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Trade-off between NO_X, Soot and EGR rates for an IDI diesel engine fuelled with JB5

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***Abstract*—**Nowadays, the focus on renewable energy and alternative fuels has increased due to increasing oil prices, environment pollution, and also concern on preserving the nature. Biodiesel has been known as an attractive alternative fuel although biodiesel produced from edible oil is very expensive than conventional diesel. Therefore, the uses of biodiesel produced from non-edible oils are much better option. Currently Jatropha biodiesel (JBD) is receiving attention as an alternative fuel for diesel engine. Biodiesel is non-toxic, biodegradable, high lubricant ability, highly renewable, and its use therefore produces real reduction in petroleum consumption and carbon dioxide (CO_2) emissions. Although biodiesel has many advantages, but it still has several properties need to improve, such as lower calorific value, lower effective engine power, higher emission of nitrogen oxides (NO_X) and greater sensitivity to low temperature. Exhaust gas recirculation (EGR) is effective technique to reduce NO_X emission from diesel engines because it enables lower flame temperature and oxygen concentration in the combustion chamber. Some studies succeeded to reduce the NO_X emission from biodiesel by EGR but they observed increasing soot emission. The aim of this study was to investigate the engine performance and soot emission by using blended Jatropha biodiesel with different EGR rates. A CI engine that is water-cooled, turbocharged, using indirect injection system was used for the investigation. Soot emission, NO_X, CO_2, carbon monoxide (CO) were recorded and various engine performance parameters were also evaluated.

***Keywords*—** EGR, Jatropha biodiesel, NO_X, Soot emission.

I. INTRODUCTION

Diesel engines are used in wide range because its advantages such as greater efficiency, durability, and good fuel economy compared to gasoline engines. The applications of diesel engines are in electric power generation, agricultural, construction, industrial fields, and mostly in transportation sector such as bus, truck, train and ship. These wide uses of diesel engines lead to increasing requirement for petroleum derived from fossil fuel. The depletion of fossil fuel and the impact of increasing environmental pollution from exhaust gas emission have led to search for alternative fuels.

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To solve both energy concern and environmental concern, the renewable energies with lower environmental pollution impact should be necessary. Nowadays, there are many sources of renewable energy. Biofuels are just one source, but a very important one [1].

Biofuel oils can produced from plants (edible or non edible), algae, and animal fats. The use of non-edible plant oil is particularly interesting, as these are generally cheaper than edible oils. Productivity of non-edible oils tend to be higher, for Jatropha as example its productivity 1590 kg of oil per hectare [2]. Therefore, big biodiesel development countries like Malaysia focus on producing biodiesel from Jatropha [3].

A. Jatropha Curcas L.

Jatropha is a non-edible plant, grow in waste lands and consume less water. Also, biodiesel from Jatropha have advantages compared to conventional diesel fuel such as [4]:

i. The Jatropha Biodiesel molecules are simple hydrocarbon chains, containing no sulfur, or aromatic substances associated with fossil fuels. They contain higher amount oxygen (up to 10%) that ensures more complete combustion of hydrocarbons.
ii. Biodiesel almost completely eliminates lifecycle carbon dioxide emissions.
iii. Jatropha Biodiesel has a high flash point, or ignition temperature, of about 300 F compared to petroleum diesel fuel which has a flash point of 125 F. This means it is safer to transport. Auto ignition, fuel consumption, power output, and engine torque are relatively unaffected by Jatropha Biodiesel.
iv. Jatropha Biodiesel has a high cetane number. Cetane number is a measure of a fuel's ignition quality. The high cetane numbers of biodiesel contribute to easy cold starting and low idle noise.
v. It can extend the life of diesel engines because of it high lubricating properties.
vi. Jatropha Biodiesel replaces the exhaust odor of petroleum diesel with a more pleasant smell of popcorn or French fries.

Although Jatropha biodiesel has many advantages, but it still have several disadvantages one of them is higher NO_X emission. The higher NO_X emission is a common disadvantage for most of biodiesel. Previous researches achieved reduction in NO_X by using exhaust gas recirculation (EGR) technique with different types of biodiesel.

