Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 05, May-2025

Impact of Exhaust Gas Recirculation on Performance and Emissions of Diesel Engine Fueled with Jojoba Methyl Ester

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Abstract
The aim of this study was to quantify the efficiency of exhaust gas recirculation (EGR) when using Jojoba Methyl Ester (JME) fuel in a fully instrumented, two-cylinder, naturally aspirated, four-stroke direct injection diesel engine. The tests were conducted in two stages. First, the engine performance and exhaust emissions of the diesel engine operating with diesel fuel and JME were measured and compared. Second, tests were performed at full load and 1500 rpm to investigate the EGR effect on engine performance and exhaust emissions including nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC) and exhaust gas temperatures. The results showed that EGR is an effective technique for reducing NO_x emissions with JME fuel in heavy duty diesel engines. With the application of EGR method, the CO and HC emissions in the engine-out emissions increased. The optimum EGR was found to be less than 12% at full load, engine economy deteriorated with increased brake specific fuel consumption (bsfc) by more than 9.6%, and the reduction in NO_x was 39%.

Keywords: **Renewable energy, Diesel engine, Jojoba Methyl Ester, Exhaust gas recirculation**

1. INTRODUCTION

Interest in renewable energy sources for energy production is not new. The need to search for new energy solutions arises from the decrease in fossil fuel resources and the associated economic factors. Many alternatives to conventional fuels including biofuels, natural gas, hydrogen, synthetic fuels, electro-fuels, liquid petroleum gas (LPG) and methanol are being considered for diesel engines. Numerous studies have been conducted to qualify various oil and their blends from plants and vegetables as alternative renewable energy sources. These renewable fuels can help in reducing the net production of CO_2 from combustion sources and our dependence on fossil fuels. The choice of vegetable oils for biodiesel production often depends on which ones are abundant in the test country. Therefore, soybean oil [1,2] is the primary interest as biodiesel source in the United States While rapeseed oil [3] is widely used in many European countries, and countries with tropical climate prefer to utilize coconut oil, hazelnut or palm oil [4–6]. Other vegetable oils, including sunflower, canola, etc., have also been investigated [7]. Furthermore, other sources of biodiesel have been studied include animal fats, fish oil and or waste cooking oils [8–12].

Several problems have hindered the widespread use of biodiesel primarily due to the economics and properties of biodiesel. Some researchers have reported that the high viscosity as one of the most significant drawbacks of using vegetable oil as a fuel [13-14]. The high viscosity can lead to blockage of fuel lines, filters, high nozzle valve opening pressures and poor atomization. The problems of high fuel viscosity can be overcome by using esters, blending and heating. The methyl esters of vegetable oils, which are produced by combining methanol with the vegetable oil [15], provide a viable alternative. These fuels tend to burn cleaner, perform comparably to conventional diesel fuel, and combust similarly to diesel fuel. It is generally recognized that biodiesel has lower emissions than conventional petroleum fuel with the exception of nitrogen oxides (NO_x). Generally, biodiesel as a renewable alternative fuel produces lower exhaust emissions when compared to the conventional diesel fuel with the exception of nitrogen oxides (NO_x).

Oxides of nitrogen are formed during combustion when localized temperatures in the combustion chamber become high enough to combine molecules of oxygen and nitrogen. Oxygen interacts at the boundary surface between the air and fuel. This boundary surface is where combustion takes place. Due to burning of the fuel droplets, the localized temperature in the vicinity of the fuel droplets exceeds the limit at which NO_x is formed. In general, high amounts of oxygen and high temperatures lead to high levels of NO_x formation. These conditions are always present in the combustion chamber of diesel engines since diesel engines always run at a

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ISSN: 2278-0181
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lean air-fuel mixture and high compression ratios [16]. Therefore, the harmful effects on human health and environment brought by its pollutant emissions are causing great concern. various methods are being investigated to reduce tailpipe emissions from diesel engine vehicles. At the present technology**,** the in-cylinder emissions reduction approach is the most effective and economical way to reduce NO_x emissions to meet the most stringent current emissions requirements.

2. EGR STRATEGY AND JOJOBA SEED OIL EXTRACTION

Despite the use of fuels of improved quality, changed engine designs or improved emission control technology, the problem of toxic gaseous substances remains. Recently, exhaust gas recirculation, has received attention as a potential solution for reducing NO_x emissions in modern engines [17,20]. Research work results showed that EGR is one of the most effective methods used in modern engines for emissions control. There are two types of EGR; internal and external. Internal EGR uses variable valve timings or other devices to retain a certain fraction of exhaust from a preceding cycle. External EGR uses piping to route the exhaust gas to the intake system, where it is inducted into the succeeding cycles and it is used in this study. External EGR is widely preferred for heavy-duty diesel engines and that due to external EGR can be cooled and that improves fuel economy and engine performance. EGR reduces NO_x because EGR gases contain much lower concentrations of oxygen as compared to ambient air. As a result, EGR gas slows down the rate of combustion as there is less oxygen in the cylinder to burn with the fuel. In addition, Dilution of the oxygen/fuel charge with exhaust gas increases the heat capacity of the unburned mixture, reducing combustion or burned gas temperature. This helps slow down combustion because more heat can be absorbed in an air-fuel mixture that contains EGR gases.

