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Exhaust Gas Recirculation (EGR): An Effective Technique for NO_x Emission Reduction of Waste Cooking-Oil Biodiesel

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***Abstract*:- Biodiesel is considered as an environmentally friendly alternative diesel fuel. In the present study, biodiesel from Waste Cooking Oil (WCO) was prepared using the usual transesterification process. Experiments performed on a single cylinder naturally aspirated direct injection diesel engine fueled with different mixed concentrations of biodiesel and diesel fuel, including B0, B10, B20 and B30.**

The effect of a water cooled Exhaust Gas Recirculation (EGR) rates as 0%, 10%, 20%, 25% and 30% on diesel engine performance characteristics and exhaust emission were investigated.

The results show that with increase of % EGR rates, value of CO emissions increases but values of NO_x and EGT decrease. Whereas 25% EGR exhibited reduction in both of NO_x emission and BSFC by 71% and 45% respectively, 30% EGR demonstrated a slight reduction in both of NO_x emission and BSFC as 72% and 23% respectively with respect to the pure petroleum diesel.

The recommended EGR is 25% which exhibited highest reduction in BSFC and NO_x emission.

Keywords: Biodiesel, Exhaust gas recirculation, NO_x emission

1. INTRODUCTION

In the recent past decades, many experts expect that the coming conflicts and wars between countries will revolve greatly around crude oil energy because of its limitation and cost, therefore exploring new clean energy resources instead of petroleum-based products has become more important and necessary than ever. Biodiesel is considered as an alternative energy resource in place of traditional fuel diesel as it is characterized with its renewability, inhibition of soot formation and potential of reducing greenhouse gas emissions [1] [2].

Biodiesel fuel could be obtained from vegetable oil or animal fats such as soybeans, Jatropha, sunflowers, palm and waste cooking oil (WCO) [3]. One of many biodiesel derived from various resources, biodiesel from (WCO) started to attract significant attention of researchers, governments and industries because of its economical preparation using usual transesterification process and reduction of waste oil disposal which considered as a valuable recycling process [4]. Whereas the biodiesel are typically associated with low CO and HC emission, the NO_x emission is high according to the environmental law [5]. The most widely accepted mechanism of NO_x formation was investigated by Zeldovich [1]. It is reported that the two main toxic pollutants (NO and NO_2) are emitted together as NO_x and directly affected with the operating temperature [6]. An effective technique for NO_x reduction in the exhaust gases is the usage of Exhaust Gas Recirculation (EGR). This technique was initially presented at the University of Birmingham [7] which based on recirculation a part of exhaust gases to the engine then blending the fresh intake air with the recirculated exhaust gas leading to lowering the excess oxygen and reduction of the adiabatic flame temperature.

Many researches were conducted with EGR by various approaches like: the variations in the engine geometry, less reaction time, compression ratio and temperature associated with the biodiesel [8] [9]. EGR classification was based on the temperature as hot, partly and fully cooled EGR [10]. In this work, a fully cooled EGR is conducted and its effects on the performance and exhaust emission characteristics of a DI Diesel engine were investigated.

Formation of NO_X in Diesel Engine

The communal term NO_X condenses various nitrogen compounds. In the engine exhaust gas, there are usually two restricted species of nitric oxide and nitrogen dioxide. NO is the dominant component, whereas NO_2 is usually only a few percent of the total NO_x emissions in the raw exhaust gas. Maximum ratios of NO_2/NO_X may be up to 30 percent, but under usual operating conditions the quantity of NO_2 lies between 5:10 percent of the total NO_X[11]. The extended Zeldovich mechanism, [1] that defines the formation of nitric oxides with excess oxygen at high local peak temperatures above 2000 K, is reflected to be the most relevant formation path for compression ignition combustion engines. Along with the N_2O mechanism, the formation of NO_x in Diesel combustion processes may be described quite completely. The N_2O mechanism depends on the reaction of N_2 + O with a third-body molecule to form N_2O, which is able to react with oxygen atoms in 2NO under lean conditions. The formation of internal engine NO_2 is not as detailed as the formation of NO. Previous studies show that NO_2 forms from already existing NO. This is the reason that NO_x emissions are accurate considering the approaches for the formation of NO.

Reaction with HO_2 is assumed to be the most dominant path for the conversion of nitric oxide to nitrogen dioxide.

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$NO + HO_2 \rightarrow NO_2 + OH$ (1)

The most important factors that influence the conversion of NO to NO_2 are: temperature, reaction time, fuel type and the initial concentration of fuel (λ), NO and O_2. It is known that NO_2 is only produced at lower temperatures as above 1200K NO_2 returns to NO [11].

