_2, NO_X, CO and hydrocarbon (HC) were measured during the tests using the analyzer of emissions (type of Multigas mode 4880). The emission analyzer was equipped with the exhaust part to record the level concentrations of emitted emissions during the tests. The G460 (Germany made) was fixed in the exhaust pipe to measure emitted SO_2 and H_2S from the engine exhaust. To get high accuracy of the results and avoid any error, double tests were carried out for each fuel and each condition. After prepared the E10, it was found that the E10 has high oxygen content in comparison with the reference fuel (diesel) as illustrated in Table 2. The ratio of EGR is the ratio of EGR amount to the charge aspired into the cylinder. EGR technology was applied to evaluate its influence on NO_X concentrations and engine performance. Different ratios of EGR (10%, 20% and 30%) were applied to analyze the effect of these ratios on emissions and engine performance. Following equation was used to calculate the ratio of EGR during the tests:

$$EGR = \frac{\dot{m}_{EGR}}{\dot{m}_{air} + \dot{m}_{EGR}} \quad (1)$$

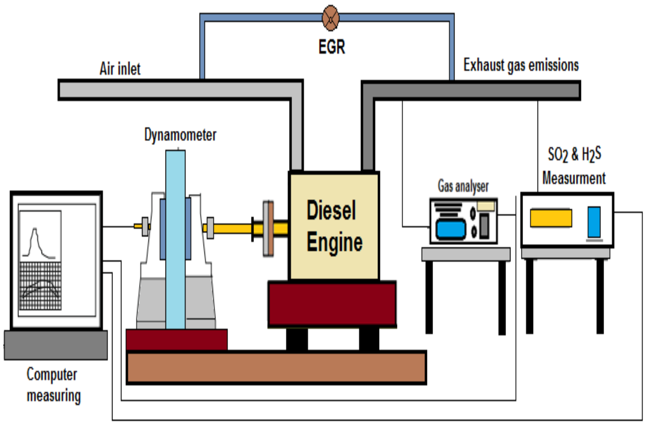

Fig. 1 Schematic of engine setup and assessories.

Where $m_{\dot{E}GR}$ is the mass flow rate of exhaust gas recirculation while $\dot{m}_{air}$ is the entering air mass flow rate to the engine. The air mass flow rate is measured using the pressure difference measurement of the air box, which is also used to dampen the oscillation of the air entering the engine as a result of opening and closing the intake valves. Air is considered as an ideal gas and the ideal gas equation was used to find $\dot{m}_{air}$. The EGR mass flow rate was evaluated using the equation of the orifice between the exhaust and the intake side (Nyerges and Zöldy, 2020).

2.4. Standard error of the products

The estimate of standard deviation (SD) of the sample mean represent the standard error (SE) in the statistics. The SE is very important for the experiment tests because it allows to gauge how accurate the sample data. To find the formula for SE, dividing the sample standard deviation by the square root of the sample size, the standard error calculated using the follwoing equation:

Standard Error = s / √n

Where;

s: $\sqrt{\Sigma^n i(x_i-\bar{x})^2}$ / n-1
x_i: i^{th} Random Variable
$\bar{x}$: Sample Mean
n: Sample Size

The accuracy can be measured by the statistical term of the SE with which a sample distribution by using standard deviation. The deviation from the actual mean of a product is represent the SE in a statistical term. In simple terms, an inferential statistic tells you that the SE is how accurately your sample data represents the whole product. The SE describes variability across multiple samples of a measurement becuse it allows to gauge how accurate the sample data, while the standard deviation describes variability within a single sample across multiple samples of measurement.