In Egypt, the search for a viable vegetable oil as source of biodiesel has identified jojoba oil as a promising candidate. jojoba ranks high as the vast area of the Egyptian deserts can be used for production the seeds are used to produce the jojoba fuel. El-Moogy [21] conducted extensive research on jojoba cultivation for investment in Egypt. The jojoba shrub was grown in Africa and also grown in the Sonora Desert at the south of the USA. The author [21] termed the jojoba oil as "green gold" as this term reflects the plant’s economic and environmental value. The seeds are used to produce oil while the residue can be used as fodder or solid fuel implying that there is no waste. Each acre which accommodates 900-1000 shrubs can produce about 540-600 kg of seeds when the plant is four years old; but the production increases gradually till it reaches 1350-1500 kg when the plant is ten years old. Jojoba seeds contain 50% of its weight as oil, so the Egyptian acre can produce 270-300 kg of oil after four years but will increase to 675-750 kg of oil after ten years of cultivation. The viscosity of raw jojoba oil is high and thus warrants treatment of oil before it can be used as a viable engine fuel. Many studies have been working on Jojoba as a promising vegetable oil fuel for diesel engines for many years [22-26]. During this time, many tests have been performed on neat jojoba and Jojoba Methyl Ester (JME). These studies showed that this fuel is a very good gas oil substitute and offered the same product guarantees for JME as for gas oil due to the fact that the physiochemical properties of JME are close to those of gas oil. An increase in the emissions of nitrogenous oxides (NO_x) at all operating conditions have been observed by [27]. The aim of the study was to determine the relationship between the addition of exhaust gas recirculation (EGR) and changes in regulated exhaust emission levels from a diesel engine fueled with JME as a renewable fuel. In this paper, all experiments described here were performed on a direct injection diesel engine in first to compare diesel fuel and JME fuel in terms of engine performance and exhaust emissions at various speeds under full load condition and the second to investigate the effect of various EGR rates with JME fuel for NO_x reduction. EGR effects on engine performance, engine emissions, exhaust gas temperature, combustion quality and fuel economy for high load engine operating condition at 1500 rpm were investigated.

In this study, the transesterification process was carried out using a transesterification process similar to the one described in Ref. [15]. The different variables that are summarized below:

Jojoba oil/alcohol molar ratio: 1:6

Type of alcohol: methanol
Catalyst of sodium hydroxide (NaOH): 0.5–1.5% by weight of the oil
Temperature of reaction: 60^{o}C

Time of reaction: 30–120 min
After establishing the experiments, the optimum parameters of base-catalyzed transesterification reaction of JME were Jojoba oil/methanol molar ratio, 1:6; NaOH amount, 1% by the weight of the oil and reaction time, 75 min. Under these conditions, approximately 90% of the jojoba oil was converted into bio-diesel. The properties of the JME fuel versus diesel fuel are shown in Table 1.

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Table 1 shows the properties of the JME fuel versus diesel fuel [12].

Properties	JME	Diesel
Density @ 15 ^{0}C	0.866	0.820
Kinematic viscosity @ 40 ^{0}C (cSt)	19.2	1.6–7.0
Flash point	61	Min. 55
Calorific value (kj/kg)	47380	44300
Cetane number	63.5	46
Water content % by mass	0.5	0.1
Carbon residue % by mass	0.5	0.1
Ash content % by mass	0.002	0.01

3. TEST SETUP AND INSTRUMENTATION

The experiments were conducted on a two-cylinder, water cooled, four-stroke, direct injection diesel engine. Since the original engine did not have an EGR system, some modifications had to be made to the engine where the exhaust manifold was connected to the air intake manifold with an EGR valve at this connection. The experimental set up is shown schematically in Fig.1 and comprises a hydraulic dynamometer, a pressure tank, a diesel particulate bag filter, a heat exchanger, an EGR valve, a liquid and gas fuel metering systems, and an exhaust gases analysis system. The engine specifications are given in Table 2. To regulate and clean the recirculated exhaust gases, several additional components were installed into the system. It was necessary to connect the exhaust manifold to the air intake manifold, with a pressure tank, a bag filter, a heat exchanger, and an exhaust gas recirculation valve to control the amount of gas exhaust circulated. The bag filter was used for particulate reduction and supply of clean gas for EGR. The pressure tank was used for reduction of exhaust pressure pulse and the heat exchanger was used for cooling exhaust gas by water flow.

An EGR valve was installed in this connection that enabled manual to control the flow rate of EGR to the intake manifold to attain various EGR ratios. The flow rate of EGR into the engine was measured with a sharp edge orifice mounted on a pipe connected to the pressure tank. An inclined manometer was used to measure the pressure drop across the orifice. The air temperature and exhaust gas temperature were measured using type K thermocouples Measurements of CO, HC, and NO_x emissions were obtained using a Testo 350 gas analyzer. The flow rate of air into the engine was measured using a laminar flow element. The laminar flow element was a honeycomb-like structure, which provides for a certain pressure drop across itself for a certain volumetric flow rate of air. This pressure drop was measured using an inclined manometer. EGR rate can be calculated based on the above data. As EGR mass rate is defined as the ratio between recirculated exhaust mass flow and the total intake mass flow entering the engine.

$$\text{EGR rate } (\%) = \left(\frac{\dot{m}_{EGR}}{\dot{m}_{Air} + \dot{m}_{Fuel}}\right) \times 100$$

Table 2 Specification of the engine used.

