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The effect of EGR rates on NO_X and smoke emissions of an IDI diesel engine fuelled with Jatropha biodiesel blends

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Abstract
The depletion of fossil fuels and the worst impact on environmental pollution caused of their burning have led to the search for renewable clean energies. Nowadays, there are many sources of renewable energy. Biodiesel is just one source, but a very important one. 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. However, previous studies have reported that combustion of JBD emitted higher nitrogen oxides (NO_X), while hydrocarbon (HC) and smoke emissions were lower than conventional diesel fuel. Exhaust gas recirculation (EGR) is one of the techniques being used to reduce NO_X emission from diesel engines; because it decreases both flame temperature and oxygen concentration in the combustion chamber. Some studies succeeded to reduce NO_X emission from biodiesel fuelled engines using EGR; but they observed increase in smoke emission with increasing engine load and EGR rate. The aim of the present work is to investigate the effect of EGR on an indirect injection (IDI) diesel engine fuelled with JBD blends in order to reduce NO_X and smoke emissions. A 4-cylinder, water-cooled, turbocharged, IDI diesel engine was used for investigation. Smoke, NO_X, carbon monoxide (CO) and carbon dioxide (CO_2) emissions were recorded and various engine performance parameters were also evaluated. The results showed that, at 5% EGR with JB5, both NO_X and smoke opacity were reduced by 27% and 17% respectively. Furthermore, JB20 along with 10% EGR was also able to reduce both NO_X and smoke emission by 36% and 31%, respectively compared to diesel fuel without EGR.

Keywords: Diesel engine, EGR, Jatropha biodiesel, NO_X, Smoke.

1. 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 [1]. 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 [2].

1.1 Jatropha Curcas

Jatropha plant can grow in waste lands and consumes less water. Furthermore, biodiesel produced from Jatropha has advantages compared to conventional diesel fuel (DF). The comparison between Jatropha biodiesel (JBD) and DF properties is investigated by Pradeep & Sharma [3], as follows:

(i) JBD molecules are simple hydrocarbon chains, containing no sulfur, or aromatic substances associated with fossil fuels.
(ii) The presence of oxygen in the structure of JBD reduces emission of particulate matter (PM), hydrocarbon (HC) and carbon monoxide (CO), as compared to DF.
(iii) It is much safer than DF, because of its higher flash point and fire point, or ignition temperature compared to DF.
(iv) It has excellent lubricity; extending diesel engines life.
(v) It has bulk modulus higher than that of DF. Bulk modulus results in advance of injection timing in biodiesel fuelled engine. The higher bulk modulus of JBD leads to a more rapid transfer of pressure waves from fuel pump to lift the needle of the injector much earlier. This advance results in more fuel accumulation before the start of combustion and leading to higher peak temperature and pressure in the premixed phase and subsequently higher nitrogen oxides (NO_X) emission.
(vi) Boiling point of JBD is higher than that of DF. Because of higher boiling point, JBD maintains its liquid phase for an increased duration, facilitating more droplet penetration into the combustion chamber. This feature can lead to increase the fuel consumption, peak temperature and higher NO_X emission.

Although JBD has many advantages, but it still has several disadvantages, one of them is higher 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 using exhaust gas recirculation (EGR) technique with different biodiesel oils.

1.2 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. A practical problem in exploiting EGR is that, at high load condition; there is a trade-off between reduction in NO_X emission and increase in smoke, CO and HC emissions [3-5].

Pradeep & Sharma [3] investigated the effects of hot EGR along with JB100 (100% Jatropha biodiesel) on engine performance and exhaust gas emissions. A single cylinder, water cooled, direct injection (DI) diesel engine was used for experiments. The results showed that, smoke opacity values were higher than 60%, at 20% and 25% EGR rates for both fuels. At full load, higher values of CO were observed beyond 15% EGR, for both fuels. The study concluded that 15% hot EGR rate effectively reduced NO_X emission without much adverse effects on the performance, smoke, and other emissions. Prasad et al. [4] investigated reduction of NO_X emission from DI diesel engine fuelled with Mahua methyl ester (MME) along with EGR. A single cylinder, DI diesel engine connected with cooled EGR system used for experiments. The results of experiments showed that at full load condition, abnormal increase in CO and smoke emissions occurred over 15% EGR rate. When EGR system was used with MME, it caused dilution of charge as well as a decrease in intake air. Therefore, NO_X emission decreased with increasing EGR rates. However, the engine performance was unstable due to insufficient oxygen. Moreover, CO and HC emissions increased to high levels. At full load condition, MME along with 15% EGR showed lowest NO_X. But, HC, smoke and CO emissions were high. Due to that reason they concluded, even though NO_X was less at 15% EGR, it is not preferable for environmental protection aspect. Rajan et al. [5] studied the effects of EGR on the performance and emission characteristics of a compression ignition (CI) engine fuelled with sunflower biodiesel. The study involved a twin cylinder, natural aspiration, water cooled, DI diesel engine was used for experiments. Sunflower biodiesel was blended with DF in different percentages, denoted by B20 (20% biodiesel by volume blended with 80% DF) and B40. When EGR was operated; it was observed higher amount of smoke emission in the exhaust compared to without EGR case. Smoke emission was increased with increasing engine load and EGR rate. At full load condition with 15% EGR rate, B20 and B40 emitted NO_X was lower by 25% and 14% respectively, compared to DF without EGR. They 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 HC emissions.

The aim of the current study is to investigate the effect of EGR on performance parameters and exhaust emissions of an indirect injection (IDI) diesel engine fuelled with JBD blends; and also is to investigate the optimum trade-off between NO_X and smoke emissions using EGR. In this experimental work, 85% of maximum engine load has been selected as high load condition for analysis.

2. Experimental works

2.1 Properties of test fuels

JBD was chosen as test fuel, because it is non-edible oil, which does not conflict with food industries. In addition, JBD has good low temperature property (i.e. cloud and pour points), compared to ordinary biodiesel feedstocks such as soybean and rapeseed [6]. The current study focused to use JBD as a blend with conventional diesel to improve its properties to be close to ordinary diesel fuel. The blending percentages are denoted by JB5 and JB20. The properties of DF and JBD blends (JB5, JB20) were measured and determined by Samion [7]. Table 1 shows the properties of test fuels.