EFFECTS OF THE OXIDES OF NITROGEN

The oxides of nitrogen are causing negative effects on human health and the natural environment. Oxides of nitrogen pollutants are known to cause destruction of the ozone layer, acidic rain, poor visibility due to smog, poor air quality, also they contribute in rising the temperature leading to global warming.[12]

Global Warming; The stratosphere ozone layer is destroyed by oxides of nitrogen emissions; therefore, it increases the high energy ultra-violet rays (UV). It also warms up the earth's surface, due to the decreased reflective capacity of the lower atmospheric layers. [12]

Smog and Visibility; Smog is a combination of smoke and fog. It represents cloud formation from photochemical reactions of the sun with the hydrocarbons and oxides of nitrogen emission wastes from automobiles and stationary engines. Smog irritates eyes and throat, and causes weakening the lungs capacity, emphysema, bronchitis, asthma, inflammation of the breathing passages, shortness of breath, damages the plants and crops, and destroys rubber products by cracking them. Poor visibility is caused by nitrogen oxide absorbing the full visible spectrum of the light energy, thus leading to poor visibility even in the absence of particulate matter (PM). [12]

The Ozone; The oxides of nitrogen are vital to the formation of ozone and aerosols ($PM2.5$) in the atmosphere which have a negative effect on air quality, acid deposition and the balance of atmospheric radiation. NO_X is decreasing the thermal layering of the stratosphere and increase the earth's surface temperature. Exposure to a concentration level of 2500 μm/m3 of NO_X for one-hour decreases a human being's lung volume and maximum breathing, thus harming breathing and can lead to death, while revelation to ozone causes pulmonary hemorrhage with symptoms such as a dry throat, stark headache, disorientation and altered breathing patterns. [12]

Toxicity; Nitrogen dioxide is a very toxic gas which annoys the entire pulmonary system. [12]

Acidic Rain; the increase of oxides of nitrogen in the atmosphere increases the acidic deposition which tends to decrease ecosystem stability. Acidic rain is caused by a chemical reaction which starts first with Sulphur dioxide compounds reacting with oxides of nitrogen that have been released to the stratosphere. Sulphur dioxide and oxides of nitrogen react and dissolve in water and can be transported by wind. Once they mix and react in the presence of moisture, they form more pollutants that form the acidic rain. [12]

2. EXPERIMENTAL SETUP

2.1 Fuel materials

The primary raw material for biodiesel preparation used is waste cooking oil (WCO), which was collected from various sources such as hostels, restaurants, cafeterias. WCO cannot be used directly in diesel engines. It's high viscosity and moisture content with low volatility may cause severe engine deposits and injector coking [13]. As a result, filtration was operated to remove impurities suspended in the oil, such as solid matter and food residues and also the traces of water present in the oil are removed before transesterification process by initial heating. The WCO produced by transesterification process and characterized with specific parameters listed in table.1 was used to fuel the engine for this study.

Fuel property	Waste cooking oil Biodiesel	Mineral diesel fuel
Kinematic viscosity (mm^2/s at 313K)	5.3	1.9 - 4.1
Density (kg/L, at 288K)	0.897	0.84
Flash point (K)	469	340 – 358
Cetane number	54	44 – 46
Water content (%)	0.4	0.02 - 0.05
Higher heating value (MJ/kg)	42.65	42.79—46.48

Table.1: Fuel properties

2.2 Instrument setup

Experiments were carried out on a single cylinder naturally aspirated direct injection diesel engine fueled with different mixed concentrations of biodiesel and diesel fuel, including B0 (diesel fuel), B10 (10% WCO + 90% diesel fuel), B20 (20% WCO + 80% diesel fuel) and B30 (30% WCO + 70% diesel fuel) by volume. The applied engine specifications are given in Table 2.

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Model	FL511
Cylinder number	1
Chamber type	Direct injection
Bore x stroke (mm)	100X105
Speed (r/min)	1500
15-minute output rating (kW/hp)	6.8/9.2
12-hour output rating (kW/hp)	5.7/7.7
Maximum torque (Nm)	44
Min. stable speed without load (r/min)	700
Power/Rev. [kW/(hp)/rpm]	5.7(7.7)/1500
	7.3(9.9)/1800
	8.2(11.1)/2000
	9.7(13.2)/2500
	10.5(14.3)/2800
	10.9(14.8)/3000
Cooling Method	Air-cooled
Starting Manner	Electrical
Net Weight (kg)	150
Gross Weight (kg)	180
Overall dimensions (L*W*H) (mm)	437*530*671

Table 2. Specifications of the engine

The overall system setup is illustrated in Figure 1. The setup is equipped with instruments for fuel flow rate, temperature, dynamic load, combustion pressure, gas analyzer and a cooled EGR where the exhaust gas is cooled before mixing with fresh intake air using a water-cooled heat exchanger; the test diagram is shown in figure 2. The experiment is performed at a constant engine speed of 1500 rpm and a constant compression ratio of 17 by loading the engine with different loads ranging from no load condition to full load. The load on the engine is measured by using a set of 6 heaters each of 1 kW, using a power variac transformer, voltmeter (accuracy of ±3%) and a current clamp (accuracy of ±2%), as shown in the figure (1). The exhaust temperature and the intake air temperature are measured by using a K-type thermocouple. The mass flow rate of the fuel is measured by putting the fuel tank on an electric balance and operating the engine for 15 minutes for every change in the load. The mass flow rate of the intake air is measured by using an air box, orifice and a manometer that are connected to the intake manifold. The air to fuel ratio and the equivalence ratio are calculated for every blend at every load by using the stoichiometric combustion equations for every blend. A gas analyzer device shown in the figure (1), of Lano type and its model is Lancom series III (accuracy of ±10 ppm) is used to measure the amount of carbon monoxide (ppm) and nitrogen oxides (ppm).