MODEL	112M- Helwan
Type	4-stroke direct injection
Cooling	Water cooling
Number of cylinder	2
Diameters of cylinder (mm)	112
Stroke length (mm)	115
Capacity (cm^3)	2266
Compression ratio	16.4
Rated speed (rpm)	1500
Max. power at 1500 rpm (HP)	26

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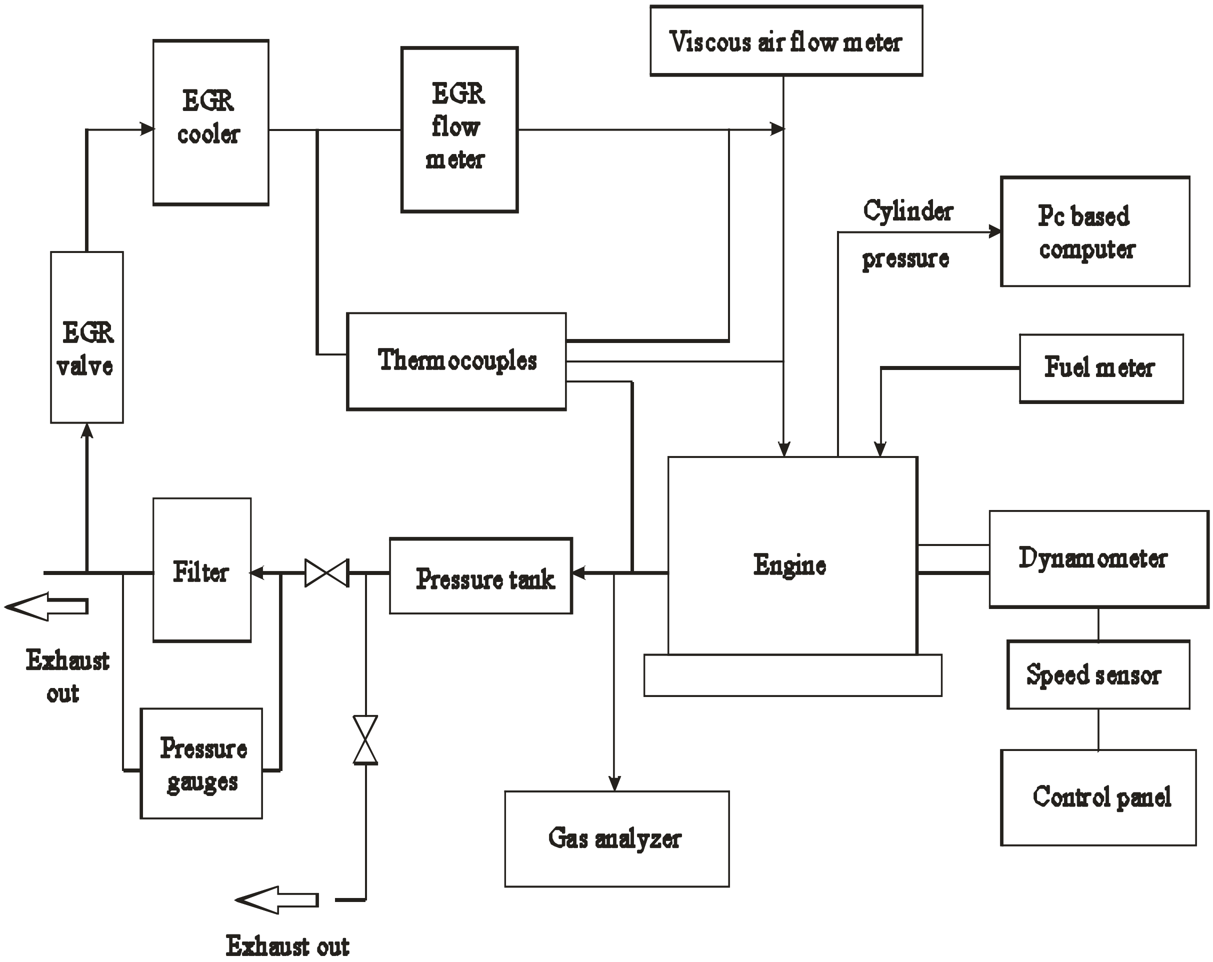

Fig. 1 Schematic of the experimental test rig

4. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results are divided into two main sections: the first compares the engine performance and exhaust emissions of diesel and JME fuel. Tests were conducted at various engine speeds under full load conditions. The second examines the impact of different EGR rates on engine emissions, exhaust gas temperatures and fuel economy of JME fuel. Tests were performed at 1500 rpm under full-load condition, representing heavy-load operation. For accuracy and repeatability, one test was performed three times under identical conditions. The experimental error was evaluated based on Ref. [28], with a maximum uncertainty ranging between 1.5% and 5.5% for any measured quantity.