Table 1. The properties of test fuels [7]

Property	DF	JB5	JB20
Percentage of JBD by volume	0%	5%	20%
Density (kg/m^3)	840.00	841.20	847.10
Kinematic viscosity at 40 °C (mm^2/s)	3.60	3.30	4.10
Flash point (°C)	71.00	153.00	143.00
Calorific value (MJ/kg)	45.70	45.38	41.90
Ash (%)	0.01	0.04	0.04
Water content (%w/w)	0.05	0.009	0.010
Carbon residue (%)	0.10	0.15	0.16

2.2 EGR system

Hot EGR system was used in the present work, as shown schematically in Figure 1. The EGR valve controller is puppet type. The exhaust gases were adjusted by this valve and directly sent to the inlet manifold. The amount of EGR was calculated using Equation 1, as follows:

$$EGR(\%) = \left[\frac{Mass\ of\ air\ admitted\ without\ EGR - Mass\ of\ air\ admitted\ with\ EGR}{Mass\ of\ air\ admitted\ without\ EGR} * 100\right] \quad (1)$$

The square edge orifice plate is designed and fabricated to measure the mass of inlet air. It is fitted on the inlet pipe between the intercooler and the inlet manifold, as shown in Figure 1. A digital manometer is mounted across the orifice plate, to measure the pressure difference inside the inlet pipe and the atmosphere. The coefficient of discharge of the orifice is determined experimentally to be 0.603. Simple software was programmed and designed by LabVIEW to calculate the EGR percentage during experiments.

2.3 Experimental setup

The experimental installation for present work consists of a 4-cylinder, water cooled, turbocharged, IDI diesel engine. Specifications of this engine are given in Table 2. The test 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 JBD. Fuel flow detector Ono Sokki model FZ-2100 was fitted between the fuel filter and fuel pump. The temperatures of intake air, exhaust gas and engine coolant were measured using K-type thermocouples. Smoke emission was measured using AUTOCHECK opacity meter. NO_X, CO and CO_2 emissions were measured using AUTOCHECK gas analyzer. Figure 2 shows the schematic diagram of the experimental setup.

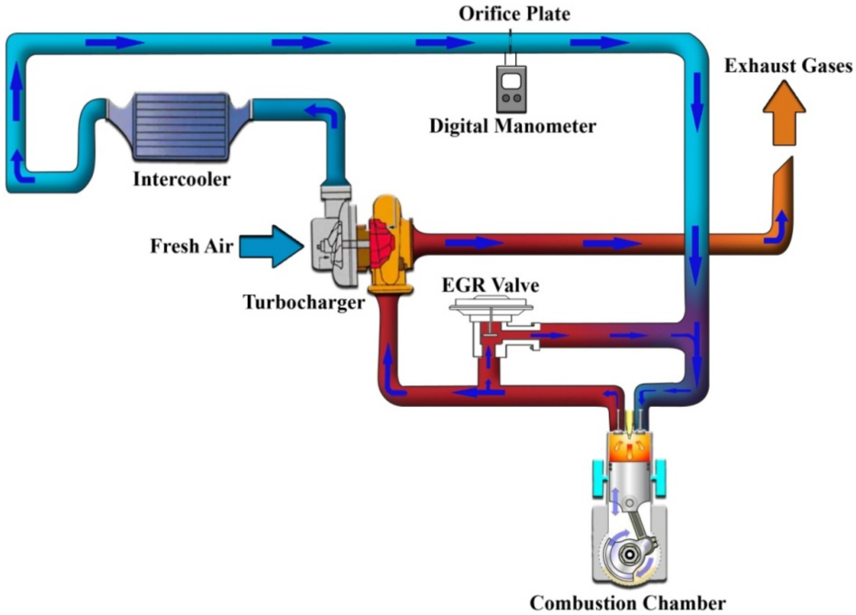

Figure 1. A schematic diagram of EGR system

Table 2. The specifications of test engine

Displacement (cc)	1998
Max. Power (Net), kW/rpm	69.14 / 4500
No. of cylinder	4
Aspiration system	Turbocharged with intercooler
Fuelling system	Indirect injection
Compression ratio	22.4

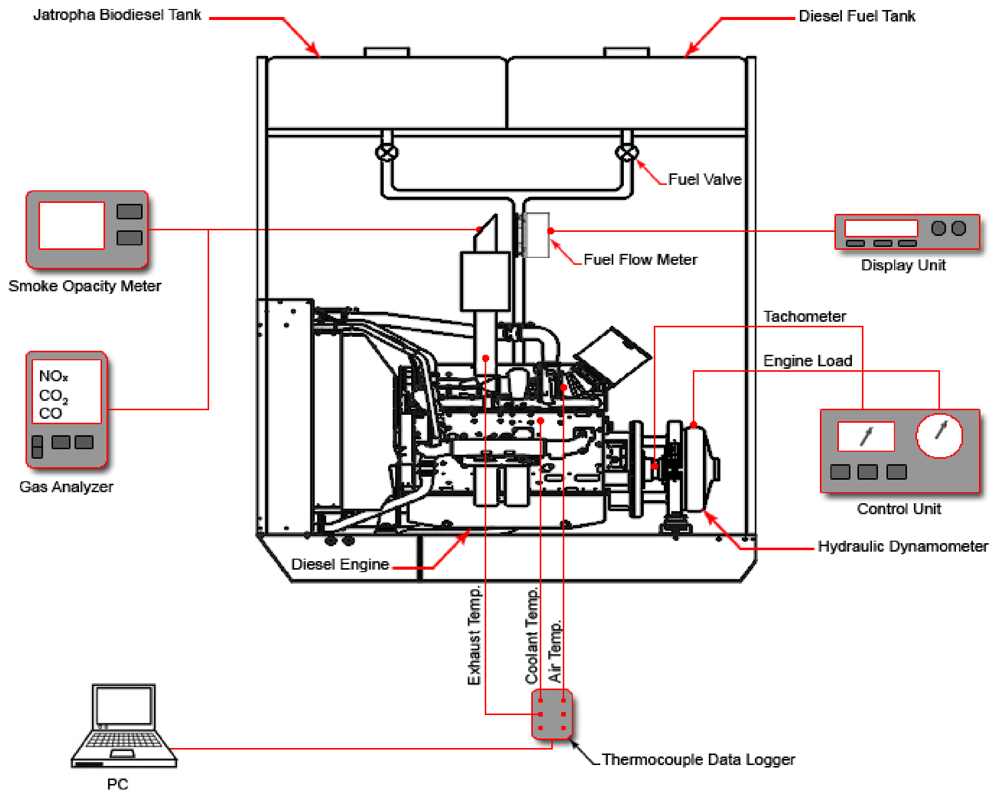

Figure 2. A schematic diagram of experimental setup

3. Results and discussion

The results and discussion based on the effect of EGR rates on engine performance and emission characteristics of JB5, JB20 and DF, compared to DF without EGR (baseline). The engine was tested at high load condition (85% of maximum load), fixed speed (2000 rpm) and various EGR rates of 5-40% (with 5% increment). The performance parameters and exhaust emissions are measured and recorded for the DF and JBD blends. Collected data were averaged to decrease the uncertainty.

