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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 increase 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 is receiving attention as an alternative fuel for diesel engine. Previous studies reported that Jatropha biodiesel was found to emit higher nitrogen oxides and lower smoke emissions compared to ordinary diesel. Exhaust gas recirculation is an effective technique to reduce nitrogen oxides emission from diesel engines; because it enables to lower both flame temperature and oxygen concentration in the combustion chamber. Some studies succeeded to reduce nitrogen oxides emission from biodiesel fuelled engines using exhaust gas recirculation. However, they observed increase in soot emission. The aim of this study was to investigate the optimum trade-off between reduction in nitrogen oxides and increase in soot emissions using exhaust gas recirculation for a compression ignition engine fuelled with Jatropha based biodiesel. A 4-cylinder, water-cooled, turbocharged, an indirect injection diesel engine was used for investigation. Exhaust emission characteristics were recorded and various engine performance parameters were also evaluated. The results showed that, at 5% exhaust gas recirculation rate along with Jatropha biodiesel blend effectively reduced both nitrogen oxides and soot emissions by 27 and 11.3%, respectively, compared to diesel fuel without exhaust gas recirculation.

Key words: Diesel engine, exhaust emissions, exhaust gas recirculation, Jatropha biodiesel

INTRODUCTION

Diesel engines are used in wide range because their 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 transportation sector. These wide uses of diesel engines lead to increase the requirement for petroleum derived from fossil fuel. The depletion of fossil fuel and the impact of increasing environmental pollution from exhaust gas emissions have led the search for alternative fuels. 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; biofuel is one of them, but it is the most important one (Drapcho *et al*., 2008). Biofuel oils can produced from plants (edible or non edible), algae, and animal fats. The use of non-edible plant oils is particularly interesting, as these are generally cheaper than edible oils. Moreover, the productivity of non-edible oils tend to be higher, for Jatropha Curcas as example its productivity 1590 kg of oil per hectare (Hossain and Davies, 2010). Therefore, big biodiesel development countries like Malaysia focus on producing biodiesel from Jatropha Curcas (Biopact, 2005).

Jatropha is a non-edible plant; it can grow in waste lands and consumes less water. Furthermore, biodiesel produced from Jatropha Curcas has advantages compared to diesel fuel (DF) such as (Jookaplee, 2007):

- Its molecules are simple hydrocarbon chains, containing no sulfur, or aromatic substances associated with fossil fuels
- It contains high oxygen amount (up to 10% by weight) that ensures more complete combustion of hydrocarbons
- It eliminates the lifecycle of carbon dioxide (CO_2) emissions
- It has a high flash point, or ignition temperature, of about 300 F compared to DF which has a flash point of 125 F. This means, it is safer to transport

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- It has a high cetane number which contributes to easy cold starting and low idle noise
- It has high lubricating properties; hence it can extend the life of diesel engines
- It replaces the exhaust odor of DF with a more pleasant smell of popcorn or French fries

Although Jatropha biodiesel (JBD) has many advantages, but it still has several disadvantages, one of them is higher nitrogen oxides (NO_X) emission compared to DF.

The higher NO_X emission is a common disadvantage of most biodiesel oils. Previous researches achieved reduction in NO_X form compression ignition (CI) engines fuelled with biodiesel using exhaust gas recirculation (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 emission, because it dilutes the intake charge and lowers the combustion temperature. The effects of EGR on engine performance and exhaust emission characteristics are investigated with different biodiesel oils. Pradeep and Sharma (2007)investigated the effects of hot EGR on a CI engine fuelled with JB100 (100% Jatropha biodiesel). A single cylinder, water cooled, Direct Injection (DI) diesel engine was used for experiments. The results showed that, at full load with15% EGR, the brake Thermal Efficiency (BTE) was found to be 30 and 32% for JB100 and respectively. At all EGR rates, the brake specific energy consumption (BSEC) of JB100 was slightly higher than that of DF. At 20 and 25% EGR rates, smoke opacity values were higher than 60% for both fuels. Higher values of carbon monoxide (CO) were observed beyond 15% EGR, at full load. The study concluded that 15% EGR effectively reduced NO emission without much adverse effect on the performance, smoke, and other emissions. Rajan and Senthilkumar (2009) studied the effects of EGR on a twin cylinder, natural aspiration, water-cooled, DI diesel engine fuelled with sunflower biodiesel. Sunflower biodiesel was blended with diesel fuel in different percentages, denoted by B20 (20% biodiesel by volume blended with 80% DF) and B40. The results showed that, higher amount of smoke was observed, when EGR was operated. At full load with 15% EGR rate, B20 and B40 reduced NO_X emissions by 25 and 14% respectively, compared to DF without EGR. The authors concluded that, the use of EGR with biodiesel was able to reduce NO_X emissions at the expense of increase in smoke, CO and unburned hydrocarbon (HC) emissions.