B. EGR technique

EGR has been used in recent years to reduce NO_X emissions in light duty diesel engines. EGR involves diverting a fraction of the exhaust gas into the intake manifold where the re-circulated exhaust gas mixes with the incoming air before being inducted into the combustion chamber. EGR reduces NO_X because it dilutes the intake charge and lowers the combustion temperature.

Prasad et al. [5], conducted experiments on a single cylinder, DI diesel engine fuelled with Mahua methyl ester (MME) biodiesel combined with cold EGR to investigate the engine performance and exhaust emissions. The rating of EGR stopped at 15% where abnormal increase in CO and smoke was observed. Exhaust gas temperature has increased with increasing EGR rate. When the EGR system was used along with the MME, it would cause dilution of the charge as well as a decrease in the intake air so that NO_X decreased when EGR percentage increased. However, engine performance was unstable due to insufficient oxygen and CO and hydrocarbon (HC) emissions increased to high levels. At full load, MME along with 15% EGR shown lowest NO_X, but at that percentage, HC and CO were high. The study concluded that due to this reason, even though NO_X was less at 15% EGR, it is not preferable.

Rajan et al. [6], study involved a twin cylinder, natural aspiration, water cooled, DI diesel engine that was used for conducting test with Sunflower methyl ester biodiesel blended with diesel fuel and combined with EGR technique. Higher amount of smoke in the exhaust was observed when the engine was operated with EGR compared to without EGR. Moreover, smoke and CO emissions were increased with increasing engine load and EGR rate. Observed NO_X emissions in case of blended biodiesel B20 and B40 have 25% and 14% lower NO_X emissions respectively with full load at 15% EGR, when compared to using diesel fuel without EGR. they concluded that engine operations with biodiesel while employing EGR were able to reduce 25% NO_X with expenses of reduction in brake thermal efficiency and increases in smoke, CO and unburned hydrocarbon (UBHC) were observed compared, to diesel fuel.

Kim et al. [7], investigated the effect of variable EGR rate on engine performance and exhaust emissions. Experiments were carried out using a single cylinder, DI diesel engine fuelled with Soybean biodiesel. Experiments result showed that, EGR was effective to control NO_X emissions. However, the EGR has brought about an increase in particulate matters (PM) resulting from the lowered oxygen concentration in the combustion flames. By comparing the combustion characteristics of diesel and biodiesel fuel under different EGR rate of 0% and 30%, biodiesel fuel showed less sensitivity to EGR on the combustion characteristics.

Pradeep et al. [8], investigated the effects of Hot EGR combined with pure Jatropha biodiesel (JB100) on engine performance and exhaust emissions. A single cylinder, water cooled, DI diesel engine was used for their experiments. The results showed that, at 15% EGR, the brake thermal efficiency at full load was found to be 30% and 32% for JB100 and diesel, respectively. Brake specific energy consumption of biodiesel was slightly higher for all levels of EGR compared to corresponding diesel values. Smoke opacity values higher than 60% were observed for EGR levels of 20% and 25% for both fuels. Higher values of CO were observed at full load for both fuels beyond 15% EGR. They concluded that Hot EGR at 15% effectively reduced NO emission without much adverse effect on the performance, smoke, and other emissions.

A practical problem in fully exploiting EGR is that, at very high levels, EGR suppresses flame speed sufficiently that combustion becomes incomplete and unacceptable levels of PM and HC are released in the exhaust. Therefore, by using EGR there is a trade of between reduction in NO_X emission and increase in soot, CO, and HC emissions.

The aim of the current study is to achieve reduction in soot and NO_X emissions using EGR for a CI engine fuelled with Jatropha based biodiesel.

In order to achieve this aim, the study took into consideration results and conclusions of the previous studies. Three parameters are selected based on previous studies: These are biodiesel type (blended or neat), injection system and aspiration system of diesel engine.

1) Biodiesel type

Previous experimental studies were conducted by Rao et al. [9], on Jatropha biodiesel and its blends. The effects of Jatropha on the performance and emissions of a single cylinder, water cooled diesel engine investigated. Experimental results showed that the engine works smoothly on B100 with performance comparable to diesel fuel operation. B100 results in a slightly increased thermal efficiency as compared to that of conventional diesel fuel. The exhaust gas temperature was decreased with B100 as compared to diesel fuel. CO_2 emission was low with B100 compared to diesel fuel. CO emission was low at higher loads for B100 when compared with diesel. NO_X emission was slightly increased with B100 compared to diesel fuel. There was significant difference in smoke emissions when B100 was used. Smoke was increased with increased in brake power. Smoke emission was lesser for blended Jatropha biodiesel compared to diesel fuel. When percentage of blend biodiesel increased, smoke density decreased, but smoke density increased for B50 and B75 due to insufficient combustion.