Table 3
Accuracies of the experimental instruments that used in this study

No.	Measurement	Accuracy	Uncertainty (%)
1	Engine load	± 2 N	±0.4
2	Engine speed	±10 rpm	±0.2
3	Fuel flow meter	±0.2 cc	±1.5
4	Thermocouples	± 2° C	±1.3
5	Air flow meter	±0.13 bar	±0.5
6	EGR flow meter	±0.2 bar	±0.2
7	NO_x	±3 ppm	±0.3
8	CO	±0.25 %vol.	±0.24
9	HC	±12 ppm	±0.6
11	CO_2	±0.08% vol.	±0.12
12	H_2S	±8 ppm	±0.32
13	SO_2	±7 ppm	±0.56

The standard errors, confidence intervals, and standard deviations could be evaluated according to the error bar values in the results (Cumming *et al.,* 2007). The values of error bar were appeared in all Figures of the current study. After calibrating the used measuring devices and determining their deviation from standard values. The test measurements of the equipment have an acceptable accuracy overall uncertainty, which is less than 3% as shown in Table 3. Each experiment was repeated at least three times to confirm the validity of the tests, and the arithmetic mean of the measurements was taken to ensure accuracy.

3. Results and discussion

3.1. Performance characteristics

The effects of E10 and EGR on BSFC are shown in Figure 2 under various conditions of engine loads. Figure 2 shows that the BSFC increased with presented ethanol fuel due to the lower energy content (27.81 MJ/kg). Besides, ethanol has high heat of evaporation (860 kJ/kg)) compared to diesel (277 kJ/kg). Table 2 shows that E10 heat of evaporation is 335 kJ/kg. This means that E10 will absorb more heat from the combustion chamber than diesel to evaporate, causing a drop in the cylinder's temperature, especially at low loads. As a result of that, combustion deteriorates and BSFC values rise. It is noticed that an improvement in BSFC under high engine loads. It is suggested that these improvements due to the better thermal cycle efficiency. A significant increase in BSFC with applied EGR as depicted in Figure 2. This could be due to replace recirculate exhaust gas with air part which in turn produces lower brake power. Thus, more fuel-air needed to achieve the required load under fixed engine speed. An increment by 3.75% in BSFC was observed from burning E10 in comparison with diesel fuel. It is suggested that the increase of fuel consumption during combustion from E10 could be due to reach the same power output generated from the diesel fuel . In addition, the main reason to justify the high BSFC form E10 for different EGR is the low calorific value (see Table 2) of E10 properties. Therefore, the combustion efficiency and fuel mass will increase from E10 combustion in comparison with diesel fuel (Figue 2). The general trend of BSFC from E10 is consistent with previous published studies (Fayad, 2020; Dhahad *et al.,* 2021). Applied three ratios of EGR lead to increase the BSFC by 18.7%, 22.4% and 37.4%, respectively, for all fuels tested.

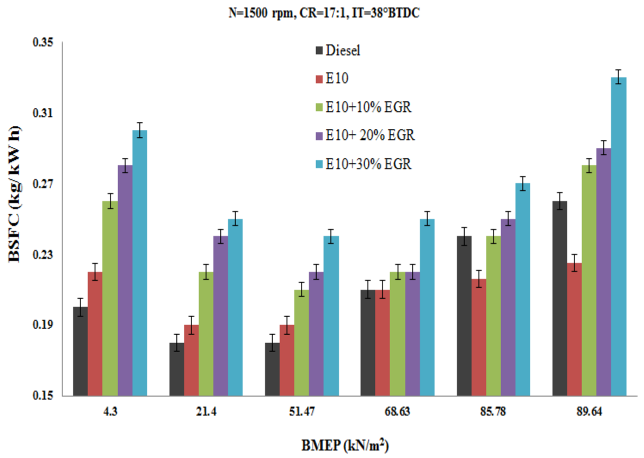

Fig. 2 Influence of E10 and EGR on BSFC under various engine loads.

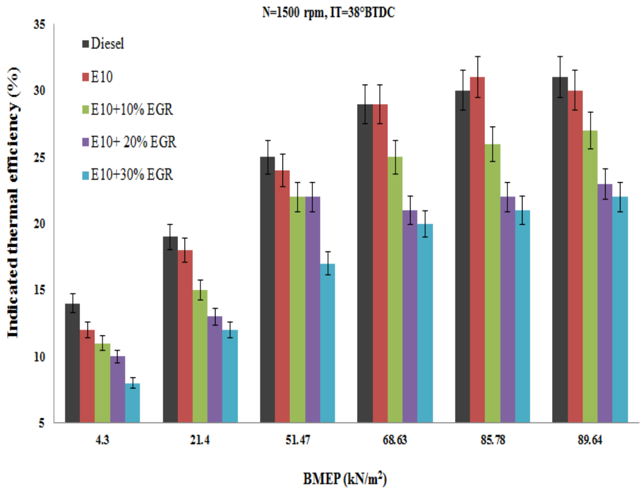

Fig. 3 Influence of E10 and EGR on thermal efficiency under various engine loads.