3.1 Performance parameters

3.1.1 Torque output

Figure 3 displays the variation of torque output of JBD blends and DF with various EGR rates. The torque output was decreased and deteriorated, when EGR was operated. In fact, the torque losses are considerable with increasing EGR rates, and more visible at higher EGR rates of 20-40%. There are two main reasons lead to deteriorate the torque output. First one is the decrease in combustion work (i.e. indicated work), and another reason is the increase in pumping work (assuming that friction remained constant) [8]. The decrease in combustion work could be due to the lower combustion temperatures and reduction in air-fuel ratio (AFR) as a result of EGR use. Therefore, the torque output was deteriorated. The torque loss of JBD blends 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 to previous findings of other researches in biodiesel fuel [9-12]. This oxygen helps to improve the combustion efficiency, thus reduce the torque deterioration. The maximum torque loss with applying EGR with JB5 and JB20 was 14.7% and 17.6%, respectively; while, it found to be 26.5% with DF, as compared to the baseline value.

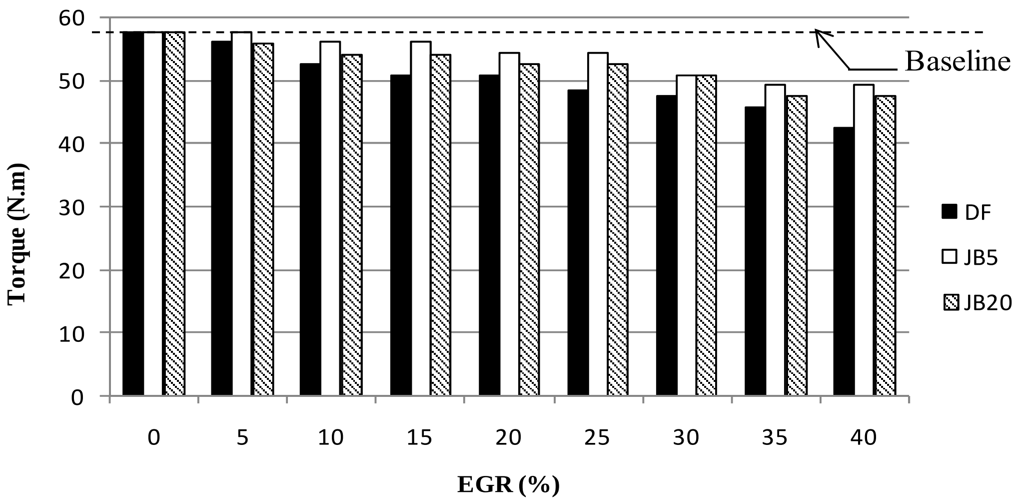

Figure 3. Variation of torque output with various EGR rates

3.1.2 Brake thermal efficiency

Figure 4 shows the variation of brake thermal efficiency (BTE) of JBD blends and DF with various EGR rates. The main observation is that JBD blends produced higher BTE than that of DF, at all operating conditions. The BTE improved with increasing biodiesel amount in the blends. As an example at 0% EGR, the highest improvement of BTE was achieved with JB20 by 4.6%, compared to the baseline value. The BTE improvement may be due to the oxygen amount of JBD blends. This oxygen can be used in combustion, especially in the fuel rich zone. Hence, help for complete the combustion process, and consequently improve the BTE [12,13]. At 5% EGR, the BTE of all test fuels improved. Similar observation was reported by Ramadhas et al. [14]. They concluded the increase in BTE may be due to re-burning of unburned HC which enters the combustion chamber with the re-circulated exhaust gases. Furthermore, the small amount of re-circulated exhaust gas mix well with fresh air helps to complete the fuel combustion. At over 5% EGR rate, the BTE started to decrease linearly with increasing EGR rates. This behavior is possible due to the dilution of the fresh charge with exhaust gases, which results in lower flame velocity and lead to incomplete combustion of fuel. At 40% of EGR, the higher reduction in the BTE was observed; the BTE of DF, JB5 and JB20 decreased by 22.3%, 16.4%, and 7.4% respectively, compared to the baseline value.