A practical problem in fully exploiting EGR is that, at high levels, EGR suppresses flame speed sufficiently that combustion becomes incomplete and unacceptable levels of smoke and HC are also released in the exhaust. Therefore, with using EGR; there is a trade-off between reduction in NO_X emission and increase in soot, CO, and HC emissions. The aim of the current study is to investigate the optimum trade-off between NO_X and soot emissions using EGR for a CI engine fuelled with blended JBD.

MATERIALS AND METHODS

Experimental facilities: JBD was blended with DF and denoted by JB5 (5% JBD by volume blended with 95% DF). The properties of JB5 compared to DF are detailed in Table 1. The experimental setup of present work consists of a 4-cylinder, water cooled, turbocharged, IDI diesel engine. The test engine specifications are shown in Table 2. This engine was connected to hydraulic dynamometer Go-Power System model DA316. The fuel supply system was connected with two fuel tanks, one for DF and another for JB5, two control valves which allowed rapid switching between both fuels. Ono Sokki fuel flow detector model FZ-2100 was fitted between the fuel filter and fuel pump. Square edge orifice plate was used for measuring air intake mass flow rate. A digital manometer was used for measuring pressure difference across the orifice plate. Re-circulated exhaust gases were controlled by poppet valve and their amounts were determined using Eq. 1:

$$\%EGR = \frac{\text{Mass of air admitted without EGR} - \text{Mass of air admitted with EGR}}{\text{Mass of air admitted without EGR}} \tag{1}$$

The temperature of intake air, exhaust gases and engine coolant were measured using K-type thermocouples. The thermocouples were connected with data logger which further connected with PC. Based on

Table 1: Test Fuels Properties

Properties	DF	JB5
Density (kg m^{-3})	840	841.2
Kinematic viscosity @ 40°C (mm^2 s^{-1})	3.6	3.3
Calorific value (MJ kg^{-1})	45.70	45.38
Ash (%)	0.01	0.04
Carbon residue (%)	0.14	0.15
Water content (%)	0.05	0.009

Table 2: Engine Specifications

Displacement	1998 cm^3
Maximum net power	69.14 kW @ 4500 rpm
No. of cylinder	4
Aspiration system	Turbocharged with intercooler
Fuelling system	Indirect injection
Compression ratio	22.4(1)