The combustion process and thermal efficiency were improved from the oxygenated fuel (E10) because of the oxygen-bond in the E10 as shown in Figure 3. Furthermore, the high thermal efficiency was observed under high engine loads compared to the other loads conditions. The presence of oxygen in the fuel composition significantly improved combustion. The effect is seen in the highly concentrated fuel and spray core regions. The addition of ethanol in a small percentage has reduced the viscosity of the mixture to a reasonable degree, and caused an improvement in fuel atomization and evaporation inside the combustion chamber, which result in the better mixture of fuel and the combustion process is improved (Zhang *et al.*, 2021). Figure 3 shows that the combustion efficiency decreased with applied EGR due to reducing the oxygen content and increasing the ignition delay as well as low mixture temperature (Lewander *et al.*, 2009). A small reduction in thermal efficiency by 2.6% was obtained with addition 10% of bioethanol to the mixture. For three EGR ratios, a significant reduction was found by 13.6%, 24.6% and 31.3% from the employing 10%, 20% and 30% of EGR, respectively, as depicted in Figure 3.

3.2. Emission characteristics

The NOx emissions variations in the exhaust part from applied EGR and fuelled with E10 are shown in Figure 4 under variable engine loads. According to the results, the NOx emissions concentration decreased when applied different ratios of EGR technology. The main reason to justify this trend may be because of the reduction oxygen concentration inside the cylinder from the applied EGR (Han *et al.*, 2021; Varatharajan and Cheralathan, 2013). Another cause is the reduction in the flame temperatures during combustion (Dhahad *et al.*, 2019; Alani *et al.*, 2022). Furthermore, Figure 4 shows that the NOx emissions are higher in case of E10 when compared with diesel fuel. It is suggested that the higher combustion temperature from E10 is the main reason to explain the trend; this is more clearly in case of high engine loads (Chen *et al.*, 2014). Also, the oxygen availability enhances the NOx formation (Alptekin, 2017). Applying EGR in ratios of 10%, 20% and 30% led to significant decrease the NOx emissions by 12.3%, 30.6% and 43.4%, respectively, when comparison with the diesel fuel under without applied EGR. The findings from the current results indicated that the use of EGR is beneficial way for inhibition the formation of NOx emissions. It is noticed from the different tests that the adding ethanol to the diesel fuel helps to decrease the effect of oxygen reduction inside combustion process due to the oxygen available in the ethanol properties as listed in Table 1. The temperatures inside cylinder changed with applied EGR (Figure 4), especially at high engine loads. These results were in agreement with the results of Yogesh and Chandramohan, 2022; Chaichan *et al.*, 2022 and Chandravanshi *et al.,* 2022. Han (2021) and Zhang (2018) explained that adding ethanol to diesel causes a decrease in the cetane number (especially in the case of the current study, where the cetane number of Iraqi diesel is basically low), which increases the ignition delay period, so the amount of fuel injected into the combustion chamber is increased during this period. As a result of all that, NOx concentrations are increased.

The concentrations of CO and HC emissions from the combined effect of EGR and E10 are shown in Figure 5 and Figure 6, respectively, via various engine loads. The emissions of CO and HC increased more when using EGR technology in comparison with the absence EGR. Poor combustion quality produced with applied EGR technology due to excessive dilution by the inert gases (D'Errico *et al.*, 2012; Bhurat *et al.*, 2021; Chaichan *et al.*, 2022). Figure 5 shows that the CO emissions increased with increasing the ratio of EGR. High concentration of CO emissions by 30.6% produced fewer than of 30% EGR for all fuels tested. In contrast, lowest level of CO emissions produced with 10% of EGR, while CO emissions increased by 17.4% with 20% of EGR ratio as presented in Figure 5. Furthermore, E10 emitted lower level of CO emissions by 8.23% in comparison with reference fuel for various EGR technology ratios. This could be because of the higher oxygen content in E10 (fuel blend) properties which help in the CO reduction. The concentrations of HC increased by 7.93%, 23.25% and 30.82% when increasing the ratio of EGR by 10, 20 and 30%, respectively, from E10 blend combustion. In case of oxygenated fuel, it was obtained that the HC emissions decreased by 6.4% from E10 for without applied EGR compared to the presence EGR.