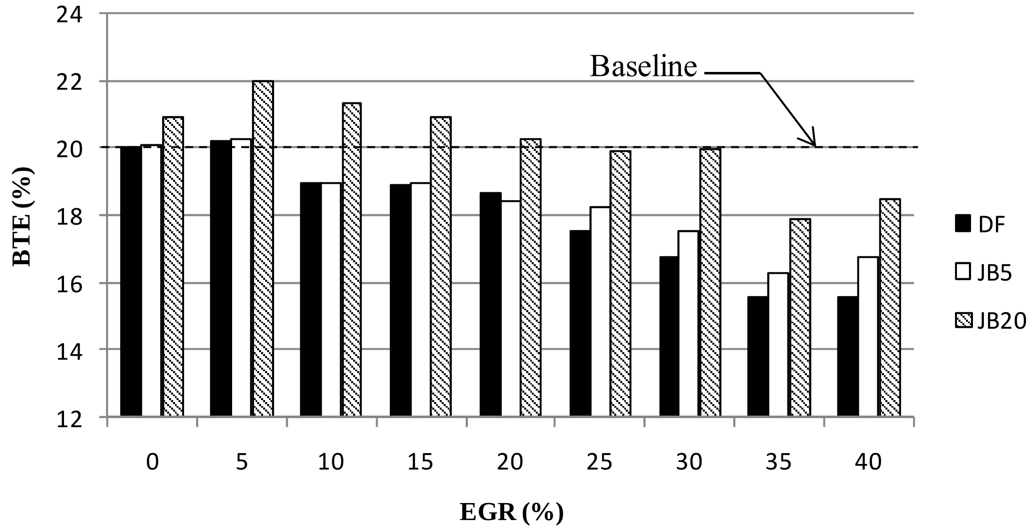

Figure 4. Variation of BTE with various EGR rates

3.1.3 Brake specific fuel consumption

Figure 5 shows the variation of brake specific fuel consumption (BSFC) of JBD blends and DF with various EGR rates. At 0% EGR, the BSFC of JBD blends was slightly higher than that of DF. This is due to the higher calorific values and densities of JBD blends, compared to DF (as shown in Table 1). At 5% EGR, the BSFC of all test fuels was lower than that of in case without EGR. This could be due to the improvement in BTE, at 5% EGR. At over 5% EGR, the BSFC increased linearly with increasing EGR rates. It increased rapidly, beyond 20%EGR. The possible reason is the significant reduction in torque output within a limit of 25-40% of EGR rate. At 40% EGR, the BSFC of DF, JB5 and JB20 increased by 28.7%, 9.4%, and 7.6% respectively, compared to the baseline value.

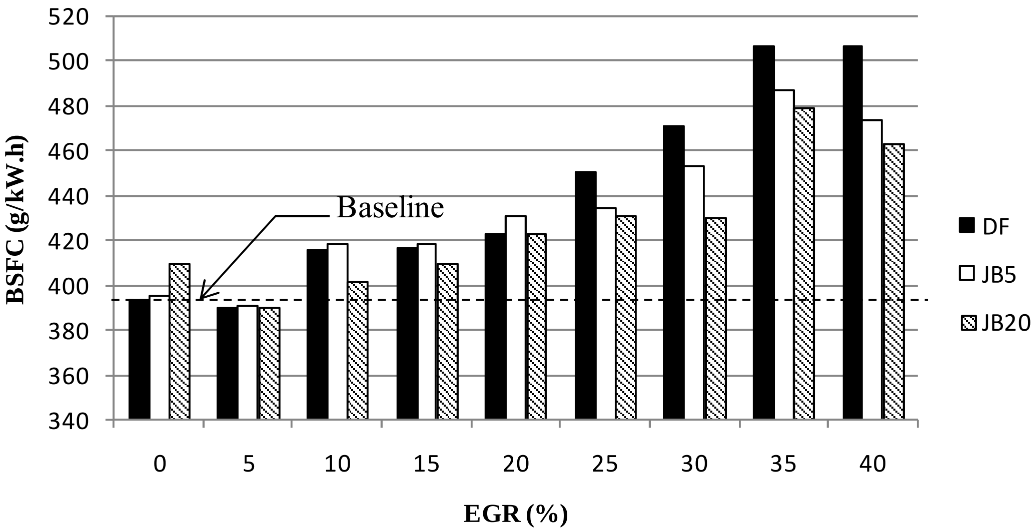

Figure 5. Variation of BSFC with various EGR rates

3.1.4 Brake specific energy consumption

The 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 to develop unit power [15,16]. Figure 6 shows the variation of BSEC of JBD blends and DF with various EGR rates. The BSEC of JBD blends was lower than that of DF, at all operating conditions. This is due to the higher BTE of JBD blends, compared to DF. The BSEC increased with increasing EGR rates. The possible reason is the increase in the BSFC with increasing EGR rates, because the BSEC is a function of BSFC and calorific value.

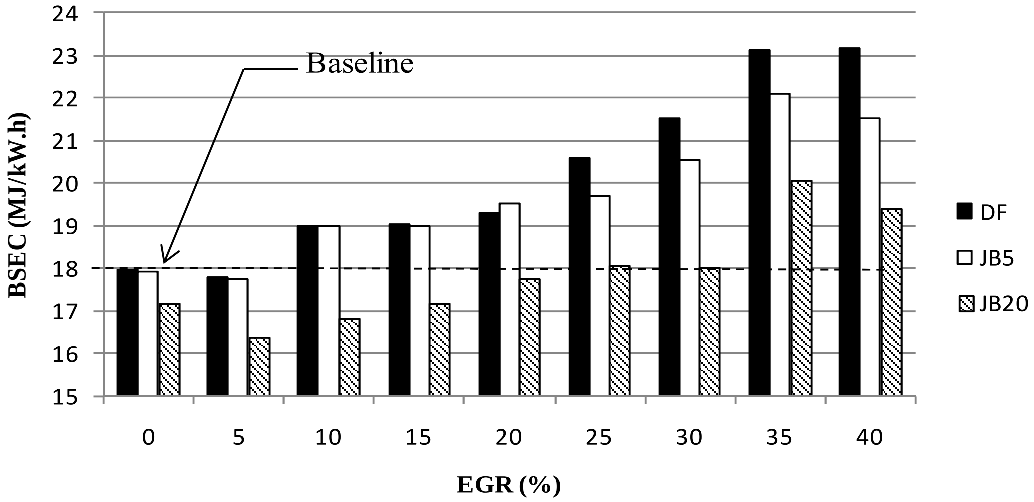

Figure 6. Variation of BSEC with various EGR rates

3.1.5 Exhaust gas temperature

The exhaust gas temperature (EGT) is an important parameter to indicate the quality of combustion process in the cylinder. Figure 7 displays the variation of EGT of JBD blends and DF with various EGR rats. At 0% EGR, JBD blends produced lower EGT than that of DF. In addition, the EGT decreased with increasing biodiesel percentage in the blends. This may be due to the improved combustion and oxidizing of more fuel, as a result of the availability of oxygen molecules amount in biodiesel blends. It is assumed that, the effective combustion was taking place in the early stages of exhaust stroke. Thus, it was saving the exhaust gas energy loss [17,18]. This behavior was reflected in the BTE and BSEC. However, the EGT increased with increasing EGR rates for all tested fuels. This may be due the late combustion phase when EGR was operated (burning of un-burnt and partial burnt fuel particles in the expansion stroke) [4].