4.1 Comparison of performance and emissions with JME and diesel fuel

The influence of engine speed on brake thermal efficiency (η_{th}) and brake specific fuel consumption (bsfc) for JME and diesel fuel under full-load conditions is illustrated in Figures 2 and 3. The experimental results indicate that brake thermal efficiency (η_{th}) increases with engine speed for both JME and diesel fuel, reaching a peak efficiency before declining slightly. The peak efficiency for both fuels occurs around 1700 rpm. JME fuel consistently shows higher brake thermal efficiency compared to diesel fuel at all engine speeds. The highest brake thermal efficiency value determined for JME fuel was found with 32.1% while for diesel fuel was 31.2%. At low speeds, JME exhibits slightly higher engine power and thermal efficiency compared to diesel fuel. At high speeds, both engine output and efficiency are greater with JME than with diesel fuel. The main reason for the higher power and efficiency may be explained by the higher calorific value of JME. The lower bsfc with JME fuel can be attributed to its higher calorific value [23]. Furthermore, JME fuel, being an oxygenated fuel, improves combustion, particularly in fuel-rich zones as indicated by [7]. Additionally, previous study [29] has shown that using methyl ester of mango seed oil and diesel blends in diesel engine resulted in a slight increase in power and efficiency.

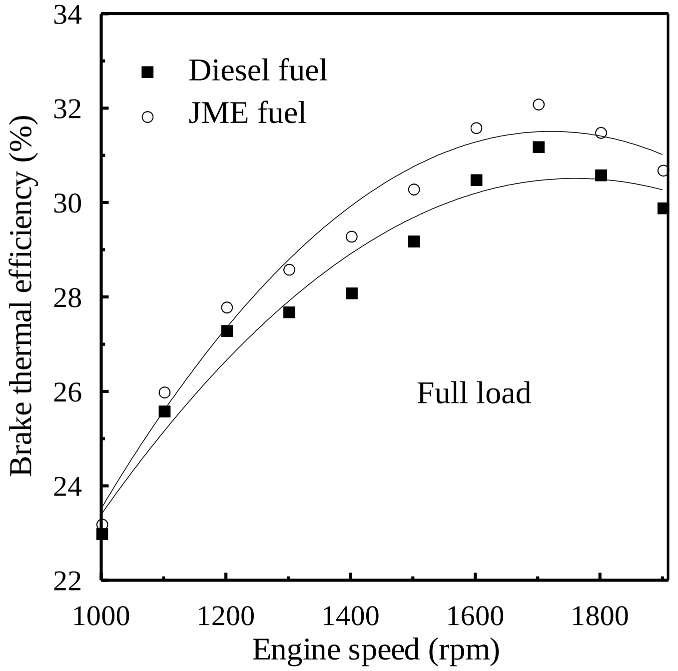

Fig. 2 Change of brake thermal efficiency with engine speed

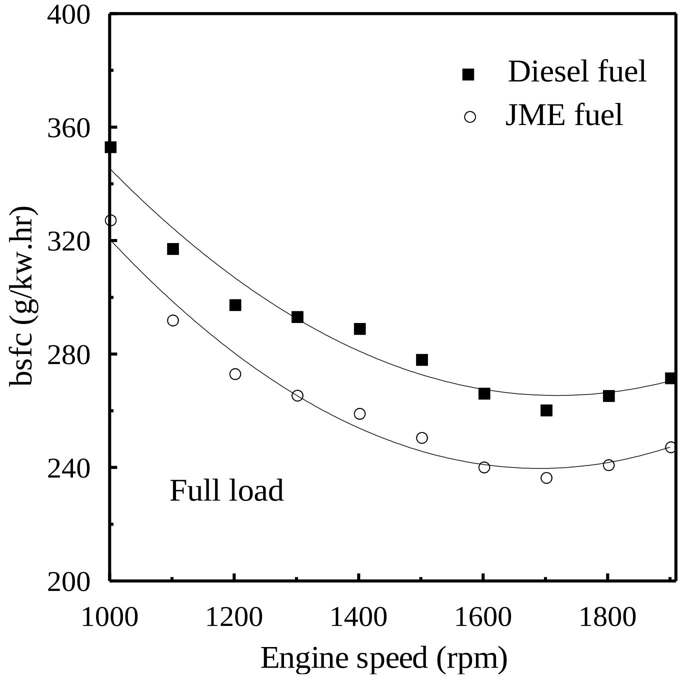

Fig. 3 Change of brake specific fuel consumption with engine speed

The variation of nitrogen oxides (NO_x) concentration with engine speed is shown in Fig. 4. The results show that NO_x emissions increase as engine speed decreases for both diesel and JME fuel. The highest NO_x emissions occur at lower engine speeds (1000–1200 rpm) and gradually decline as the engine speed increases. As the reduction in engine speed at full load increases the engine volumetric efficiency, the maximum rate at which fuel is discharged from the injector nozzle and the quantity of fuel injected per stroke [16]. Increasing in the amount of fuel injected leads to higher cylinder temperatures which result in higher NO_x emissions. it is expected that fuels with higher in-cylinder temperatures would produce more NO_x emissions [30]. Since JME fuel was higher combustion chamber temperature as indicated from measured exhaust gas temperature, as

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shown in Fig. 5. JME fuel consistently produces higher NO_x emissions than Diesel fuel at all engine speeds. It is may be due to high oxygen content of JME fuel, which leads to high combustion temperatures, favoring NO_x formation [17-19]. As shown in Fig. 4, at N = 1300 rpm, NO_x emissions with JME fuel are approximately 10.5% higher than with Diesel fuel and about 38% at N= 1800 rpm. The results of NO_x emission for JME fuel used in the study were in the range of 740-290 ppm.