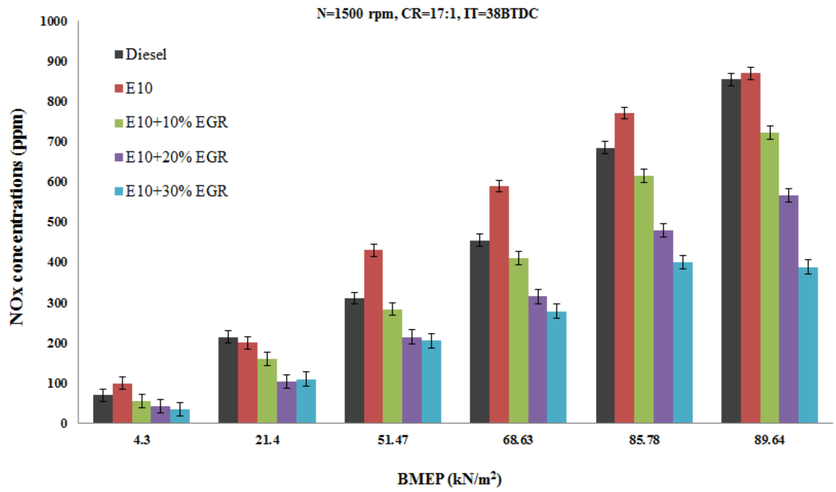

Fig. 4 Influence of E10 and EGR on NOx emissions under various engine loads.

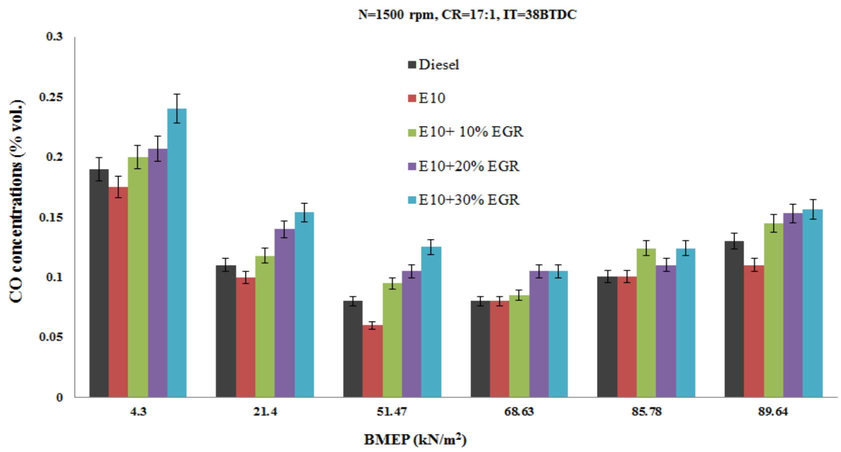

Fig. 5 Influence of E10 and EGR on CO emissions under various engine loads.

Both CO and HC are the result of incomplete oxidation of the fuel and since the fuel used has an abundance of oxygen (coming from the ethanol content) with dilution (coming from the use of EGR) both are contradictory factors in their effect on combustion efficiency. Therefore, the increase in CO and HC rates in the exhaust means that the second factor (EGR) is superior to the first (oxygen abundance). The formation of carbon dioxide is a sign of complete oxidation takes place at high combustion temperatures. Despite the abundance of oxygen in the ethanol composition, and its latent heat of vaporization is very high, while its energy density and viscosity are low, which causes a decrease in the temperature of the cylinder during evaporation that result in rise the levels of CO and HC emitted. The prolonged ignition delay of ethanol could be added as the reason for the increased levels of CO and HC. These results were in agreement with the findings of Gnanamoorthi and Devaradjane, (2015); Yilmaz and Atmanli, (2017).