Rao et al. [10], used single cylinder, water cooled, DI diesel engine used to investigate the performance and emission characteristics of Jatropha and other two types of non-edible oils on diesel engine. They observed slight drop in thermal efficiency with methyl esters when compared with diesel. Biodiesel gave less smoke density compared to petroleum diesel. When percentage of blend biodiesel increases, smoke density decreases, but smoke density increased for B80 and B100 due to insufficient combustion. Smoke, HC, and CO emissions at different loads were found to be higher for diesel, compared to B10, B20 and B40. In conclusion, good mixture formation and lower smoke emission were the key factors for good CI engine performance. These factors are highly influenced by viscosity, density, and volatility of the fuel. For biodiesels, these factors are mainly decided by the effectiveness of the transesterification process.

Banapurmath et al. [11], carried out experiments by using a single cylinder, direct injection, air cooled diesel engine fuelled with JB100. The experiments result presented that was JB100 had a thermal efficiency lower than diesel fuel. Also observed, JB100 had slightly higher smoke emissions than diesel fuel.

Therefore, this study decided to use blended Jatropha biodiesel because the blended biodiesel is better than the pure biodiesel. Blended biodiesel has high durability with the engine because its properties close to conventional diesel fuel. The brake thermal efficiency is higher than pure biodiesel. It has smoke and brake specific fuel consumption lower than pure biodiesel. The blended percentage was selected in this study is JB5 denoted by (5% Jatropha biodiesel by volume blended with 95% diesel fuel). This is lower than B50 to avoid high smoke emissions.

2) Injection system

From previous studies, Rao & Mohan [12], on performance of DI and IDI diesel engines with Jatropha biodiesel, the experiments results showed that the exhaust of IDI engine was less smoky when compared to DI engine. The lower pollution levels were achieved in IDI engine with biodiesel and IDI engine operation with biodiesel can be regarded as eco-friendly performance. Also, IDI engine operation with biodiesel not only improves the performance but also tremendously reduces the gummy deposits.

Therefore, the study also used an IDI diesel engine due to the low production of smoke emission.

3) Aspiration system

Karabektas [13], investigated the effect of turbocharger application with biodiesel. The experiments result showed that the application of turbocharger provides increased air to the diesel engine and enables mixing of fuel-air easily in the combustion chamber, hence improving the performance and reducing the exhaust emissions.

The test engine will also use turbocharger to achieve good performance and low emissions.

II. EXPERIMENTAL SETUP AND TEST PROCEDURES

A. Experimental facilities

The properties of blended Jatropha biodiesel (JB5) relative to diesel fuel are detailed in Table I. The experimental installation used in the present work consists of a 4-cylinder, water cooled, turbocharged, indirect injection diesel engine (see Table II). This engine was connected to hydraulic dynamometer Go-Power System model DA316. The fuel supply system was connected in two fuel tanks, one for diesel fuel and another for JB5, two control valves which allowed rapid switching between the diesel oil used as a standard and the test alternative fuel, and fuel flow detector Ono Sokki model FZ-2100 was fitted between the fuel filter and the fuel pump. Square edge orifice plate was used for measuring air intake mass flow rate. A digital manometer was used for measuring pressure drop across the orifice plate. EGR was controlled by poppet valve and the rates were determined by using the following equation:

$$\%EGR = \frac{\text{Mass of air admitted without EGR} - \text{Mass of air admitted with EGR}}{\text{Mass of air admitted without EGR}}$$

Air temperature, exhaust temperature and coolant temperatures were measured using K-type thermocouples. The wires from thermocouples were connected with thermocouple data logger which connected to USB cable connected with PC.

Based on measurements of intake air temperature and pressure drop across orifice plate, convenient software by LabView was designed to instantly calculate the air mass flow rate, the percentage of EGR and display. By controlling the EGR valve, the percentage of EGR can be adjusted to the desired value.

