Performance and Emission Comparison of a DI Diesel Engine Fueled by Diesel and Diesel-biodiesel Blend without and with EGR Condition

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ABSTRACT

This study investigated the performance and emissions of a direct injection (DI) diesel engine fueled by neat diesel and 20%-80% blend of biodiesel and diesel (B20) under various load conditions and engine speeds without and with low percentage of exhaust gas recirculation (EGR) conditions. Here 10% EGR was attempted. Two parameters were measured during the engine operation: one is engine performance (brake thermal efficiency and brake specific fuel consumption), and the other is the exhaust emissions (NOx and CO). The result showed that, the brake thermal efficiency (η_{th}) of B20 was almost similar or a slight lower, but brake specific fuel consumption (bsfc) was a little higher than neat diesel. At no load or low load conditions without EGR, carbon monoxide (CO) was higher and oxides of nitrogen (NOx) were lower with B20 than that of diesel. However, under high load conditions, NOx became higher and CO reduced significantly with B20. In case of EGR, diesel and B20 produced no change in thermal efficiency and bsfc in comparison to non-EGR. Furthermore, B20 showed higher reduction in NOx than diesel. Hence, B20 with 10% EGR can safely be used in diesel engine without any significant penalty in engine performance and with higher NOx reductions.

Keywords: DI diesel engine, performance and emissions, renewable alternative fuel, biodiesel, B20, EGR.

1. INTRODUCTION

The growing concern on environmental pollution caused by the extensive use of conventional fossil fuels has led to search for more environment friendly and renewable fuels. Biofuels such as alcohols and biodiesel have been proposed as alternatives for internal combustion engines [1, 2]. In particular, biodiesel has received wide attention as a replacement for diesel fuel because it is biodegradable, nontoxic and can significantly reduce toxic emissions and overall life cycle emission of carbon dioxide (CO_2) from the engine when burned as a fuel [3, 4]. Several countries including India have already begun substituting the conventional diesel by a certain amount of biodiesel [5]. The use of biodiesel is being promoted by EU countries to partly replace petroleum diesel fuel consumption in order to reduce greenhouse effect and dependency on foreign oil. Meeting the targets established by the European Parliament for 2010 and 2020 would lead to a biofuel market share of 5.75% and 10%, respectively [6]. In near future, biodiesel fuels offer a potentially very interesting alternative regarding harmful emissions. Additionally, biodiesel does not contain any sulfur. Although biodiesel has many advantages, it still has several properties, needed to be improved, such as lower calorific value, lower effective engine power, higher emission of NOx, and greater sensitivity to low temperatures.

Many investigations have shown that using biodiesel in diesel engines can reduce hydrocarbon (HC), CO and particulate matter (PM) emissions but NOx emission may increase [4, 7, 8]. The increase in NOx emission serves as biodiesel's major impediment to widespread use [9]. In order to reduce this adverse effect, investigations have been carried out on different approaches for reducing NOx emission when biodiesel is used. The increase in NOx emission can be avoided through modifying the properties of the biodiesel [9] or through adjusting engine setting [10]. Szybist et al. [9] looked into the problem by considering the use of cetane improver for modifying ignition delay and the use of biodiesel with different bulk modulus for modifying fuel injection timing; both approaches have the potential for reducing NOx emission. Leung et al. [10] concluded that controlling an individual engine operating parameter cannot acquire satisfactory results on optimizing engine emission; thus, multiparameter adjustment is required for reducing simultaneously HC, NOx and PM emissions. Fernando et al. [11] reviewed the NOx reduction methods for biodiesel fuels. They concluded that the thermal NOx mechanism is the major contributor to NOx emission, thus NOx can be reduced through the application of water injection, water emulsified biodiesel, ignition timing retardation or exhaust gas recirculation which can lead to reduction in flame temperature. However most of these methods will normally lead to deterioration in engine performance as well.