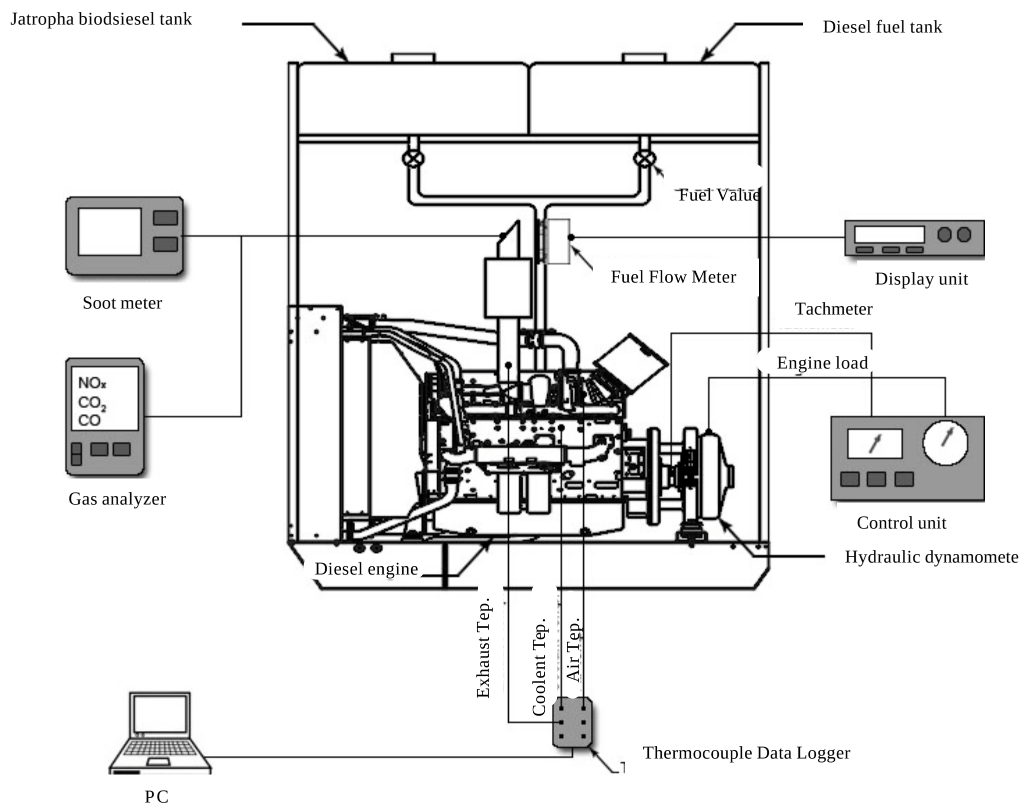

Fig. 1: A schematic diagram of experimental setup

measurements of intake air temperature and pressure difference across the orifice plate; convenient software was designed using Lab VIEW to calculate the air mass flow rate and the amount of EGR. By controlling the EGR valve, the amount 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. Fig. 1 shows the schematic diagram of the experimental setup.

Experimental procedures: The test engine was started until it achieved the stable idling condition. Then the engine 2000 rpm. The type of experiment was a steady state, constant engine speed (2000 rpm) and fuel flow rate was set to obtain full load, at 0% EGR condition. Then the EGR system was operated and varied manually by EGR control valve. EGR rate was increased gradually from 5% until 40% with increment 5%. The same conditions, methods and procedures were used for both fuels. The intake air mass flow rate, fuel consumption, CO, CO_2, NO_X and soot emissions were measured and recorded. Also, considerable engine performance parameters were calculated like BTE, BSEC.

RESULTS AND DISCUSSION

The results and discussion based on the effect of EGR rates on engine performance and exhaust gas emissions for DF and JB5, compared to DF without EGR (baseline).

Torque output: The experiments were carried out at 0% EGR, full load and 2000 rpm as initial condition; for both fuels. When EGR system was operated, the torque output started to decrease gradually with increasing EGR rate. Fig. 2 shows the variation of torque loss with various EGR rates of both fuels. There are two main reasons lead to deteriorate the torque output, one is the decrease in combustion work (i.e., indicated work) and another is the increase in pumping work (assuming that friction remained constant). The decrease in combustion work could be due to the lower combustion temperature and reduction in air-fuel ratio (AFR) which contributes to deteriorate the combustion efficiency (Bhat and Hebbar, 2009). The torque loss of JB5 was lower than that of DF, at all EGR rates. This is expected due to the extra oxygen amount of biodiesel approximately 10-12% by weight, in accordance