Soot emission was measured using AUTOCHECK soot meter. NO_X, CO and CO_2 emissions were measured using AUTOCHECK gas analyzer. The experimental setup is shown schematically in Fig. 1.

TABLE I
FUELS PROPERTIES

Properties	Diesel	JB5
Density (kg/m^3)	840	841.2
Kinematic viscosity @ 40°C (mm^2/s)	3.6	3.3
Calorific value (MJ/kg)	45.70	45.38
Ash (%)	0.01	0.04
Carbon residue (%)	0.14	0.15
Water content (%)	0.05	0.009

TABLE II
ENGINE SPECIFICATIONS

Displacement	1998 cm^3
Maximum net power	69.14 kW @ 4500 rpm
No. of cylinder	four
Aspiration system	Turbocharged with intercooler
Fuelling system	Indirect injection
Compression ratio	22.4

B. Experimental procedures

The test engine was started until it achieved the stable idling condition. Then the engine speed was increased gradually up to 2000 rpm. At the same time, the dynamometer, all analyzers and meters for measurements were switched on and the proper preparations and settings for measurements were carried out as the recommended methods by the manufacturer's instruction manuals. When the test engine got stable condition and preparations and settings for the measurements were finished the experiments were started. The type of experiment is a steady state engine test with full load.

The air intake mass flow rate was measured by orifice plate without EGR. Fuel consumption, intake air temperature, exhaust gas temperature, engine coolant temperature, carbon dioxide (CO_2) emission, carbon monoxide (CO) emission; nitrogen oxides (NO_X) emission and soot emission were also measured and recorded.

Then, the EGR valve was opened step by step and controlled manually. The EGR rates were started from 5% until 40% and the increment was 5%.

The same conditions, methods and procedures were used for both blended Jatropha biodiesel (JB5) and diesel fuel (baseline).