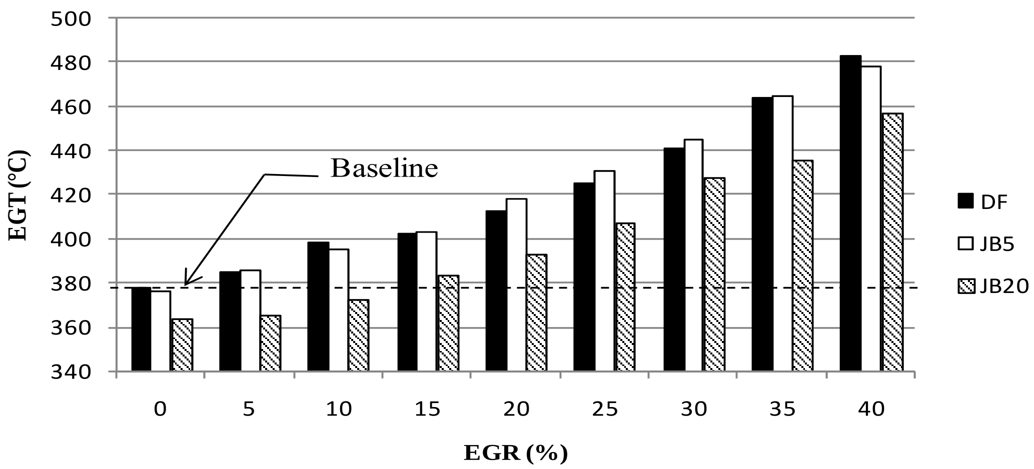

Figure 7. Variation of EGT with various EGR rates.

3.2 Emission characteristics

3.2.1 CO emission

Generally, CO emission is forming resulted of incomplete combustion of fuel. However, if the combustion is complete, CO is oxidizing to CO_2. Usually, CO emission of diesel engines is low, because diesel combustion occurs with lean mixture [19]. Figure 8 shows the CO emission of JBD blends and DF with various EGR rates. The CO emission of JBD blends was lower than that of DF, at all operating conditions. This is expected due to the extra oxygen amount of biodiesel molecules, which complete the fuel combustion and helps to oxidize CO to CO_2 [9,20]. At 0% EGR, JB5 and JB20 emitted similar rate of CO with 75% reduction, compared to DF. The CO emission increased with increasing EGR rates. This could be due to the reduction in the oxygen availability for combustion process, as a result of rich air-fuel mixtures, at different locations inside the combustion chamber. As the use of EGR contributed to decrease the AFR and consequently, CO emission eventually increased [16]. At over 20% EGR, CO emission of all test fuels increased rapidly. This could be due to the incomplete combustion, accordance to the phenomena of CO emission. The incomplete combustion occurred beyond 20% EGR, and it was reflected in torque output, BTE and BSEC.

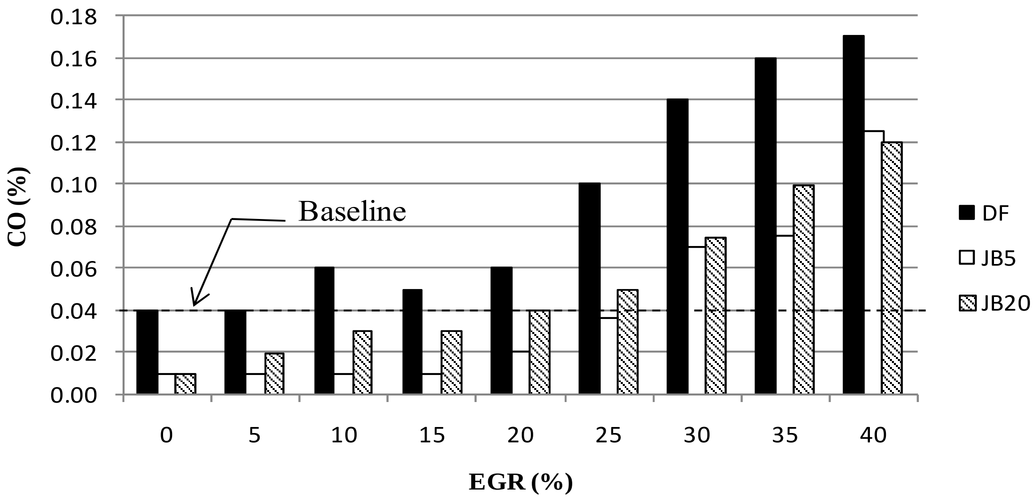

Figure 8. Variation of CO emission with various EGR rates

3.2.2 CO_2 emission

Figure 9 shows the variation of CO_2 emission of JBD blends and DF with various EGR rates. The CO_2 emission increased with increasing biodiesel amount in the blends. More amount of CO_2 in the exhaust emission is an indication of complete combustion of fuel [13,21]. The CO_2 emission of DF increased slightly, when EGR was operated. While, the CO_2 emission of JBD blends increased rapidly; especially at over 20% EGR. Beyond 20% EGR, the CO_2 emission from JBD blends was higher than that of DF. As discussed before that the oxygen availability for combustion process decreased with increasing EGR rates. Thus, the phenomena for oxidizing CO to CO_2 decreased, as well. However, it existed with JBD blends, because of their inclusion of additional oxygen amount. Therefore, the CO_2 emission of JBD blends was higher than that of DF. The higher increase in CO_2 emission was observed, at 40% EGR. The CO_2 emission of JB5 and JB20 increased by 53.7% and 62.0%, respectively; while for DF increased by 21.9%, compared to the baseline value. However, the EPA has reported at the end of 2009 that CO_2 has a direct effect on both environment and human health. CO_2 contributes to climate change, because it is one of greenhouse gases (GHG). In addition, CO_2 is threatening the human health, at its high concentration (toxicity) in the air. It can cause unconsciousness and death [22].