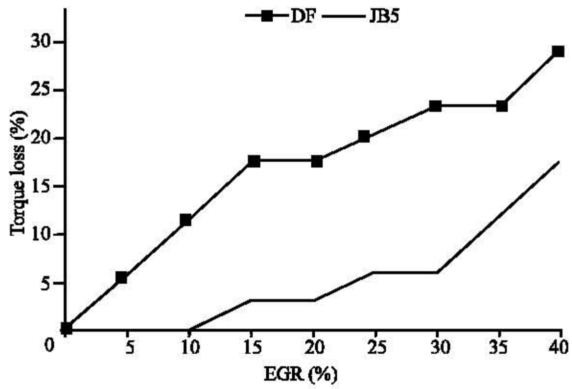

Fig. 2: Torque loss with various EGR

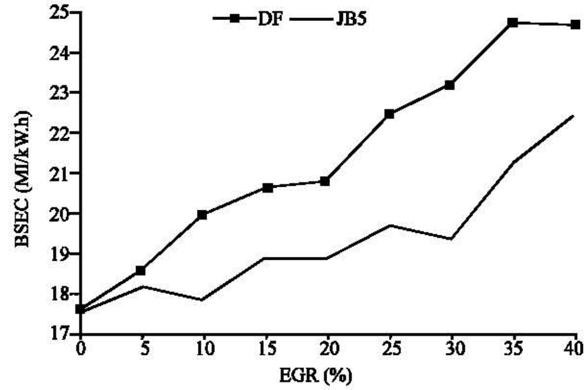

Fig. 5: BSEC with various EGR

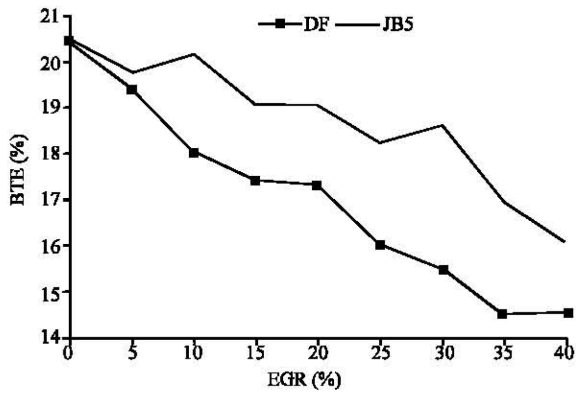

Fig. 3: BTE with various EGR

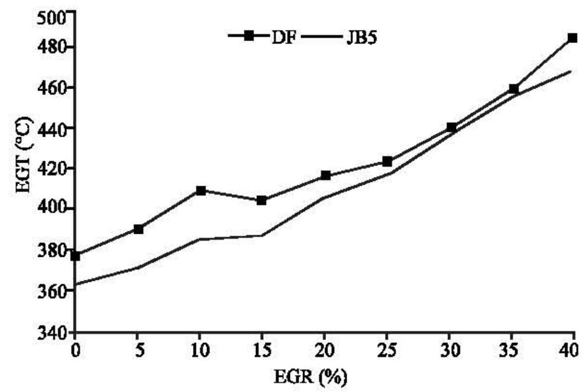

Fig. 6: EGT with various EGR

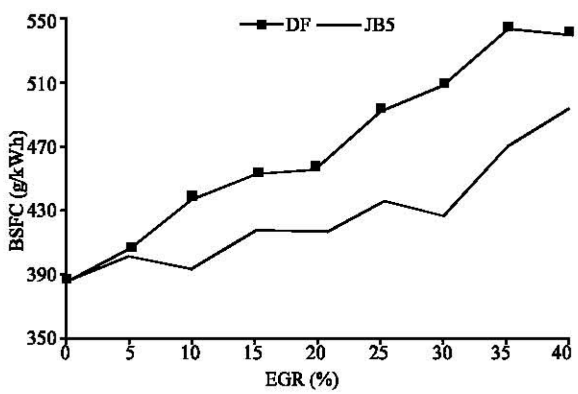

Fig. 4: BSFC with vrious EGR

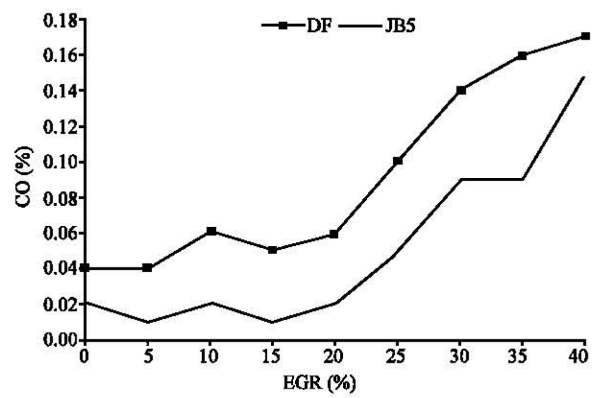

Fig. 7: CO emission with various EGR

to previous findings of other researches in biodiesel fuel (Nabi *et al*., 2009; Puhan *et al*., 2009; Karabektas, 2009; Ren *et al*., 2008). The maximum torque loss for JB5 was 17.6%, while for DF was 29.4%.

Brake thermal efficiency: Figure 3 shows the variation of BTE of JB5 and DF with various EGR rates. The BTE decreased with increasing EGR rate. The reduction in BTE with using EGR is due to the replacement of oxygen amount in the fresh charge with exhaust gas which results lower flame velocity and consequently, the combustion deteriorated (Lloyd and Thomas, 2001). At all EGR rates, the BTE of JB5 was higher than that of DF. This is may be due to the higher oxygen amount in biodiesel (Rajan and Senthilkumar, 2009; Deepak *et al*., 2006). The BTE decreased by 21.4 and 28.5% from the lowest to highest EGR rate for JB5 and DF, respectively.