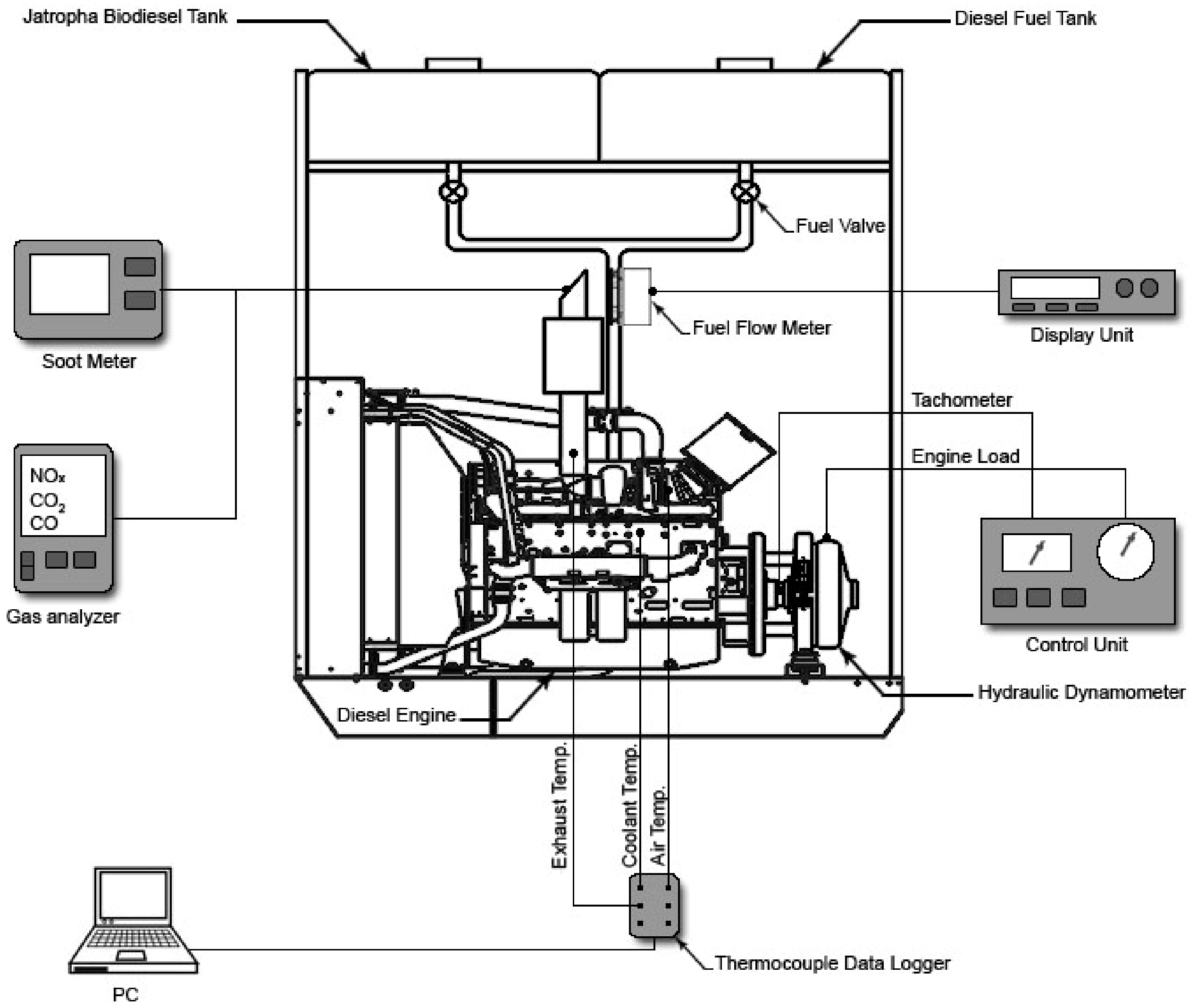

Fig. 1 Experimental setup diagram

III. RESULTS AND DISCUSSION

The results and discussion based on the effect of EGR rates on engine performance and emissions for both fuels JB5 and diesel (baseline).

A. Torque drop

The experiments were performed for both fuels under the same load. Fig. 2 shows the torque drop during increasing EGR rates. The torque decreased 29.4% and 17.6% from the lowest to the highest EGR level for diesel and JB5 respectively.

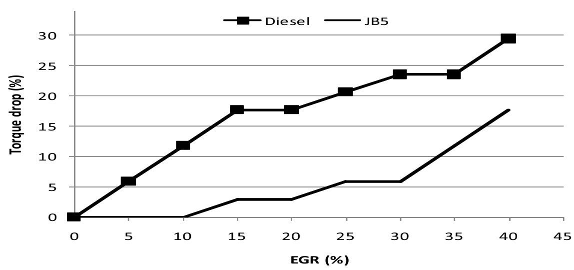

Fig. 2 Torque drop with EGR rates

B. Thermal efficiency

Fig. 3 shows the thermal efficiency of JB5 and diesel fuel at various EGR rates. An important observation is that the JB5 has higher thermal efficiency than the baseline data [14]–[15]. The thermal efficiency decreased with increasing EGR rate compared without using EGR for JB5 and diesel fuel. The reduction in the thermal efficiency with EGR is due to the dilution of the fresh charge with the exhaust gas which results in lower flame velocity and hence deterioration of the combustion [16].

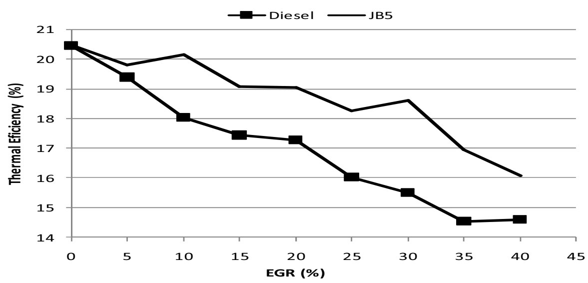

Fig. 3 Variation of thermal efficiency with EGR rates

C. Brake specific fuel consumption (BSFC)

Fig. 4 shows the BSFC of JB5 and diesel fuel at various EGR rates. JB5 has low BSFC than diesel fuel, this is at comparable with high thermal efficiency found at lower BSFC [14]-[15]. The BSFC was increased with increasing EGR rate due to dilution of the charge. Upon sending exhaust gas along with the intake air, the amount of intake air will be decreased, and lead to high fuel consumption [5].