Figure 7 shows PM emitted when ethanol and EGR were added under the influence of variable engine loads. PM concentrations are high at start-up and at low loads due to the cold combustion chamber, which results in poor combustion (Chaichan, 2020). These concentrations decrease at medium loads and rise at high loads for all the studied cases, its noticed that these levels were decreased by burning E10 at these loads. EGR causes increased charge dilution, thus reducing flame temperatures. The EGR also contains particulate particles of recycled exhaust gases that contribute to raising the measured PM levels. Adding ethanol raises the oxygen content in the fuel, which improves the combustion efficiency. Therefore, PM concentrations decreased by 7.7% to 13.33% at medium and high loads. PM levels decreased with increasing mass of oxygen in the diesel-ethanol mixture, and this effect is evident under high load conditions. Adding ethanol to diesel enhances the oxidation process and improves the diffuse combustion in the expansion and exhaust phases (Ren et al., 2008). The results of the current study are consistent with the results of Ghazikhani (2010), which concluded that the PM decreased with the addition of oxygenate to diesel. Added ethanol reduces the rich spray area and improves fuel oxidation in the post-flame area, as well as improving the diffuse combustion phase, with the end result being lower PM levels. The addition of EGR causes the engine to operate in low temperature conditions resulting in incomplete combustion and elevated PM levels. The increment rates in PM levels with EGR additions were 1.3%, 7.5% and 12.6% for adding 10%, 20% and 30% of EGR, respectively. The addition of 10% of EGR rate indicated the effect of oxygen in the fuel blend effect.

Iraqi diesel fuel contains a high percentage of sulfur (from 1% to 2.5%), which is considered the highest percentage fuel in the world. The reason for this sulfur is Iraqi crude oil, which has a high content of oil and requires harsh filtering processes to remove it. Till today, the distillation techniques are not currently available in Iraqi refineries to decrease the high sulfur content.

Figure 8 shows the concentration of SO_2 emitted from the engine exhaust under various engine load. The SO_2 concentrations decreased in E10 fuel, as well as when using EGR and fueling engine with E10. It is also decreased with increasing engine load. Engine running at low loads emitted high concentrations of SO_2, and these concentrations decrease with increasing the engine load. Operating the engine at a low load condition causes a decrease in the combustion temperature while providing the time required for completing the sulfur oxidation process. However, when the engine is running at high loads, the combustion temperature will increase due to the increase in the amount of fuel injected into the combustion chamber as well as the heat-dependent reactions improved. Consequently, part of the sulfur is oxidized to form SO_2 and the rest of the sulfur reacts with other molecules to form aromatic compounds and PM (Wang *et al.*, 2012). Thus, the concentration of SO_2 emitted decreased from the above reasons. It can be seen that the concentration of SO_2 decrease when working with E10 fuel by 68% compared to diesel. When the engine is running with applied EGR at rates of 10%, 20% and 30%, the SO_2 emissions are reduced by 31.75%, 39.75% and 47.85%, respectively, compared to diesel fuel.

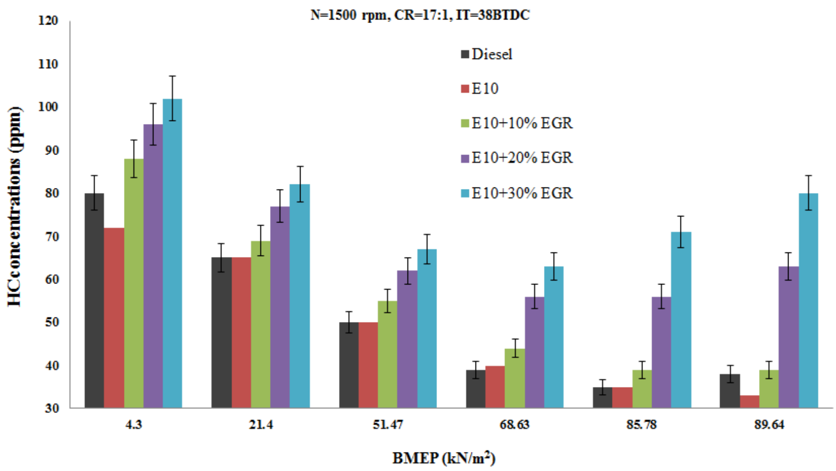

Fig.6 Influence of E10 and EGR on HC emissions under various engine loads.