It was reported that engine parameters have significant effect on performance and emissions of diesel engine when run with biodiesel and its blend with diesel [12–14]. Hence, a study was undertaken at RUET, Bangladesh to gather information on behavior of diesel engine when operated with biodiesel and its blend with diesel at varying engine parameters. Engine tests were carried out at different engine speeds and loads without and with EGR. A low percentage of EGR was attempted to reduce NOx emissions without deterioration in engine performance.

2. EXPERIMENTAL SETUP AND MEASUREMENT

A four-stroke single cylinder naturally aspirated DI diesel engine with specifications as in Table 1 was used in this experiment.

Table 1: Engine specifications

Engine type	4-stroke DI diesel engine
Number of cylinders	One
Bore × Stroke	80 × 110 mm
Swept volume	553 cc
Compression ratio	16.5:1
Rated power	4.476 kW@1800 rpm
Fuel injection timing	24^0 BTDC

All experimental data were taken at various engine speeds after engine warm-up. The diesel fuel used in this study was available in the local market. Loads were measured by electric dynamometer. Corresponding to each data point, exhaust emissions and fuel consumption were measured for diesel and B20. A flue gas analyzer (IMR 1400) was used to measure CO and NOx of exhaust gases.

2.1. Production of Soy Biodiesel

The most common method of biodiesel production is transesterification (alcoholysis) of oil (triglycerides) with methanol in the presence of a catalyst which gives biodiesel (fatty acid methyl esters, FAME) and glycerol (by-product). The basic biodiesel reaction and flow chart of soy biodiesel production is illustrated in Fig. 1. Reacting one part vegetable oil with three parts methanol gives three parts methyl esters (biodiesel) and one part glycerol. In practical terms, the volume of biodiesel will be equal to the input volume of vegetable oil. Soy biodiesel was produced by transesterification process in this study. Methanol was used as alcohol and NaOH as lye catalyst. Instead of methanol and NaOH, ethanol or KOH can also be used for making biodiesel. Methanol and NaOH were used in this study for lower cost. NAOH catalyst is in solid form and does not readily dissolve into methanol, it is best to start agitating the methanol in a mixer and add the catalyst slowly and carefully. The procedure to make biodiesel followed in this study is from [15]. The catalyst (3.5 grams) was dissolved into the methanol (200 ml) by vigorous stirring in a small flask. Once the catalyst completely dissolves in the methanol, the methoxide is ready to be added to the oil. Heating the oil prior to the mixing can increase the reaction rate and hence shorten the reaction time. The temperature is kept just below the boiling point of the alcohol (64.5ºC in case of methanol). The heated soybean oil (at 60ºC) is transferred into the biodiesel reactor (a blender in this study), and then, the catalyst/alcohol mixture is added into the oil (1 liter). The final mixture is stirred vigorously for half an hour in the blender in ambient pressure. A successful transesterification reaction produced two liquid phases: ester and crude glycerin.

Crude glycerin, the heavier liquid, will collect at the bottom after several hours of settling. Phase separation can be observed within 10min and can be completed within 2 h of settling. Complete settling can take as long as 20h. Crude soy biodiesel was separated after 24 hours of settling. After separation from the glycerol phase, crude biodiesel is mainly contaminated with residual catalyst, water, unreacted alcohol, free glycerol, and soaps that were generated during the transesterification reaction. Generally, three main approaches are adopted for purifying biodiesel: water washing, dry washing, and membrane