D. Agarwal et al. [14], said, the BSFC is not a very reliable parameter to compare fuels of different calorific values and densities. Brake specific energy consumption (BSEC) is a more reliable parameter for comparison.

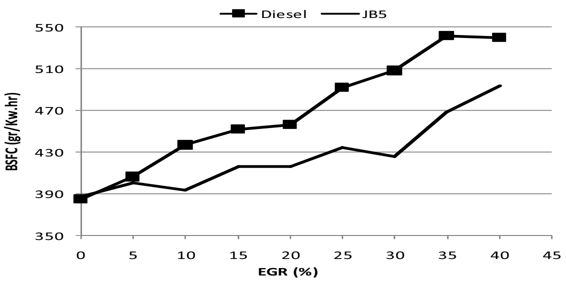

Fig. 4 Variation of BSFC with EGR rates

D. Brake specific energy consumption (BSEC)

Fig. 5 compares the BSEC of JB5 and diesel fuel at various EGR rates. BSEC for JB5 is lower than diesel fuel with increasing EGR rate, due to higher thermal efficiency [14].

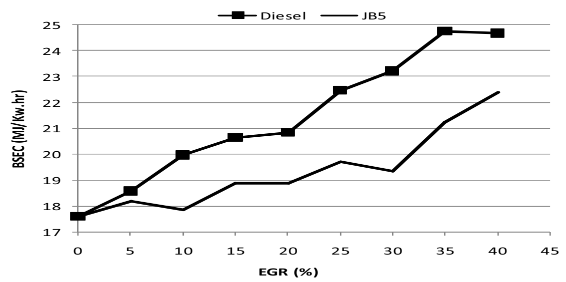

Fig. 5 Variation of BSEC with EGR rates

E. Exhaust temperature

Fig. 6 shows the effect of EGR rate on exhaust temperature for both fuels. The exhaust gas temperature has increased with increasing EGR dilution. The reason could be due to combustion or late combustion, or late combustion phase (burning of un-burnt and partial burnt fuel particles in the expansion stroke) with EGR [17].

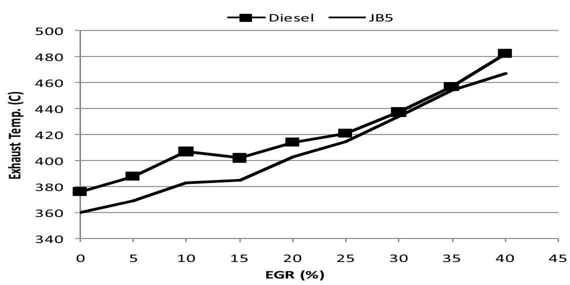

Fig. 6 Variation of exhaust temperature with EGR rates

F. Carbon dioxide (CO_2)

Fig. 7 shows the plots of CO_2 emissions at various EGR rates for JB5 and diesel fuel. CO_2 emission increased with increasing EGR level for both fuels. High CO_2 in exhaust is an indication of the complete combustion of fuel. This supports the higher value of exhaust temperature. The combustion of fossil fuels produces carbon dioxide, which are getting accumulated in atmosphere and leads to many environmental problems.

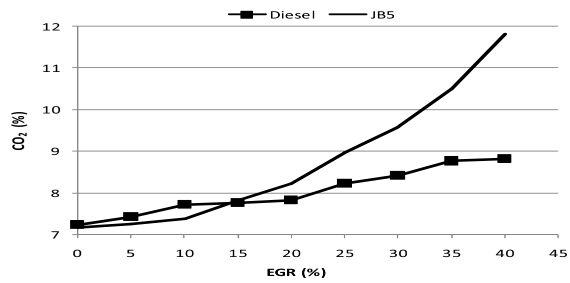

Fig. 7 Variation of CO_2 with EGR rates

G. Carbon monoxide (CO)

Fig. 8 shows the plots of CO emissions at various EGR rates for JB5 and diesel fuel. CO emission increased with increasing EGR rate. The possible reason may be lower excess of oxygen available for combustion. Lower excess oxygen concentration results in rich air-fuel mixture at different locations inside the combustion chamber. With EGR, the air-fuel ratio decrease and CO eventually increase [5]-[14]. CO emissions of JB5 were comparatively lower. For biodiesel the excess oxygen content is believed to have partially compensated for oxygen deficient operation under EGR. The values of CO emission were low because the compression ignition engines operate on lean side of stoichiometric and therefore produce very little CO emissions [19].