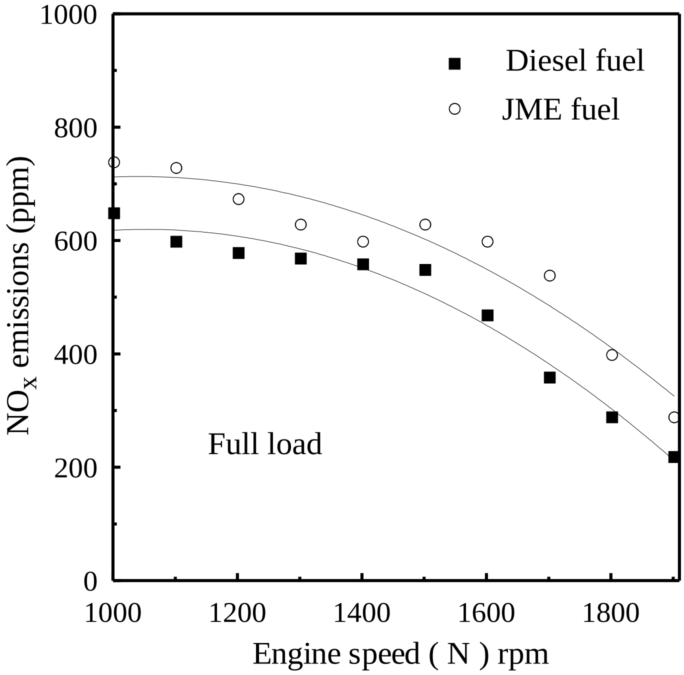

Fig. 4 Change of nitrogenous oxides emissions with engine speed

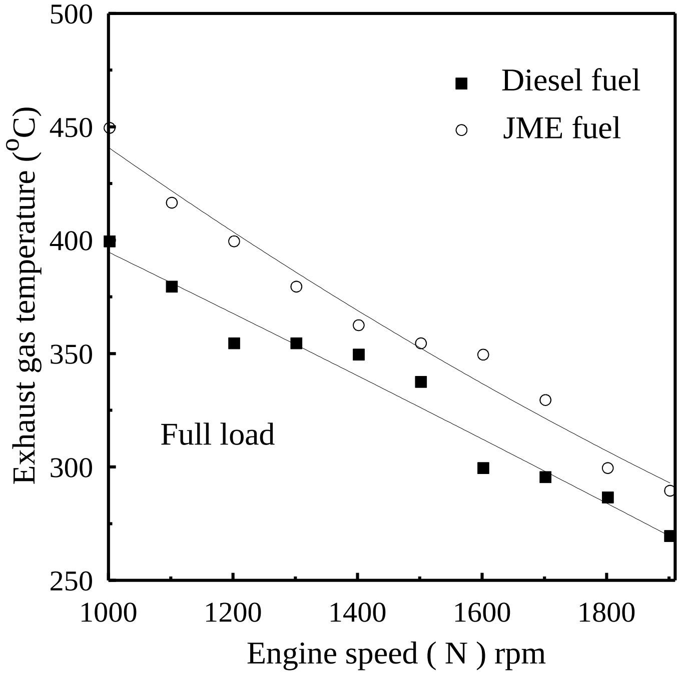

Fig. 5 Change of exhaust gas temperature with engine speed

The variation of carbon monoxide (CO) emissions versus engine speed at full load is shown in Fig. 6. The results indicate that the reduction in engine speed produce higher CO in the exhaust for both diesel fuel and JME fuel. The highest CO emissions occur at lower engine speeds (1000–1200 rpm). It may be due to the increasing of the amount of fuel per stroke and decreasing in swirl intensity within the cylinder which causes poorer mixing [16]. At low speeds, CO emissions with JME fuel are slightly higher than the diesel fuel and that due to the higher viscosity of JME fuel which causes poorer atomization and distribution of the JME fuel air, affecting combustion quality [13]. As shown in Fig. 6, At high speeds, CO emissions from JME fuel are lower than those from diesel fuel that may be due to the beneficial effect of JME fuel as an oxygenated fuel which promotes more complete combustion as previously mentioned. In the case (N= 1500 rpm), CO emissions of JME fuel decreases by 4.8% compared to diesel fuel while with 1900 rpm decreases by 11%.