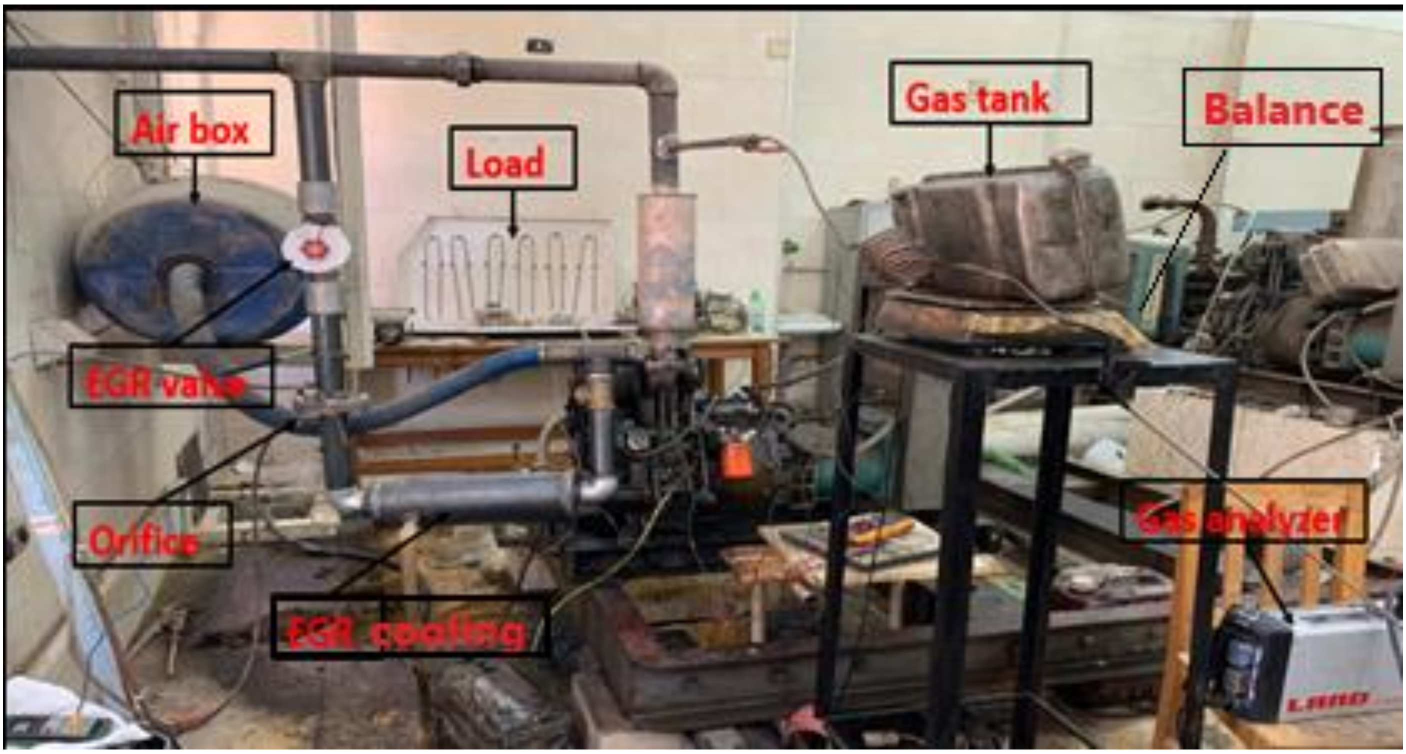

Figure 1: System setup

International Journal of Engineering Research & Technology (IJERT)
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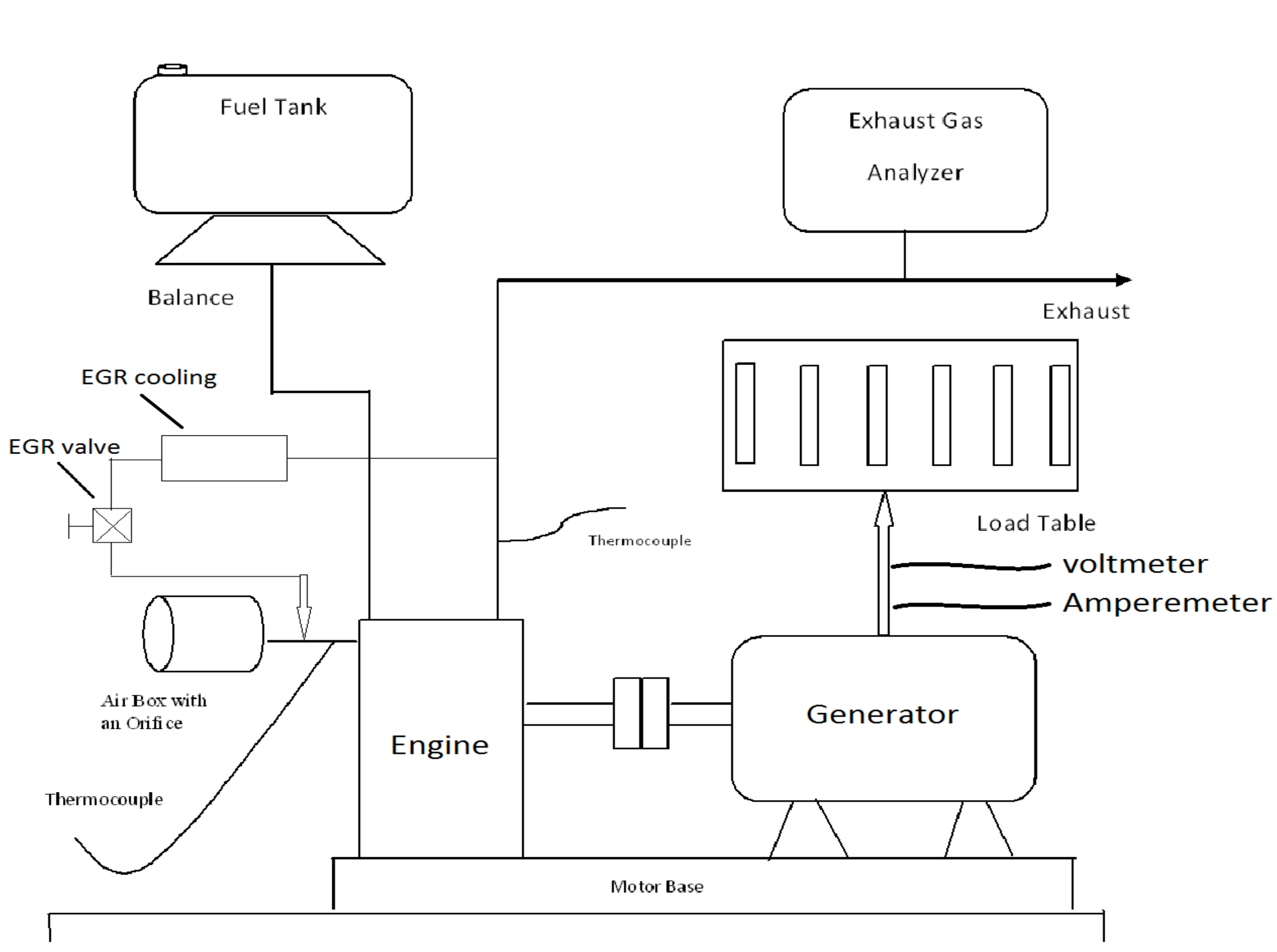

Figure (2) Schematic diagram of the test rig.

The EGR percentage is defined as the volume of EGR to total intake charge into the cylinder. As shown in equation 1.

$$\% \text{ EGR} = \frac{\text{Volume of EGR}}{\text{Total intake charge into cylinder}} x \; 100 \qquad \text{Equ.1}$$

The different EGR rates of 0%, 10%, 20%, 25% and 30% were considered to study the impact of EGR on performance and emission characteristics for an engine fueled with waste cooking oil Biodiesel blends with diesel. The variation of gaseous emission characteristics (NO, CO), Brake Specific Fuel Consumption (BSFC), Exhaust Gas Temperature (EGT) with EGR were investigated

3. RESULTS AND DISCUSSION

3.1 NO_x emissions