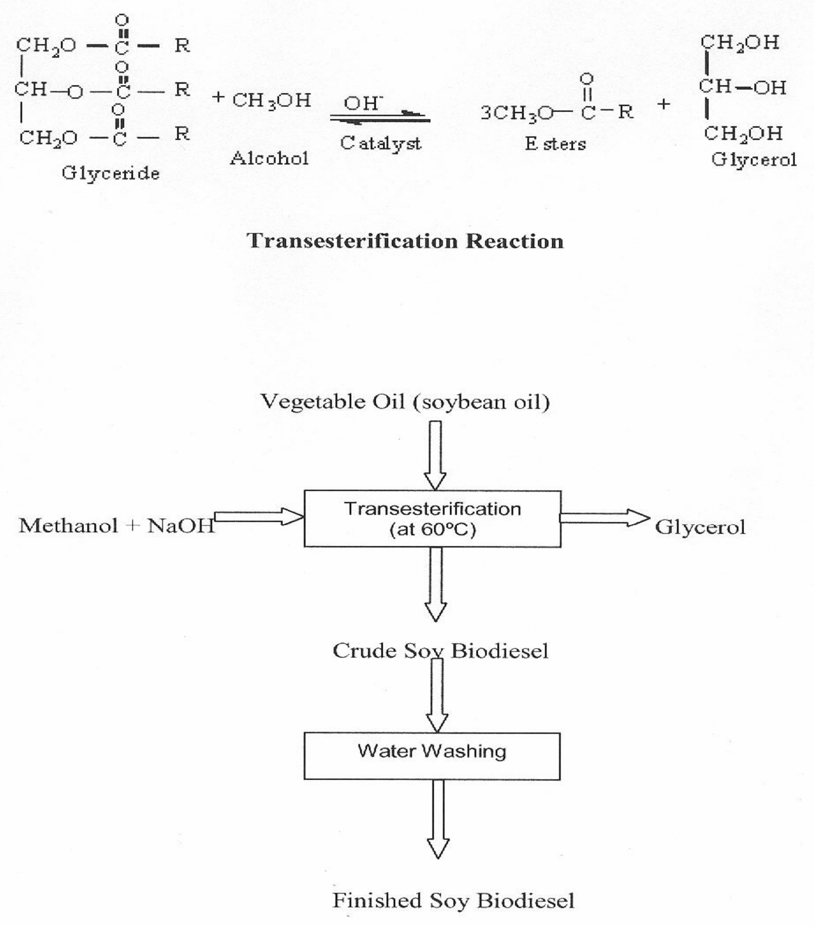

Figure 1: Basic biodiesel reaction and flow chart of soy biodiesel production

extraction. Since both glycerol and alcohol are highly soluble in water, water washing is very effective for removing both contaminants. It also can remove any residual sodium salts and soaps. Water washing (twice) was used in this study to wash the impurities in the crude biodiesel. After washing, finished soy biodiesel was obtained. The collection efficiency was more than 95%.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Engine performance

After the engine reached the stabilized working condition for each test, fuel consumption, load and exhaust emissions were measured, from which bsfc, torque and efficiency were computed. The variations of these parameters with respect to torque are presented.

Figure 2 shows brake thermal efficiency (η_{th}) and bsfc with diesel and B20 without and with 10% EGR at 600 rpm for various engine loads. Fig. 1(a) is for non-EGR and 1(b) for 10% EGR condition. It is seen that, brake thermal efficiency with B20 and neat diesel increased without and with EGR condition as the engine torque was increased. On the other hand, bsfc with B20 and neat diesel decreased without and with EGR condition as the engine torque was increased. Brake thermal efficiency with B20 without and with EGR condition is very similar or a little lower than neat diesel for various loading conditions. At low load condition, thermal efficiency with B20 and neat diesel is only about 6%. At medium load condition, it is increased to about 10%, and at high load condition, it is about 17%. Brake specific fuel consumption with B20 is a little higher than neat diesel, about 1-2% without and with EGR condition. It decreased from about 1.5 kg/kw-hr to less than 0.5 kg/kw-hr, when engine torque was increased from 2.45 to 9.8 N-m.

Figure 3 illustrates the variation of brake thermal efficiency and bsfc with engine torque at 1000 rpm without and with EGR condition for neat diesel and B20. Brake thermal efficiency with B20 and neat diesel increased without and with EGR condition, as the engine torque was increased, and bsfc with B20 and neat diesel decreased without and with EGR condition as the engine torque was increased. Brake thermal efficiency with B20 without and with EGR condition is very similar to that with neat diesel for various loading conditions. The trend is similar to that described in Fig. 2.

At low load condition, thermal efficiency with B20 and neat diesel without and with EGR condition is about 16%. At medium load condition, it is increased to about 26%, and at high load condition, it is about 30%. This is the highest thermal efficiency obtained in this study. Brake specific fuel consumption with B20 is a little higher than neat diesel, about 1-3% without and with EGR condition. It decreased from about 0.54 kg/kw-hr to less than 0.3 kg/kw-hr, when engine torque is increased from 6 to 24 N-m.