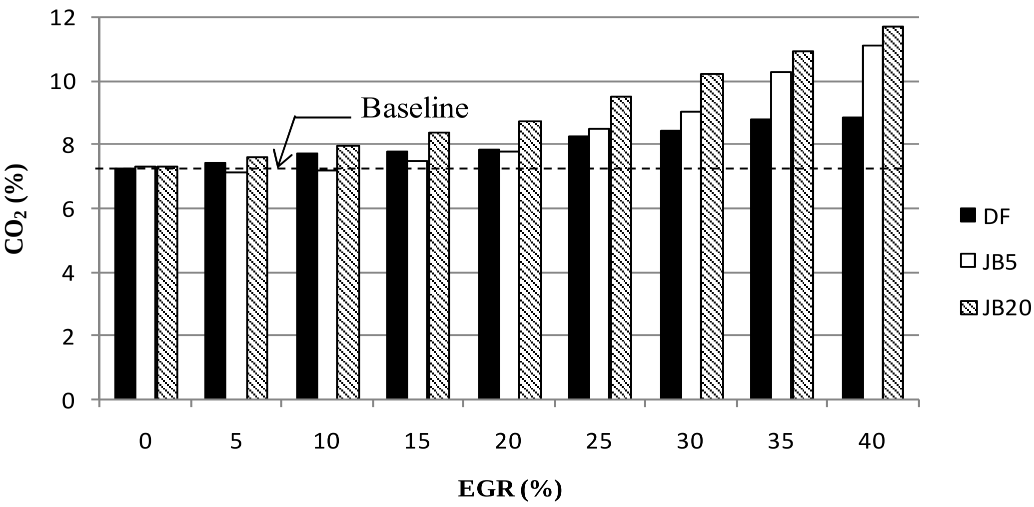

Figure 9. Variation of CO_2 emission with various EGR rates

3.2.3 NO_X emission

Figure 10 shows the variation of NO_X emission of JBD blends and DF with various EGR rates. The NO_X emission of test fuels is analyzed related to the baseline value. Therefore, it displays at Figure 10 as $NO_X/NO_{X(Baseline)}$. The important observation is that JBD blends emitted NO_X was slightly lower than that of DF, at 0% EGR. Mostly the NO_X formation depends on two factors. These are, the combustion temperature and oxygen availability in the engine cylinder [18,23]. The NO_X emission increases with increasing combustion temperature, which in turn indicated by the prevailing EGT. Since, the result of Figure 7 that the EGT of DF was higher than that of JBD blends. Therefore, the NO_X emissions of JBD blends were lower than that of DF. At 0% EGR, the NO_X emission of JB5 and JB20 was lower than the baseline value by 23% and 11%, respectively. The NO_X emission of all fuels decreased linearly, when EGR was operated. This may be due to the decrease in flame temperature due to the reduction in oxygen concentration in the combustion chamber [5,16,24,25,26]. The NO_X emission increased with increasing biodiesel amount in the blends. In addition, the NO_X emission of JBD blends was higher than that of DF, especially at higher EGR rates over 20%. Although, the result of EGT of JBD blends at Figure 7 that the EGT of JBD blends was lower than that of DF, at all EGR rates. However, the oxygen availability in JBD blends was the major reason for increasing NO_X emission, when EGR was operated. Even though, the use of EGR lead to decrease the oxygen availability of fuel combustion, but JBD blends have extra oxygen amount which contributes for NO formation by oxidize the nitrogen present in the combustion chamber. At 40% EGR, the maximum reduction in NO_X emission was observed. It was 71% for both JB5 and JB20; while for DF was 79%, compared to the baseline value.

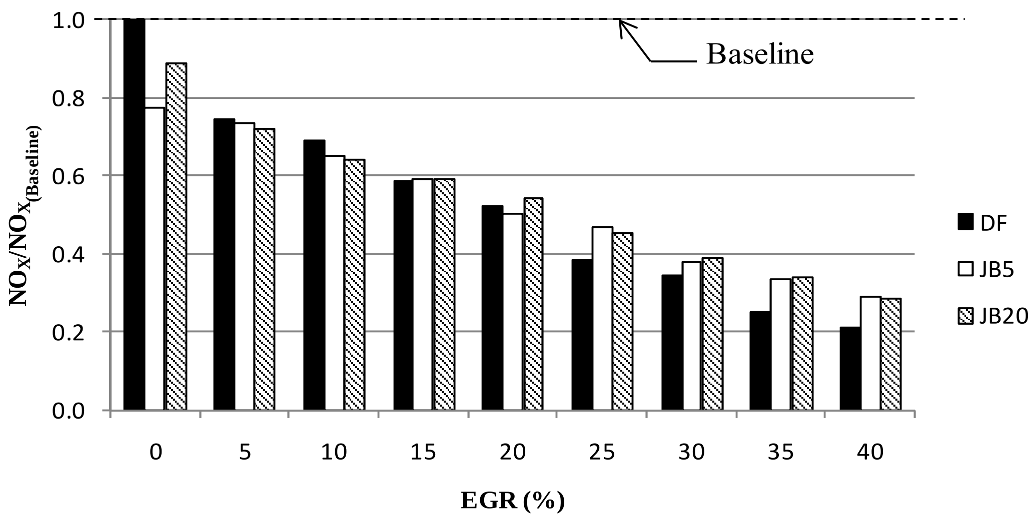

Figure 10. Variation of NO_X emission with various EGR rates

3.2.4 Smoke opacity

The comparative analysis of smoke opacity is indicated in percentage, as shown in Figure 11. The smoke opacity of JBD blends was lower than that of DF, at all operating conditions. This may be due to the oxygen amount in the blends which contributes to complete and stable combustion process [27]. The smoke opacity decreased with increasing biodiesel amount in the blends. The smoke opacity of test fuels increased linearly with increasing EGR rates. This could be due to the re-circulated exhaust gases which reduce the availability of oxygen amount for fuel combustion and lead to incomplete combustion, consequently increase the smoke opacity [16]. The significant increase in smoke opacity occurred, at higher EGR rates beyond 20%. The possible reason is the increase in re-circulated exhaust gas amount lead to significant reduction in oxygen amount sucked into the combustion chamber [24]. At 40% EGR, the maximum level of smoke opacity of JB5 and JB20 was 43.8% and 34.5%, respectively; while, for DF was 62.4%. As a Malaysian regulation for acceptable smoke opacity level is shall not exceed 50 HSU [28]. Since, the HSU is equivalent to percent opacity [29]. Thus, the smoke opacity level of DF was unacceptable, at 40% EGR.