The gaseous emissions including total nitrogen oxides (NO_x) and carbon monoxide (CO) were measured and compared when the engine is fueled with various test fuels at different engine loads and EGR.

Figure 3 shows the variation of NO_x emissions at different loads. The NO_x emissions were noted to be higher for blended fuels compared to diesel at all applied load. When the blend ratio increases NO_x emissions also increased. It could be investigated as differences in the viscosity and compressibility between the diesel fuel and biodiesel blends [14].These results agree with the results of Senthilkumar, K. R., Deshmukh, P.A. , and Pandhare, P., and disagree with the results of Mavropoulos, G. C. This may be due to differences in the properties and type of the used biodiesel.

International Journal of Engineering Research & Technology (IJERT)
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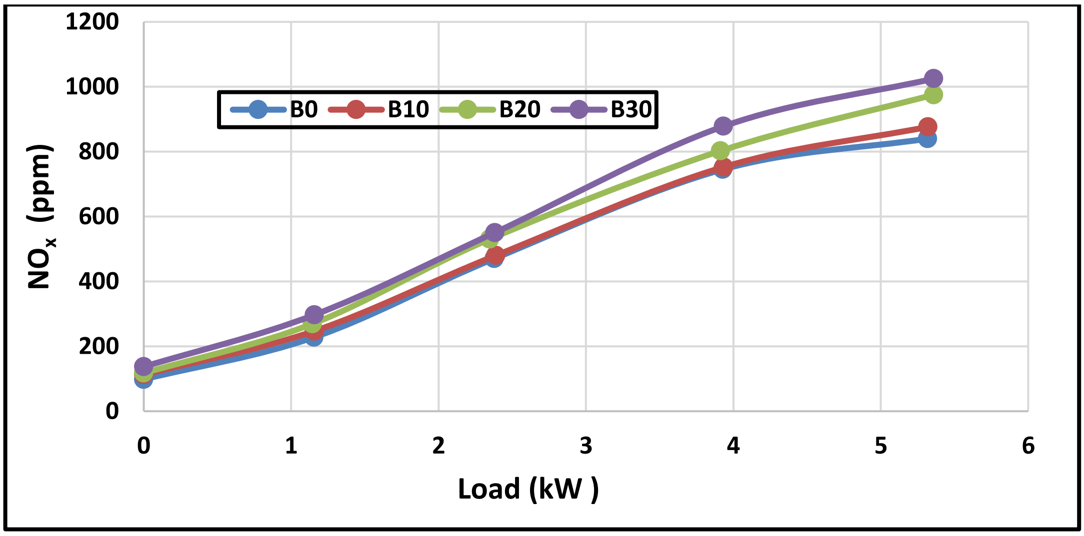