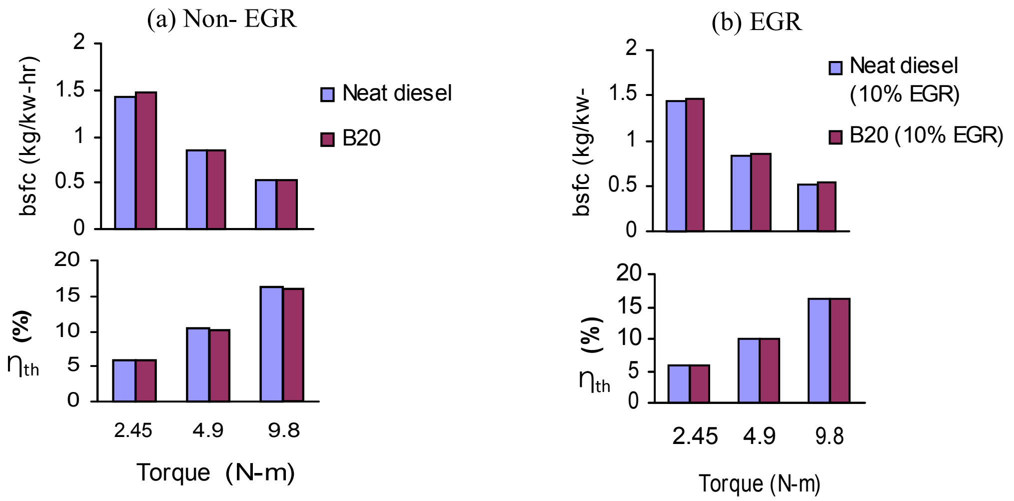

Fig. 2: Brake thermal efficiency and bsfc with diesel and B20 without and with EGR condition at 600 rpm

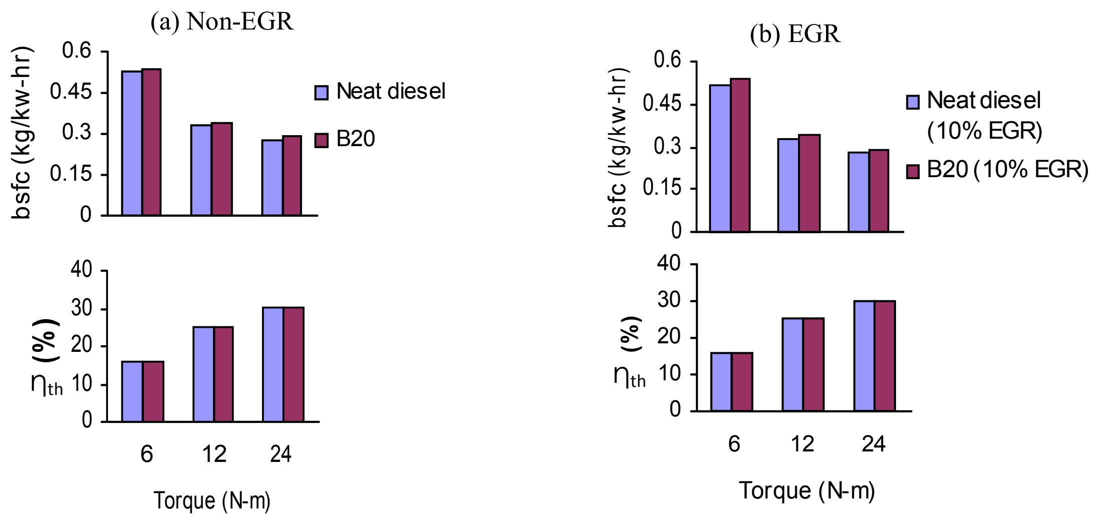

Fig. 3: Brake thermal efficiency and bsfc with diesel and B20 without and with EGR condition at 1000 rpm