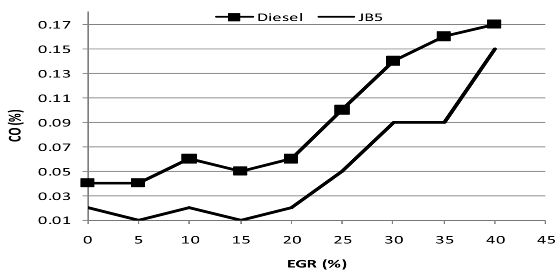

Fig. 8 Variation of CO with EGR rates

H. Nitrogen oxides (NO_X)

Fig. 9 shows the normalized NO_X emission at various EGR rates. An important observation is that JB5 has lower NO_X emission than the baseline diesel until 20% EGR level. Possible reason may be because the formation of NO in the combustion chamber is due to higher pressures at high temperatures during combustion. However, the inbuilt oxygen in blended biodiesel compensates the required oxygen for combustion, and the remaining oxygen caused the formation of NO at high pressures and temperatures. Due to this reason, obviously the available oxygen as well as nitrogen are less and lead to the decrease in NO.

The other reason for decrease in NO is the decrease in the peak pressure upon an increase in the EGR percentages. Due to decrease the peak pressure and increase exhaust temperature with increasing EGR, these lead to heat release in the late combustion phase. Heat release in the late combustion phase caused the increase in exhaust temperature but not NO [5].

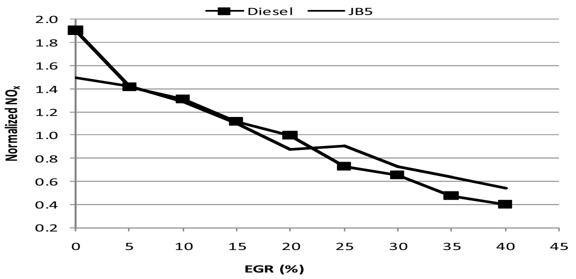

Fig. 9 Variation of NO_X with EGR rates

I. Soot emission

Fig. 10 shows the plots of soot emission at various EGR rates. Observed that is by using higher EGR ratio there was sharp increase in soot emission level due to reduction oxygen available for combustion [14]-[18]. Soot emission for JB5 with EGR is noticed to be generally lower than that of diesel. The molecule of biodiesel contains some oxygen that takes part in combustion and this may be a possible reason for lower soot emission [5].

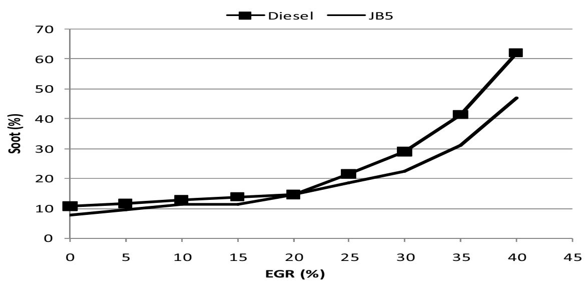

Fig. 10 Variation of soot with EGR rates

J. Trade-off between NO_X, soot and EGR rates

The NO_X emission was higher for JB5 than diesel fuel over 20% EGR. Also, in both cases increasing EGR rate will increase torque loss. However, the torque drop with JB5 (2.9%) was lower than diesel fuel (17.5%) at 20%EGR, although CO, CO_2 and soot emissions (20% EGR) are slightly higher than at 15% EGR (JB5), While at 15% EGR (JB5) exhibits the same values of torque drop, thermal efficiency, and BSFC with 20% EGR. At 15% EGR (JB5), the NO_X was similar to diesel fuel while CO, CO_2 and soot emissions lower than diesel fuel. Therefore 15% EGR is preferable for operating this IDI engine.

IV. Conclusion

On the basis of experimental data, it was found that blended biodiesel and EGR both can be used in compression ignition engine to simultaneously reduce NO_X and soot emissions. The JB5 blended Jatropha biodiesel together with 15%EGR was found to be useful in improving both of brake thermal efficiency, brake specific energy consumption and reduces exhaust emissions.

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