Figure 3: Variation of NO_X emission with load

As a result, the biodiesel would take long combustion time compared to diesel resulting in higher exhaust temperature. The disassociation of NO_2 is repressed by the higher temperature resulting in the formation of higher amount of NO_x in biodiesel.
Also, with increase in load, the NO_x values increased. This increase in NO_x is attributed to more heat release caused from dissociation of gases.
Figure 4 shows the favorable impact of EGR in reducing NO_x emission from the engine. NO_x emission decreases significantly with EGR rates for different blends. This result may be explained by the fact of low peak temperatures and less oxygen concentration of the working fluid in the combustion chamber [15]. This result agrees with the results of all authors in references.

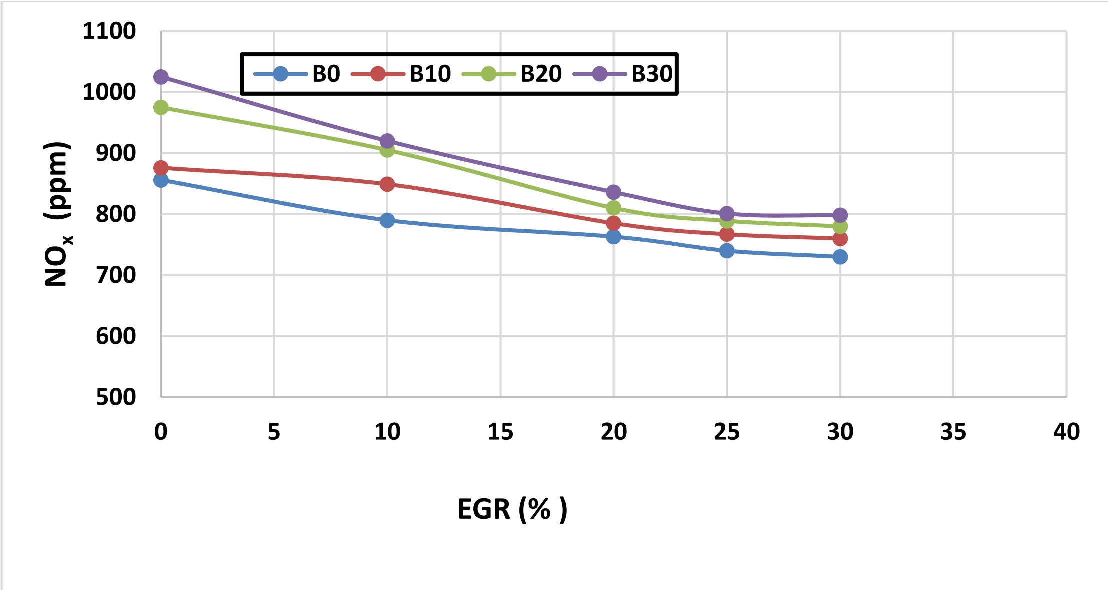

Figure 4: Variation of NO_X emission with EGR at maximum applied load.

3.2 CO emissions

Figure 5 shows the variation of CO emission of B0, B10, B20 and B30 fuel with EGR rates at full load condition.

International Journal of Engineering Research & Technology (IJERT)
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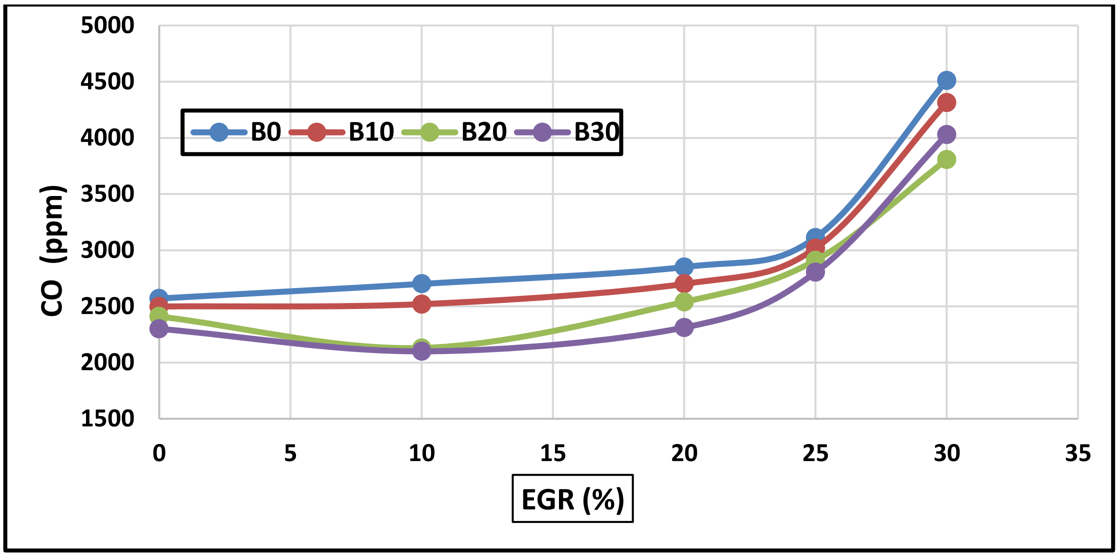

Figure 5: Variation of CO emission with EGR at maximum applied load.