Figure 4 shows brake thermal efficiency and bsfc with diesel and B20 without and with 10% EGR at 1200 rpm for various engine loads. Brake thermal efficiency and bsfc with diesel and B20 are similar to that in Figs. 2 and 3. At low load condition, thermal efficiency with B20 and neat diesel is about 15%. At medium load condition, η_{th} is increased to about 20%, and at high load condition, η_{th} is less than 20%. Brake specific fuel consumption with B20 is always a little higher than neat diesel, about 2-4% without and with EGR condition. It decreased from about 0.59 kg/kw-hr to less than 0.4 kg/kw-hr, where engine torque is increased from 7.5 to 30 N-m.

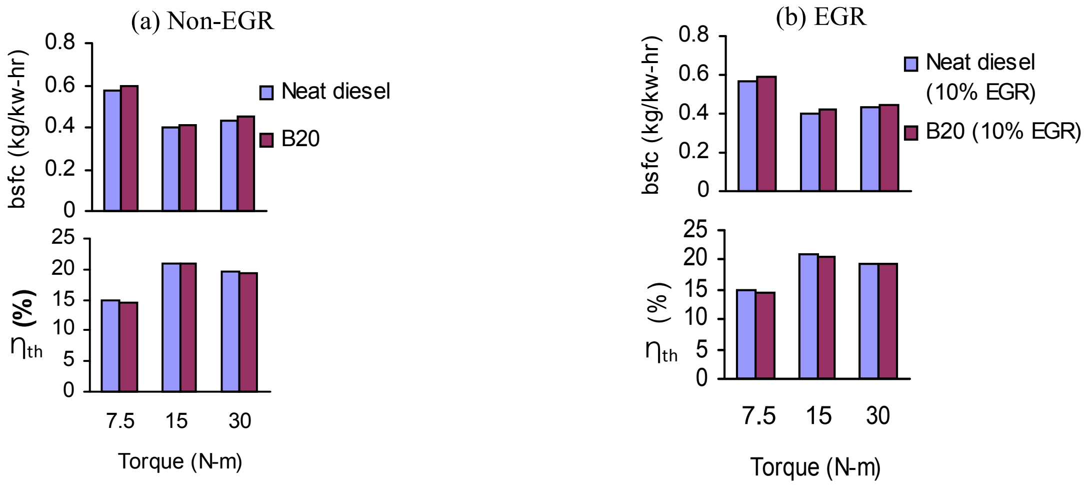

Fig. 4: Brake thermal efficiency and bsfc with diesel and B20 without and with EGR condition at 1200 rpm

3.2. Engine emissions

Figure 5 shows the variation of CO and NOx emissions with engine torque without and with EGR at 600 rpm for neat diesel and B20. Fig. 5(a) is for non-EGR and 5(b) for 10% EGR condition. From the figure, it is seen that at no load or low load conditions CO emission with B20 is always higher than neat diesel without and with EGR condition. However, CO decreased with B20 and increased with neat diesel with increasing engine load.

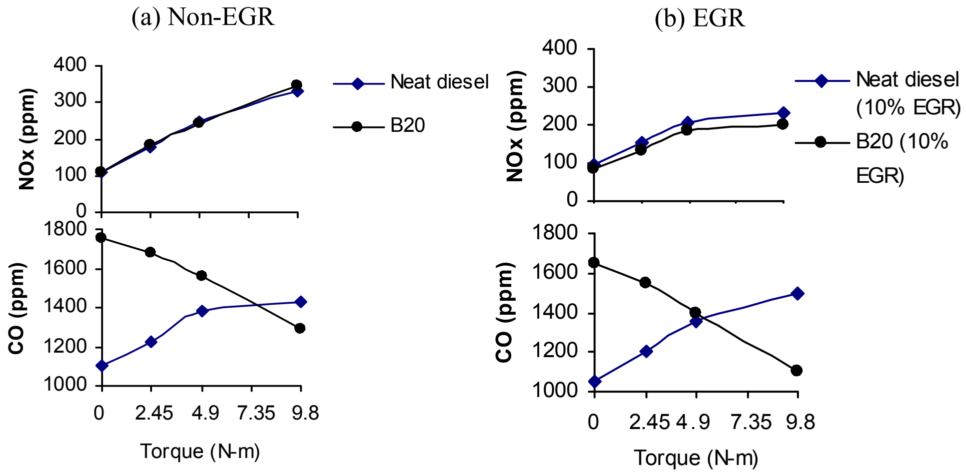

Fig. 5: CO and NOx emissions with diesel and B20 without and with EGR condition at 600 rpm