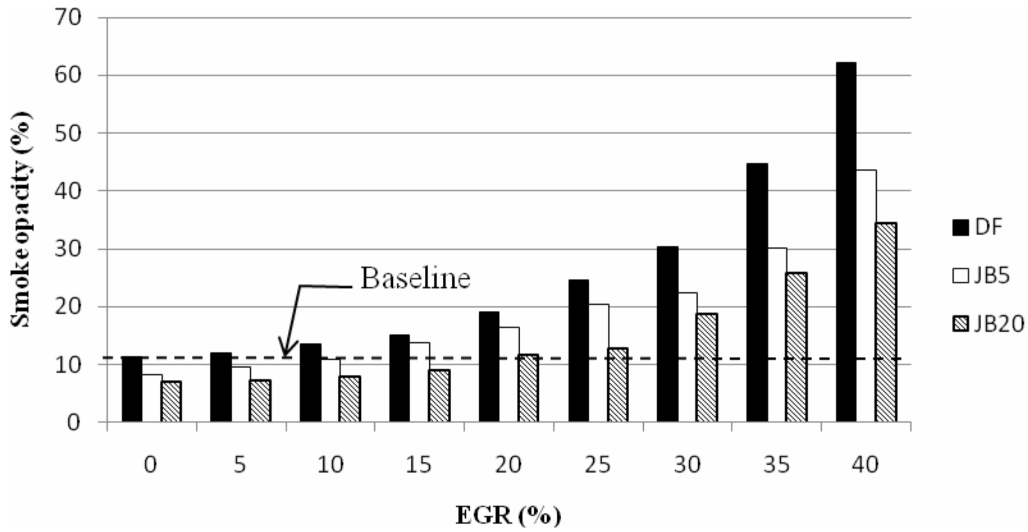

Figure 11. Variation of smoke opacity with various EGR rates

3.3 The trade-off between NO_X and smoke emissions for EGR rates at different JBD blends

Based on the results, the acceptable limit of EGR is obtained from 5% to 20%. The objective of the current study is to reduce both NO_X and smoke emissions simultaneously, without much adverse effects on engine performance. To attain this objective, a trade-off between NO_X and smoke must be achieved.

3.3.1 Fuelling using JB5

Figure 12 shows the optimum trade-off between NO_X and smoke emissions for various EGR rates with JB5. The optimum trade-off occurred, at about 10% EGR. At 10% EGR with JB5, both NO_X and smoke opacity decreased by 35% and 4.1% respectively, compared to the baseline values.

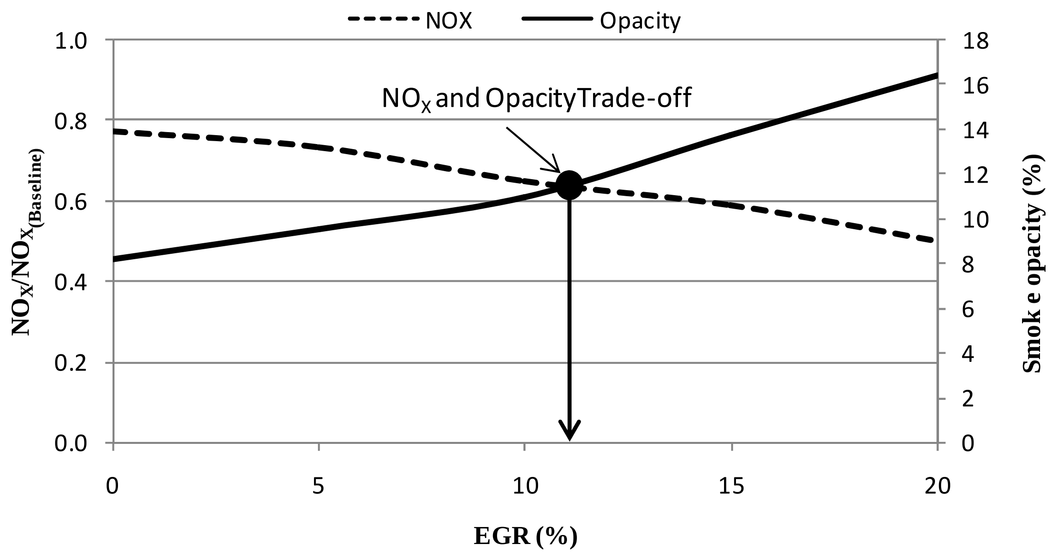

Figure 12. The optimum trade-off between NO_X and smoke opacity for different EGR rates with JB5

The current study focused to obtain the better engine performance with the optimum trade-off between NO_X and smoke emissions. Therefore, as shown in Table 3, the comparison between the effects of EGR rates within limits of 5-15% on engine performance and exhaust emissions is made, relative to the baseline values. The 5% and 10% EGR were selected for comparison, because these rates around 10% EGR (optimum rate). These rates may be produced similar exhaust emissions of 10% EGR, but with better engine performance or vice versa.

Table 3. The effects of EGR on engine performance and exhaust gas emissions with JB5 at different EGR rates (5-15%) relative to the baseline values

Parameter (percentage difference)	5% EGR	10% EGR	15% EGR
Torque (%)	0.0	2.9↓	2.9 ↓
BTE (%)	1.3 ↑	5.2 ↓	5.2 ↓
BSFC (%)	0.6 ↓	6.2 ↑	6.2 ↑
BSEC (%)	1.3 ↓	5.5 ↑	5.5 ↑
CO (%)	75.0 ↓	75.0 ↓	75.0 ↓
CO_2 (%)	1.5 ↓	0.6 ↓	3.5 ↑
NO_X (%)	27.0 ↓	35.0 ↓	41.0 ↓
Smoke opacity (%)	17.0 ↓	4.1 ↓	20.0 ↑

Note: ↑increase; ↓decrease.

As shown in Table 3, the maximum reduction in NO_X emission (41%) occurred, at 15% EGR. However, the smoke opacity increased by 20%, compared to baseline value. Furthermore, the engine performance is not preferable because, the penalty in BTE and BSFC. At 10% EGR, the engine performance was similar to that of in case of 15% EGR, with sufficient reduction in smoke opacity. Whereas, at 5% EGR, it achieved significant reduction in exhaust gas emissions (CO, NO_X and smoke opacity) compared to the baseline values. Moreover, the engine performance improved slightly. JB5 along with 5% EGR succeeded to reduce NO_X (27%) and smoke opacity (17%) simultaneously, without torque output deterioration. Furthermore, the BTE and BSFC improved by 1.3% and 0.6%, respectively. Therefore, it can be concluded that the preferable EGR rate is 5%.