The CO amounts increase with the increase in EGR rates. The higher EGR rates, the higher CO emissions because of lower availability of oxygen due to EGR leading to incomplete combustion caused by shorter combustion duration and less homogeneous mixture. All recent studies agree with these results.

3.3 Exhaust Gas Temperature

Figure 6 shows the variation of Exhaust Gas Temperature (EGT) with EGR. It has been observed that EGT decreases with the increase in EGR rates.

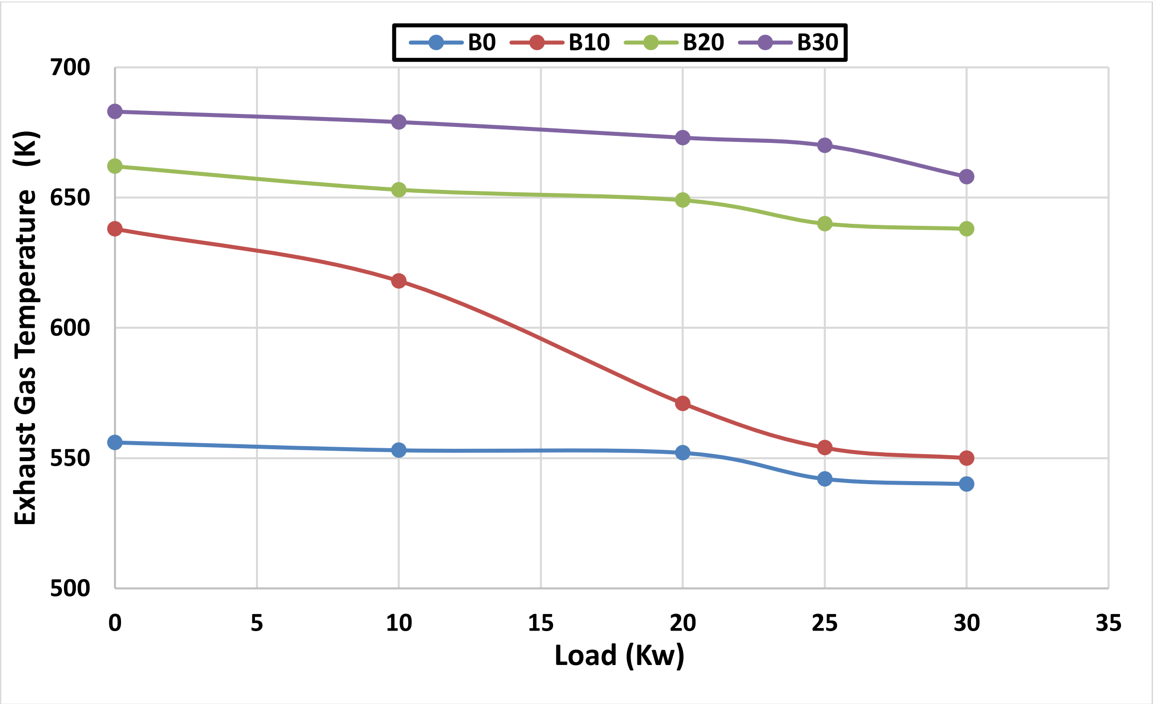

Figure 6: Variation of Exhaust gas temperature with EGR.

The reasons for exhaust gas temperature reduction are related to the lower availability of oxygen for combustion and higher specific heat of intake air mixture. The exhaust gas increases the specific heat of the mixture due to non-reacting matter present during the combustion. As a result, the reduction of the peak combustion temperature is presented [16]. These results are close to the results of Pandhare P. and disagree with Khote M.A. This may possibly because he used a hot EGR or the type of biodiesel used.

Figures 7 and 8 show the variation of NO_x emissions with Exhaust Gas Temperature (EGT) at 0% and 25% EGR. It has been observed that NO_x emissions increase with the increase in EGT. The relationship between NOx emitted and the exhaust temperature was correlated non-linearly, and the fitted equation was shown on curves, the fitted data was excellent, the R squared ranged between (0.952:0.984), these results are more accurate than Al-Shemmeri T.T. as he used linear curve fitting.