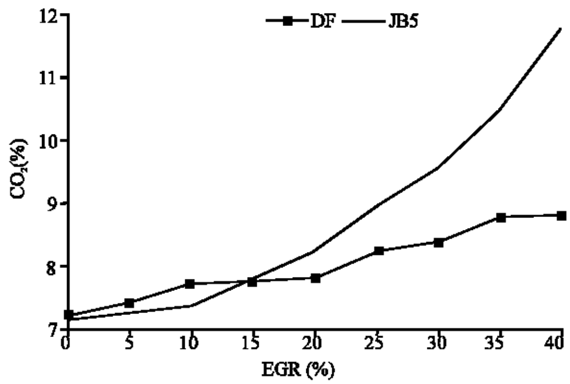

Fig. 8: CO_2 emission with various EGR

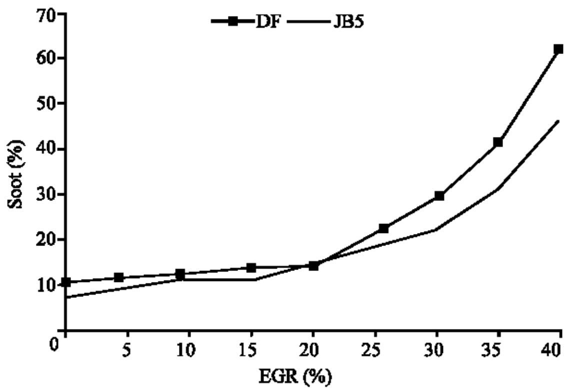

Fig. 9: Soot emission with various EGR

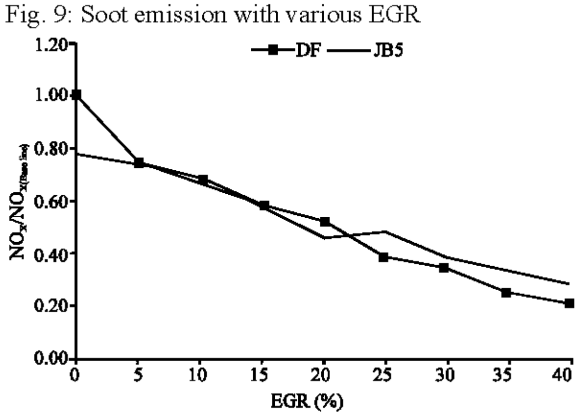

Fig. 10: NO_X emeission with various EGR

Brake specific fuel consumption: Figure 4 shows the variation of BSFC of JB5 and DF with various EGR rates. The BSFC of both fuels increased with increasing EGR rate. This could be due to the dilution of fresh air intake as a result of sending exhaust gases along with intake air; hence the BSFC increased (Prasad *et al*., 2009). The BSFC of JB5 was lower than that of DF, at all EGR rates. This could be due to the torque production with using JB5 was higher than that of DF at all EGR rates. Hence, the power output of JB5 higher than that of DF; therefore the BSFC of JB5 was lower than that of DF.

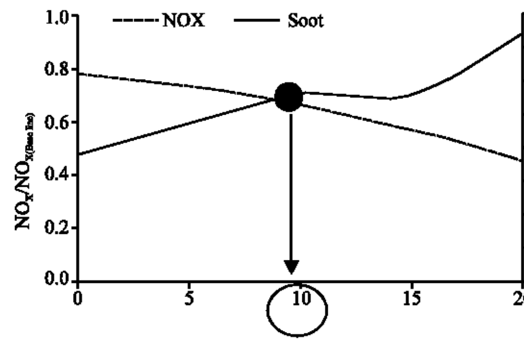

Fig. 11: The optimum trade-off between NO_X and soot emissions with various EGR with JB5

Brake specific energy consumption: BSEC is more reliable parameter for comparison of usage energy as compared to BSFC, especially for fuels with different calorific values and densities. The BSEC definition is the energy input required develop unit power (Deepak *et al*., 2006; Qi *et al*., 2009). Figure 5 shows the variation of BSEC of JB5 and DF with various EGR rates. At all EGR rates, BSEC of JB5 was lower than that of DF. This could be due to the higher BTE of JB5(Deepak *et al*., 2006). The BSEC increased with increasing EGR rate. The BSEC increased by 27.3 and 40.1% from the lowest to the highest EGR rate for JB5 and DF, respectively.

Exhaust gas temperature: Figure 6 shows the plots of exhaust gas temperature (EGT) of JB5 and DF with various EGR rates. At all operating conditions, the EGT of JB5 was lower than that of DF. This may be due to the higher oxygen amount in biodiesel which leads to efficient combustion and hence decrease the exhaust gas temperature (Ramadhas *et al*., 2005). The EGT increased with increasing EGR rate. This is assumed due to the late combustion or late combustion phase with introducing EGR (Prasad *et al*., 2009).