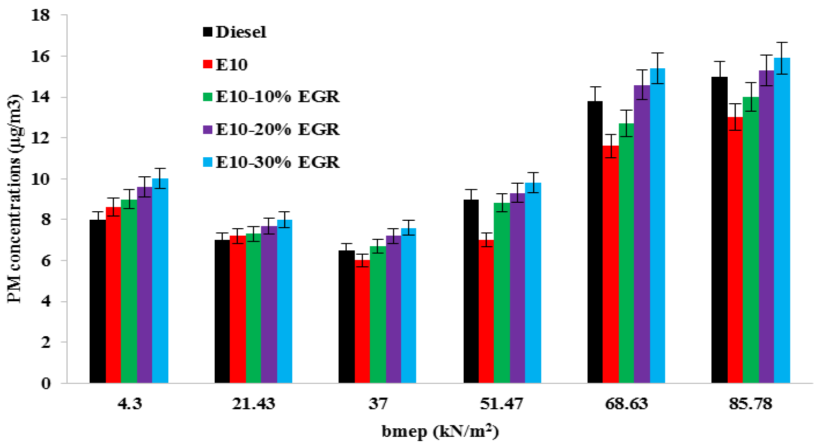

Fig.7 Influence of E10 and EGR on PM emissions under various engine loads.

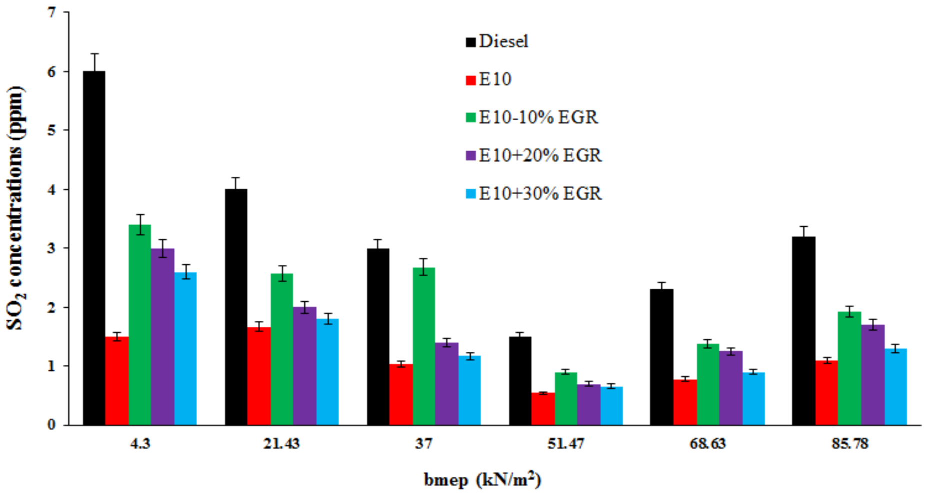

Fig.8 Influence of E10 and EGR on SO_2 emissions under various engine loads.