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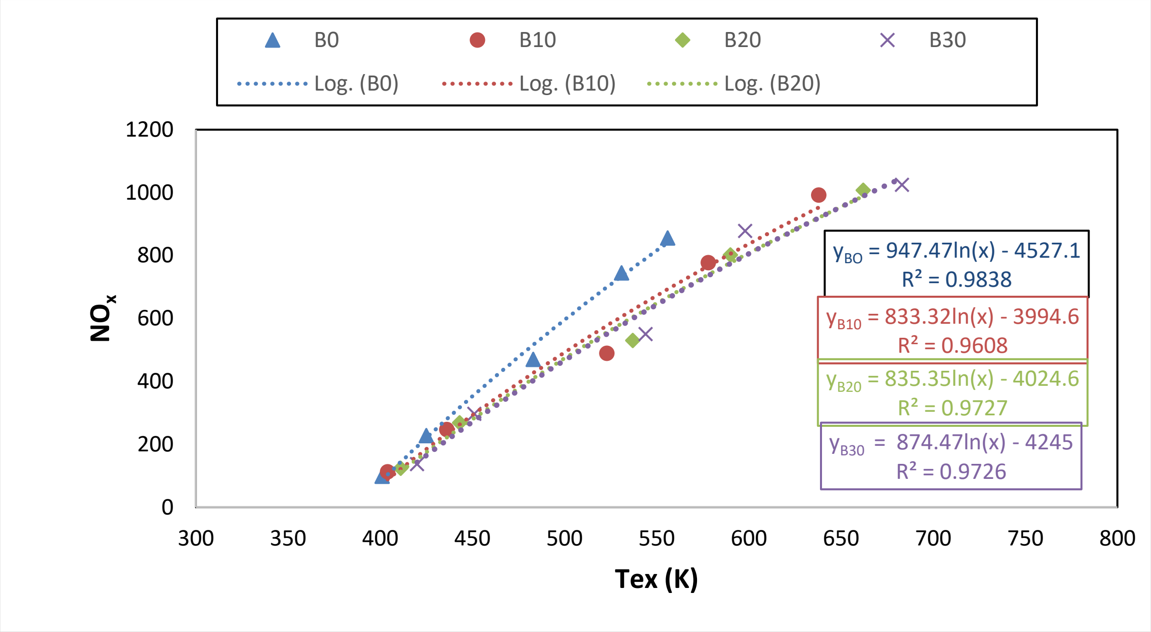

Figure 7: Variation of NOx emissions with Exhaust gas temperature at 0% EGR.

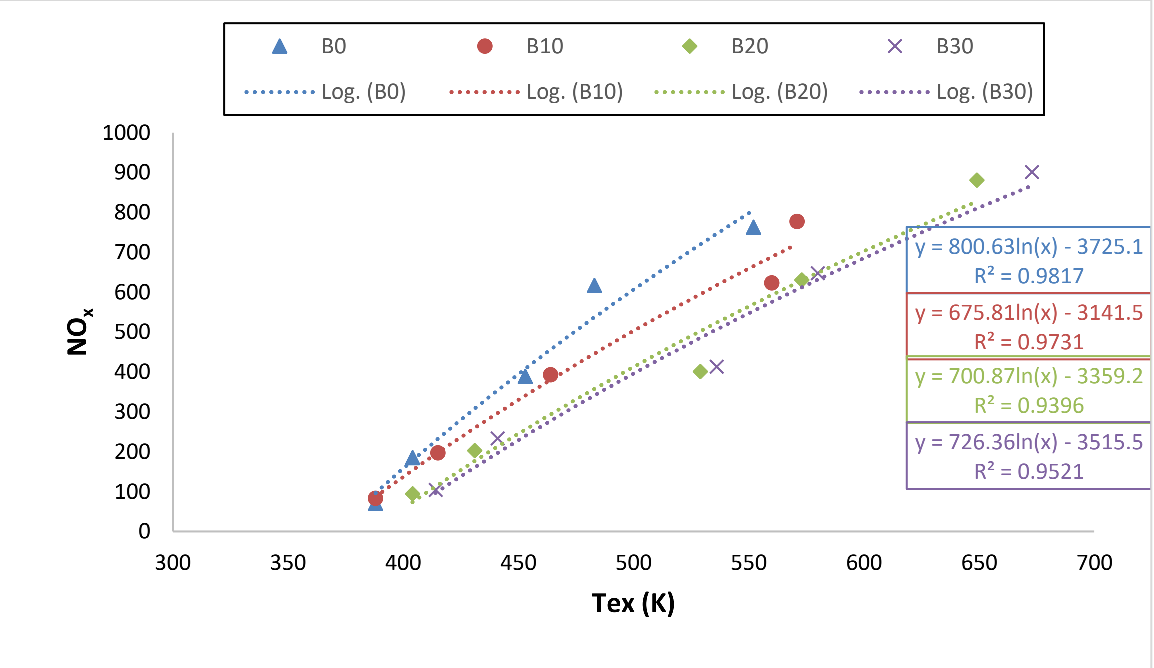

Figure 8: Variation of NOx emissions with Exhaust gas temperature at 25% EGR.

3.5 Brake Specific Fuel Consumption (BSFC)

Figure 9 shows the variation of (BSFC) with various applied loads for both diesel and biodiesel. It is observed that, while the load increases, BSFC of all fuels decreases. The minimum BSFC was obtained for diesel in comparison with all other biodiesel/diesel blends used in this study.