CO emission: Figure 7 shows the variation of CO emission of JB5 and DF with various EGR rates. CO emission increased with increasing EGR rate. This could be due to the reduction in AFR which leads to reduce the availability of oxygen amount for fuel combustion, hence CO emission eventually increase (Deepak *et al*., 2006; Prasad *et al*., 2009). At all operating conditions, JB5 emitted CO lower than DF. This could be due to the biodiesel oxygen amount which helps to complete the combustion; hence reduce the CO emission (Rajan and Senthilkumar, 2009; Mahla *et al*., 2007). At over 20% EGR, CO emission increased rapidly for both fuels. This may be due to incomplete combustion as result of higher amount of EGR inside the combustion chamber.

CO_2 emission: Figure 8 shows the plots of CO_2 emission of JB5 and DF with various EGR rates. CO_2 emission increased with increasing EGR rate for both fuels. CO_2 emission of DF increased slightly with increasing EGR rate. While, CO_2 emission of JB5 increased rapidly with increasing EGR rate, especially at over 20% EGR. In addition beyond 15% EGR, JB5 emitted CO_2 higher than DF. This may be due to the extra oxygen amount of JB5 which helps for oxidizing CO to CO_2.

NO_X emission: Figure 9 shows the variation of NO_X emission of JB5 and DF with various EGR rates. The NO_X emission of test fuels is analyzed related to the baseline value. Therefore, it displays at Fig. 9 as $NO_X/NO_{X(Baseline)}$. NO_X emission decreased with increasing EGR rate for both fuels. This could be due to the reduction in oxygen concentration and flame temperature in the combustion chamber, hence NO_X decreased (Rajan and Senthilkumar, 2009; Mahla *et al*., 2007). NO_X emission of JB5 was slightly lower than that of DF, within rates of 0-20% EGR. This could be due to the lower EGT (i.e, indication of combustion temperature) of JB5 compared to DF. While at over 20% EGR, the NO_X emission of JB5 was higher than that of DF. Although, the EGT of JB5 still lower than that of DF. However at over 20% EGR, it was not significant difference between EGT values of JB5 and DF. On the other hand, the extra oxygen amount of JB5 plays a role for NO_X formation by oxidizing the nitrogen present in the combustion chamber. Therefore, the oxygen availability in the fuel was the major reason for higher NO_X emission of JB5 as compared to DF. The NO_X emission decreased 63.6 and 79.9% from the lowest to the highest EGR rate for JB5 and DF, respectively.

Soot emission: Figure 10 shows the curves of soot emission of JB5 and DF with various EGR rates. At all operating conditions, JB5 emitted soot lower than DF. This could be due to the molecules of blended biodiesel (JB5) contains some oxygen that takes vital part in combustion. Hence, it is improved the combustion and caused reduction in soot emission (Deepak *et al*., 2006). At over 20% EGR, sharp increase in soot emission for both fuels was observed. This may be due to the reduction in oxygen availability for fuel combustion which leads to incomplete combustion and increase in soot emission (Mahla *et al*., 2007).

Trade-Off between NO_x, soot and EGR rates: Through the results of EGR effect on exhaust gas emissions of JB5, a better trade-off between NO_X and soot emissions can be obtained within limited EGR rates of 5-20%, without much adverse effect on engine performance, compared to DF. Figure 11 shows the optimum trade-off between NO_X and soot emissions of JB5 with the acceptable limit of EGR within rates of 5-20%. It is found that, the optimum trade-off between NO_X and soot emissions is occurred at 10% EGR. At 10% EGR with JB5, NO_X emission decreased by 33.6%. However, soot emission increased by 5.6%, compared to the baseline values. Whereas at 5% EGR with JB5, it is obtained sufficient reduction in exhaust gas emissions (CO, CO_2, NO_X and soot) relative to the baseline values. The 5% EGR with JB5 effectively reduced both NO_X and soot emissions by 27 and 11.3%, respectively, compared to the baseline values. Therefore, even though the optimum trade-off between NO_X and soot emission is obtained at 10% EGR, it is not preferable.

CONCLUSION

On the basis of experimental results, it was found that blended Jatropha biodiesel (JB5) and EGR technique both can be used in an IDI diesel engine to simultaneously reduce NO_X and soot emissions. A better trade-off between NO_X and soot emissions can be attained within a limited EGR rate of 5-20% without much adverse effect on performance. The 5% EGR with JB5 effectively reduced both NO_X (27%) and soot (11.3%) emissions compared to diesel fuel without EGR (baseline).

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