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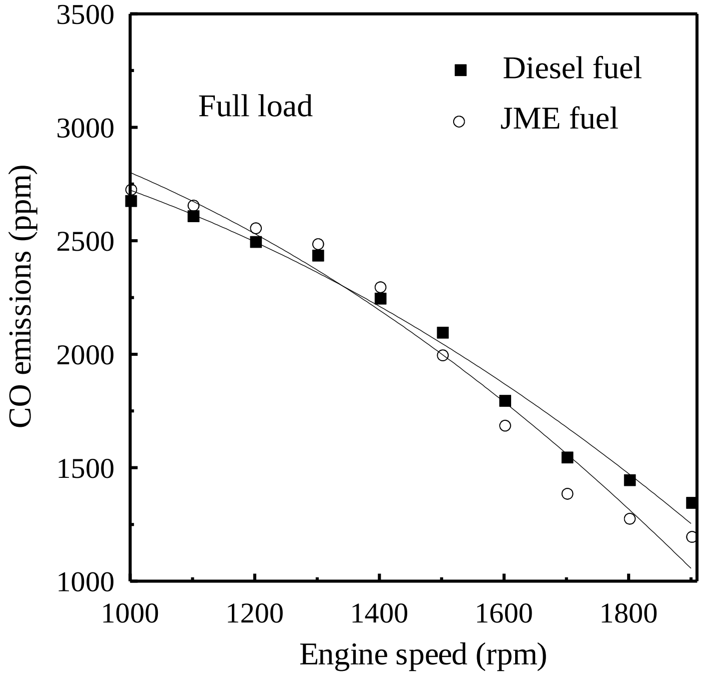

Fig. 6 Change of CO emissions with engine speed

Figure 7 illustrates the variation of unburned hydrocarbon (HC) emissions with engine speed at full load. As shown in the Figure, HC emissions decrease as engine speed increases for both diesel and JME fuel. The high engine speeds lead to the complete mixing process and complete combustion [16]. Conversely, as engine speed decreases, HC emissions increase due to poorer fuel-air mixing. Under these conditions, there is fuel and air mixed locally to proportions less than the lean flammability limit. Thus, this local fuel mixture does not burn and will increase the HC concentration. Additionally, as engine speed decreases, Higher heat loss to the coolant increases leading to lower combustion temperatures and higher HC emissions in the exhaust gases. As shown in Fig. 7, at engine speeds of 1000–1400 rpm, JME fuel exhibits slightly higher HC emissions than diesel fuel. However, there is no appreciable difference between HC emissions with JME and diesel fuel at high speeds (1400–1900 rpm).

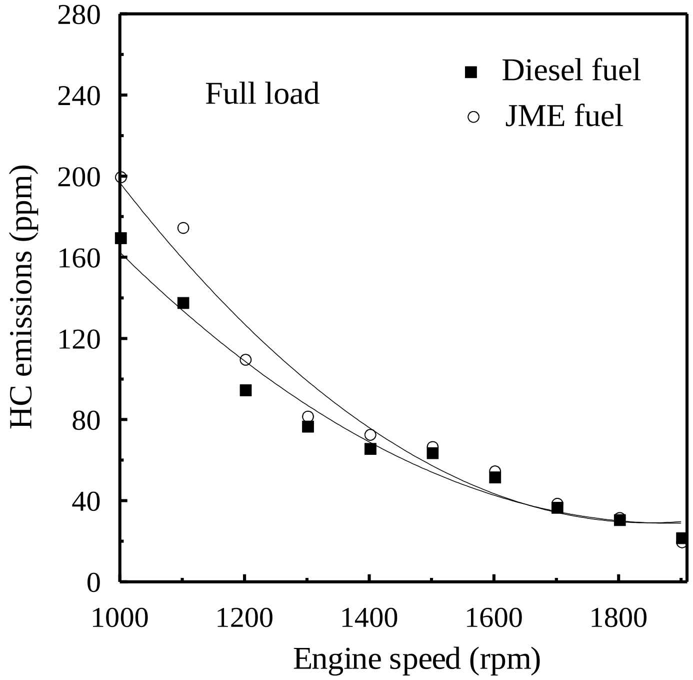

Fig 7 Change of HC emissions with engine speed

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In this section, a decrease in CO and HC emissions was observed under most operating conditions when using JME fuel compared to diesel fuel. However, an increase in NO_x emissions was noted across all operating conditions. Overall, the engine performance with JME was equivalent to that of conventional diesel fuel. The next section focuses on reducing NO_x emissions by utilizing a wide range of exhaust gas recirculation (EGR) rates with JME as fuel.

4.2 Experimental study on diesel engine with JME using EGR technique

Figure 8 shows the influence of different exhaust gas recirculation (EGR) rates on NO_x emissions and brake specific fuel consumption when using JME fuel with 1500 rpm under full load. In general, the results indicate that increasing EGR rates leads to an increase in bsfc and a decrease in NO_x emissions. As stated before, this is mainly attributed to dilution of fresh intake air by exhaust gases, which causes decrease of oxygen concentration of in-cylinder combustible and lowers the peak combustion temperature. To optimize NO_x emissions reduction while minimizing bsfc penalty, EGR rate should be increased gradually from 0% to the maximum allowable value by using an EGR valve.