3.3.2 Fuelling using JB20

Figure 13 shows the optimum trade-off between NO_X and smoke emissions for EGR rates with JB20. The optimum trade-off obtained, at about 15% EGR. At 15% EGR with JB20, both NO_X and smoke opacity decreased by 41% and 21.9% respectively, compared to the baseline values.

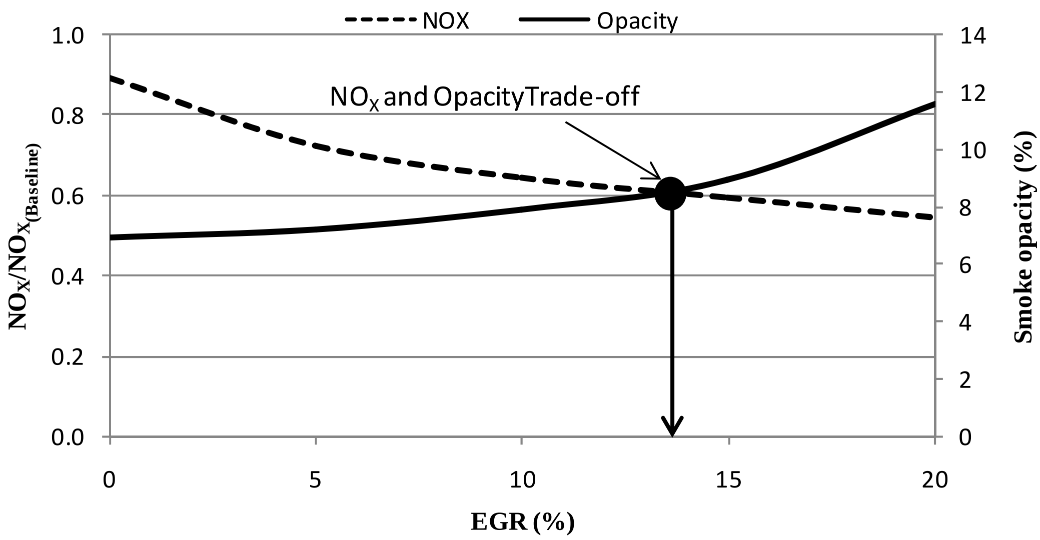

Figure 13.The optimum trade-off between NO_X and smoke opacity for different EGR rates with JB20

Table 4 shows the comparison between the effects of EGR rates within limit of 10-20% on engine performance and exhaust emission, relative to the baseline values.

As shown in Table 4, the maximum reduction in NO_X (46%) obtained, at 20% EGR. At 20% EGR, the smoke opacity increased by 1.8%. Furthermore, the BSFC increased by 7.6%, and the torque output deteriorated by 8.8%. For these reasons, 20% EGR is not preferable. At 15% EGR, the engine performance parameters (BTE, BSFC and BSEC) were better than that of in case of 20% EGR. Moreover, it achieved reduction in both NO_X and smoke opacity by 41% and 21.9%, respectively. When, the engine performance parameters and exhaust emissions in case of 15% EGR compared to that of in case of 10% EGR, it was found the performance parameters in the case of 10% EGR were better. Both BTE and BSEC improved by 6.8% and 6.4%, respectively. However, the BSFC increased slightly by 2.1% and torque output deteriorated by 5.9%. Although at 10% EGR, the engine performance influenced slightly, but still better than that of in case of 15% EGR. Furthermore at 10% EGR, it achieved significant reduction in exhaust emissions. The smoke opacity, NO_X and CO emissions decreased by 31%, 36% and 25%, respectively. However, CO_2 emission increased by 10.2%, it was lower by about 6%, compared to that of 15% EGR case. Therefore, in case of JB20; the preferable EGR rate is 10% because, it is more effective for exhaust emissions reduction and improve engine performance, with slightly loss in torque output and little increase in BSFC.

Table 4. The effects of EGR on engine performance and exhaust gas emissions with JB20 at different EGR rates (10-20%) relative to the baseline values

Parameter (percentage difference)	10% EGR	15% EGR	20% EGR
Torque (%)	5.9 ↓	5.9 ↓	8.8 ↓
BTE (%)	6.8 ↑	4.7 ↑	1.3 ↑
BSFC (%)	2.1 ↑	4.2 ↑	7.6 ↑
BSEC (%)	6.4 ↓	4.5 ↓	1.3 ↓
CO (%)	25.0 ↓	25.0 ↓	25.0 ↓
CO_2 (%)	10.2 ↑	16.0 ↑	20.9 ↑
NO_X (%)	36.0 ↓	41.0 ↓	46.0 ↓
Smoke opacity (%)	31.0 ↓	21.9 ↓	1.8 ↑

Note: ↑increase; ↓decrease.

4. Conclusion

The effects of EGR rates along with Jatropha biodiesel blends on performance parameters and exhaust emissions were investigated in an IDI diesel engine. The main conclusions from this study are summarized as follows:

- EGR usage deteriorated the fuel combustion efficiency. There were reduction in torque output and BTE. Moreover, the BSFC and BSEC increased, using all test fuels, especially over 20% EGR.
- Smoke opacity, CO and CO_2 emissions increased with increasing EGR rates. On the other hand, NO_X emission decreased with increasing EGR rates.
- At 40% EGR, the smoke opacity level of diesel fuel was unacceptable; whereas for JBD blends were acceptable.
- Using JBD blends; the better trade-off between smoke opacity and NO_X emissions can be attained within a limited EGR rate of 5-15%, with little effects on engine performance.
- The 5% EGR was preferable for JB5 to achieve acceptable performance and emissions reduction. At 5% EGR with JB5, both NO_X and smoke opacity were reduced by 27% and 17% respectively.
- While, in case of JB20, 10% EGR was preferable. JB20 with 10% EGR reduced both NO_X and smoke emission by 36% and 31%, respectively.

Through all of these results and observations, it is could be concluded that blending JBD with DF up to 20% (by volume) along with EGR rates up to 15%, could replace DF for running the IDI diesel engine with less emissions and without much adverse effect on engine performance. This will help in controlling air pollution to a greater extent.

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