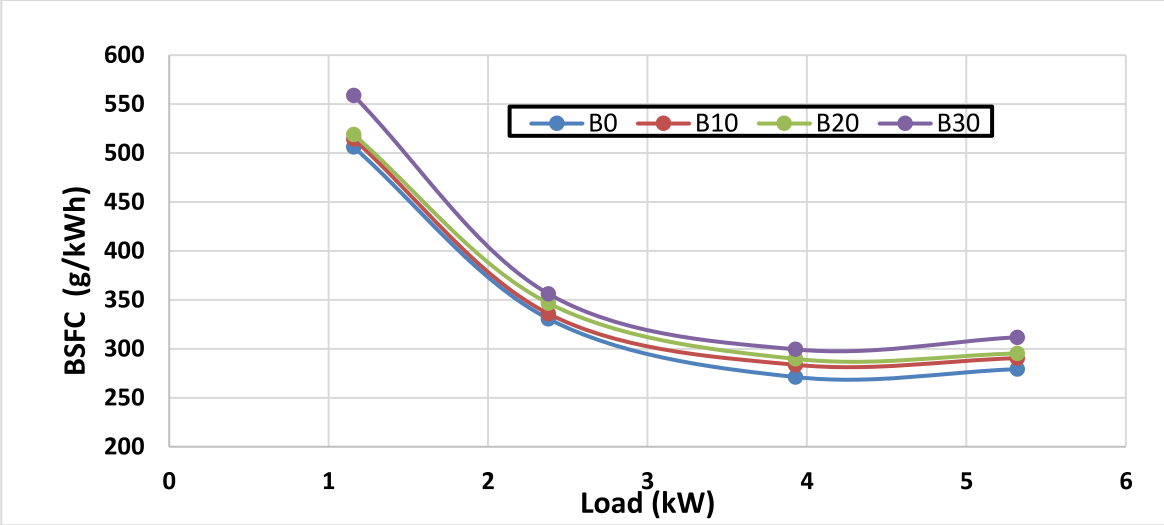

Figure 9: Variation of brake specific fuel consumption with load.

The primary reason for this increase in BSFC with the increase in fuel blends, is the additional consumption of biodiesel fuel by the test engine in order to maintain constant power output. Additionally, the density of biodiesel fuels is higher than that of diesel, the plunger (in the injection pump) discharges more blended fuel compared to that of diesel to maintain constant output power.

Figure 10 shows the variation of both of NO_X emission and BSFC with EGR for B30 at full load.

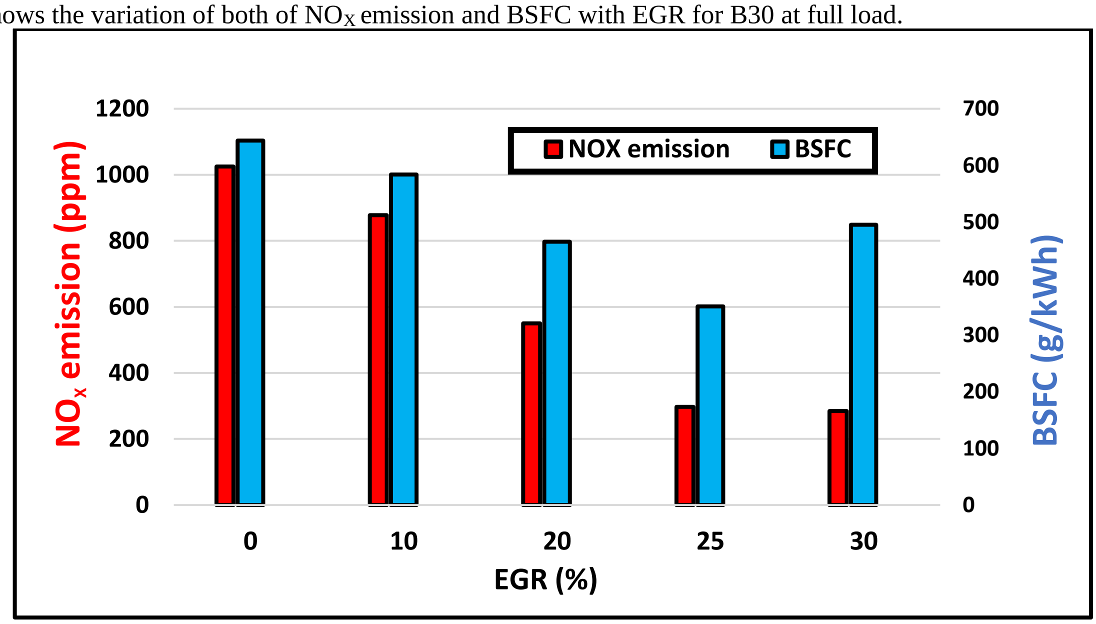

Figure 10: Variation of NO_X emission and BSFC with EGR % with different blends at maximum load

Whereas 25% EGR exhibited reduction in both of NOx emission and BSFC by 71% and 45% respectively, 30% EGR demonstrated a slight reduction in both of NOx emission and BSFC as 72% and 23% respectively with respect to the base diesel. BSFC dramatically increases with EGR rates above 25% at all blends, this may be due to the fact that the formation of rich mixture with less oxygen availability.

4. CONCLUSION, RECOMMENDATIONS, AND FUTURE WORK:

4.1 Conclusion:

Generally, biodiesel leads to a reduction of CO and HC, but an increase in NO_x. Moreover (EGR) technique can reduce NO_x emissions without negative effect in the performance characteristics. The lowest BSFC was obtained for all blends at 25% EGR. BSFC increases with the increase of EGR rates above this value because of the formation of rich mixture due to insufficient oxygen supply.

Eventually, these results show that the EGR rate 25% shows lower BSFC and NO_X emission, so it is recommended for the tested system.

4.2 Recommendations:

1. Add a computerized and electro controlled valve to control the amount of EGR entering the intake manifold.
2. Add more cooling to EGR system to improve the efficiency.
3. Use more factors for controlling No_x Emissions as: Injection timing, Injection rate, Air-Fuel ratio, Compression ratio. [12]

4.3 Future work:

1. Opacity of exhaust gases should be measured.
2. Particulate matters measurement.
3. Difference in cooling water temperature inside the EGR cooler.
4.

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