As shown in Figure 8, the maximum reduction in NO_x emissions with minimal impact on fuel economy occurs at an EGR rate of 3–6%. Up to this range, bsfc decreases, or fuel economy improves, with increasing EGR. This improvement is due to the enhanced thermal efficiency of the engine, as unburnt hydrocarbons in the recirculated exhaust gases may undergo re-combustion, reducing unburnt fuel in the exhaust [16]. Additionally, lower combustion temperatures with EGR help to minimize heat loss to the cylinder walls. When EGR rates exceed 14%, NO_x emissions are significantly reduced, but bsfc increases sharply, making such high EGR rates impractical for real-world applications. This comes at the cost of increased fuel consumption. At higher EGR rates with 20%, NO_x emissions drop significantly (~220 ppm). At 0% EGR, bsfc is approximately 250.8 g/kWh, rising to 360 g/kWh at 20% EGR. Under high-load conditions, the temperature of the mixture of EGR and fresh air increase, the cylinder trapped mass decrease and that has a detrimental effect on the volumetric efficiency [30]. Studies [16,17] also indicate that, at high load, the heat capacity increases as the concentrations of CO_2 and H_2O are substantially higher. Both these molecules have higher than air heat capacities and with H_2O being much higher than CO_2 at typical combustion temperatures. With the higher heat capacity of the mixture, more energy is required to pre-heat the incoming mixture, thus lowering the flame temperature and deterioration in diffusion combustion. As shown in Figure 7, employing EGR rates with16% becomes challenging, as it results in excessive increases in bsfc up to 24%. At this level of EGR, NO_x emissions are reduced by approximately 49%, but the fuel consumption penalty may outweigh the emissions benefits.

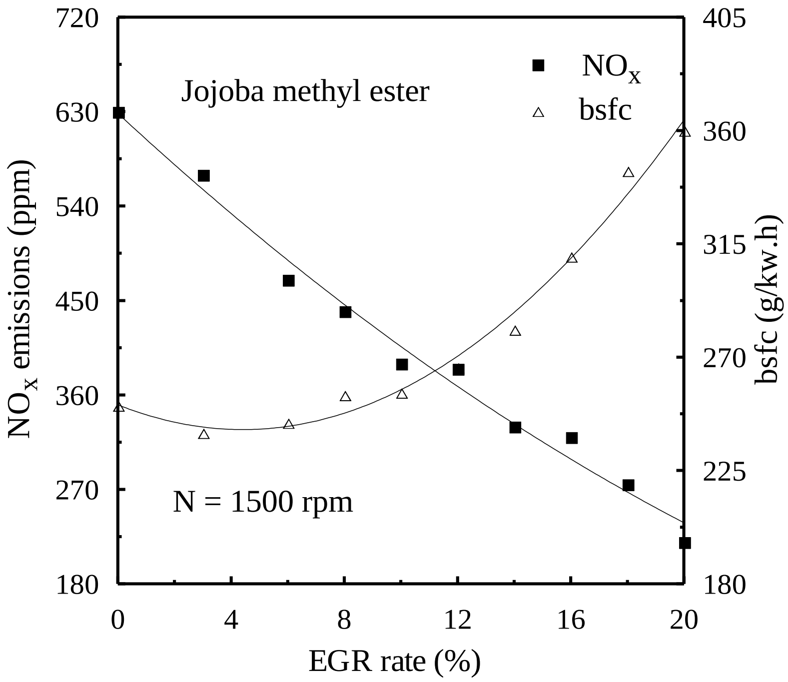

Fig. 8 Change of NO_x and bsfc with EGR rate at N=1500 rpm

The effect of EGR rate on exhaust gas temperature is illustrated in Fig. 9. As expected, exhaust gas temperature decreases gradually with an increasing EGR rate. Since the composition of the EGR of diesel engine varies with load. At full load, the heat capacity increases as the concentrations of CO_2 and H_2O are substantially higher so EGR rate can be used for reduction in exhaust gas temperature from 355°C at 0% EGR to about 183°C at 16% EGR rate. As stated before; Increasing EGR rate augments the amount of inert gas in the combustion chamber, lowering the burned gas temperature and therefore lowering the NO_x emissions [16]. The drop in exhaust gas temperature with an increasing EGR rate is in agreement with the previous studies [17-20]. Therefore, EGR technique is an effective strategy for NO_x control in diesel engines.

It is important to measure the quantity of HC and CO emissions in the exhaust gases when using EGR method with JME fuel as they are an indicator of the completeness of the combustion [16]. NO_x emissions depend strongly on temperature. While HC and CO emissions are reduced by an increase in combustion temperature, NO_x generally increases due to the increased reaction rate of chemical reactions involving oxygen and nitrogen. The effect of EGR rate on HC and CO emissions is shown in Fig. 10. It is observed that at EGR rates up to 6%, combustion efficiency remains relatively stable, with minimal decreases in CO emissions and no noticeable changes in HC emissions. This indicates a more efficient, more complete combustion process and thus explains the lower CO emissions. Adding 6% of EGR rate to JME fuel reduced CO emissions by 5.6%. The presented results indicate that CO emissions in tests increase with addition of EGR rates greater than 6%. Unfortunately, CO emissions increase rapidly with greater levels of EGR rate and this mean that combustion quality worsens with the increase of EGR rate. The high EGR levels introduce more recirculated exhaust gases and that reduce oxygen availability in the combustion chamber. As a result, incomplete combustion occurs. At a 16% EGR rate, CO emissions increase by 58% while HC emissions increase by 34% compared to 0% EGR. There is trade-off between HC, CO and NO_x emissions with increasing EGR rate because of reduction of HC and CO emissions needs high temperature and complete combustion, which requires good fuel/air mixing and enough oxygen [17,18]. Therefore, EGR can bring satisfactory results for NO_x reduction, but at the same time, HC and CO emissions increase, negatively affecting engine efficiency. Based on the emissions data presented above, a better trade-off between HC, CO and NO_x emissions can be achieved within a limited EGR rate of 6% to 12%.