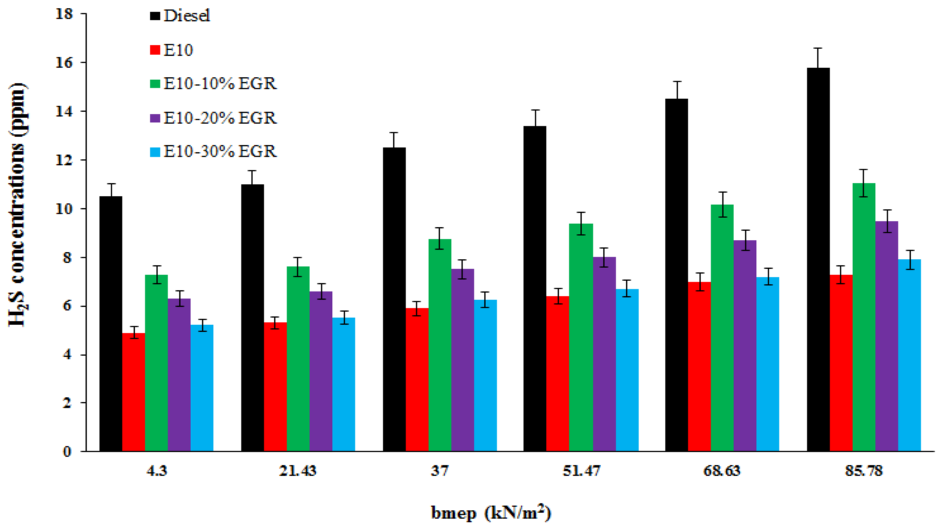

Fig.9 Influence of E10 and EGR on H_2S emissions under various engine loads.

The recycled exhaust gas absorbs part of the heat released into the combustion chamber, reducing its temperature. But sulfur molecules are highly reactive and their rapid reaction results in a significant concentration emitted. The emission of SO_2 is a harmful gas as it reacts with water vapor resulting from combustion to form sulfuric acids with a high ability to damage the exhaust system, and its smell causes ulcers of the respiratory system of humans and animals (Smith *et al.*, 2010). One of the serious damages of SO_2 is poisons the catalysts and damages it. Hence, the sulfur content in diesel fuel should be reduced to get rid of these serious damages.

Figure 9 shows the effect of the fuel type used and the engine load on the H_2S emitted. The concentrations of H_2S depend on the amount of fuel injected into the combustion chamber. These concentrations rise with increasing engine load, as in these conditions, the fuel injected into the combustion chamber is increased. Since both hydrogen and sulphur are highly reactive, H_2S pollutants are clearly formed. H_2S concentrations decreased when E10 was used due to the decrease of sulphur content in the fuel in addition to the presence of OH radicals, which result in enhance the reactions and increased their growth. The addition of EGR to the air intake manifold reduced these concentrations (Figure 9). The H_2S concentrations decreased by 26.22%, 31.69% and 40.37% when applied EGR at 10%, 20%, and 30% to E10, respectively. The concentrations measured in the experiments did not reach dangerous levels. However, such concentrations in closed areas such as tunnels and indoor garages have great risks to human and animal health (Wang *et al.*, 2012; Mihanović *et al.*, 2020). This pollutant causes health risks to humans, as its presence in concentrations of 100 parts per million and more is an actual threat to humans when exposed to it for a period of time from 1 to 4 hours (Mihanović *et al.*, 2020). If H_2S concentrations exceed 500 ppm, it causes immediate loss of consciousness and sometimes death.

The above results showed that the possibility of using a bioethanol-diesel blend to run a (CI) combustion engine without any modifications to the engine and its systems.

The use of B10 with 10% EGR introduced promising results in terms of reducing most pollutants with a slight impact on the engine performance. The current study could be a key to many future studies to reduce more pollutants and improve engine performance by taking advantage of engine operational variables such as injection timing, injection angle, injection pressure, and the use of turbocharger. It is also possible to add some of the engine design modifications such as the shape of the combustion chamber or the compression ratio to reach the same goal.

4. Conclusion

In the current study, the possibility of adding bioethanol produced from Iraqi dates to Iraqi diesel (with high sulfur content) was examined. The effect of adding EGR to control NOx emissions was also investigated. The most important results that were extracted from this practical study are that the BSFC was increased when ethanol is added to diesel fuel by a maximum of 37.4% when applying 30% EGR. The NO_X emissions decreased more compared to diesel fuel and E10 without EGR technology. The maximum reduction achieved was 43.4% when adding 30% EGR. The use of EGR increased the emissions of both HC and CO compared to the conventional fuels due to incomplete combustion. The highest increases in HC and CO emission concentrations were 30.82% and 30.6%, respectively, compared to the diesel when EGR was added at 30%. Adding ethanol to diesel reduces PM levels from 7.7 to 13.33% for miduim and high loads. In contrast, the adding EGR to the blend increased PM concentrations as the maximum value achieved was 12.6% when 30% of EGR technology was added. The interaction between E10 and EGR has a beneficial effect on reducing SO_2 and H_2S emissions, as these pollutants decreased by 47.85% and 40.37% compared to the diesel when applied 30% of EGR technology.

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