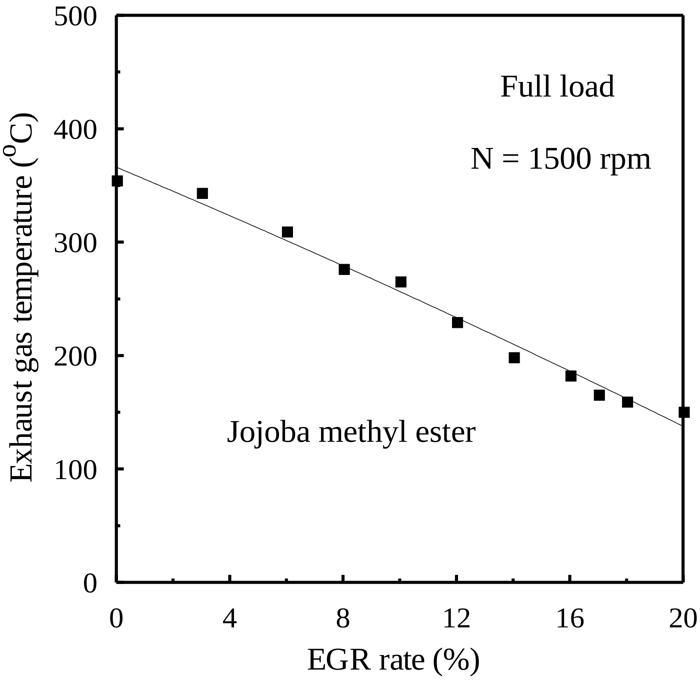

Fig. 9 Change of exhaust gas temperature with EGR rate at N = 1500 rpm

International Journal of Engineering Research & Technology (IJERT)
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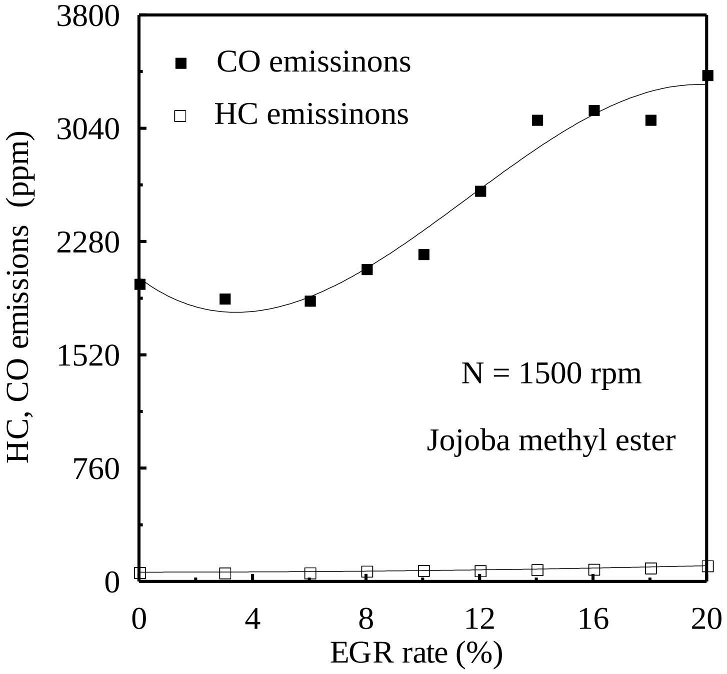

Fig. 10 Change of CO and HC emissions with EGR rate at N= 1500 rpm

5. CONCLUSIONS

The study examined the experimental effect of exhaust gas impairment (EGR) on emissions and performance in a diesel engine fuel with jojoba methyl ester (JME). Key findings from analysis of thermal efficiency, emissions, exhaust gas temperature and combustion quality are summarized as follows:

1. JME fuel provides better thermal efficiency than Diesel fuel across all engine speeds.
2. CO emissions from JME fuel are lower than diesel fuel, particularly at higher speeds, making it a more environmentally friendly alternative.
3. At lower engine speeds, JME fuel exhibits slightly higher HC emissions than diesel fuel. However, at higher engine speeds, the difference becomes negligible.
4. NO_x emissions were higher with JME fuel compared to diesel fuel under various operating conditions.
5. An optimal EGR rate was identified to achieve NO_x emissions reduction while minimizing the BSFC penalty.
6. EGR rates above 16% significantly reduce NO_x but cause a substantial increase in bsfc, making them impractical for most applications.
7. With the application of EGR method, the CO and HC emissions in the engine-out emissions increased.
8. The exhaust gas temperatures were reduced continuously with increasing EGR rate.
9. A better trade-off between HC, CO and NO_x emissions can be achieved with an EGR rate between 6% and 12%, minimizing economic penalties.
10. JME fuel remains a viable alternative with minor performance compromises, making it especially suitable for applications prioritizing sustainability.

International Journal of Engineering Research & Technology (IJERT)
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