Improved combustion as well as less CO was expected with biodiesel than diesel due to biodiesel's inherent O_2 content. However, at no or low load conditions, biodiesel showed poorer combustion and higher CO than diesel. Higher viscosity and boiling temperature of biodiesel as well as lower combustion temperature at low engine speed produced improper local mixture producing higher CO emission than diesel. The trend is reversed after a certain load. When the fuel-air equivalence ratio (φ) increases at higher engine loads, O_2 in biodiesel helps to produce less CO, whereas CO increases with diesel combustion. NOx emission without EGR with B20 and diesel is very similar. However, NOx reduction with EGR for B20 fuel is higher than diesel fuel.

Specific heat of biodiesel is higher than that of neat diesel. Therefore, higher amount of combustion heat is absorbed by the recirculated biodiesel exhaust lowering the combustion temperature. This helps to reduce higher NOx than diesel.

Figure 6 illustrates the variation of CO and NOx emission with engine torque without and with EGR condition at 1000 rpm for diesel and B20. At no load condition, CO emission with B20 is higher than that of neat diesel without and with EGR condition. CO with B20 is decreased than that of neat diesel when engine load is increased. At higher engine speed of 1000 rpm, only no load condition produced poorer combustion with higher CO emission with B20 than neat diesel.

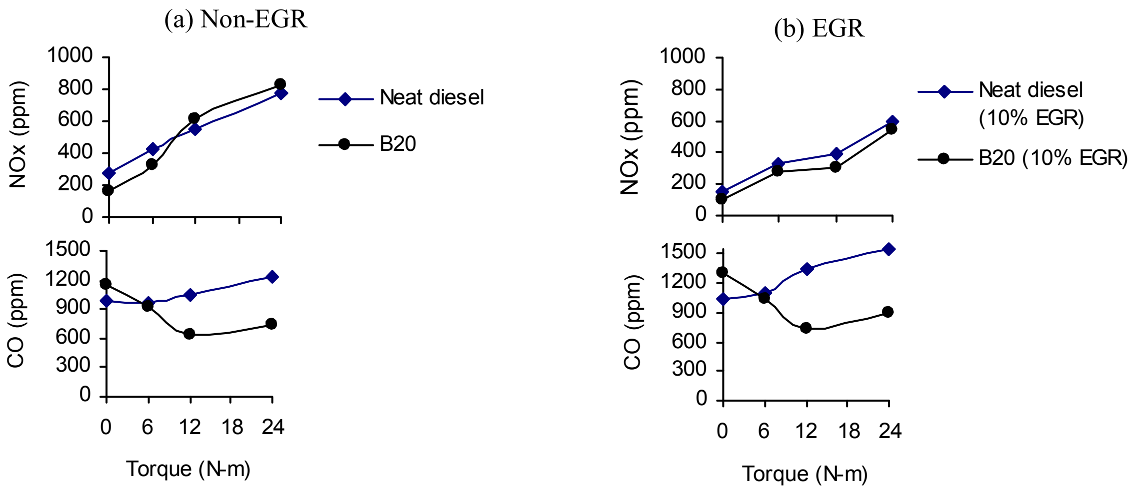

Fig. 6: CO and NOx emissions with diesel and B20 without and with EGR condition at 1000 rpm.

Without EGR, NOx emission with B20 at lower load condition is lower and at higher load condition it is higher than that of neat diesel. However, with EGR B20 always produced lower NOx than that of neat diesel similar to that in Fig. 5.

Figure 7 shows the variation of CO and NOx emission with engine torque without and with EGR condition at 1200 rpm.

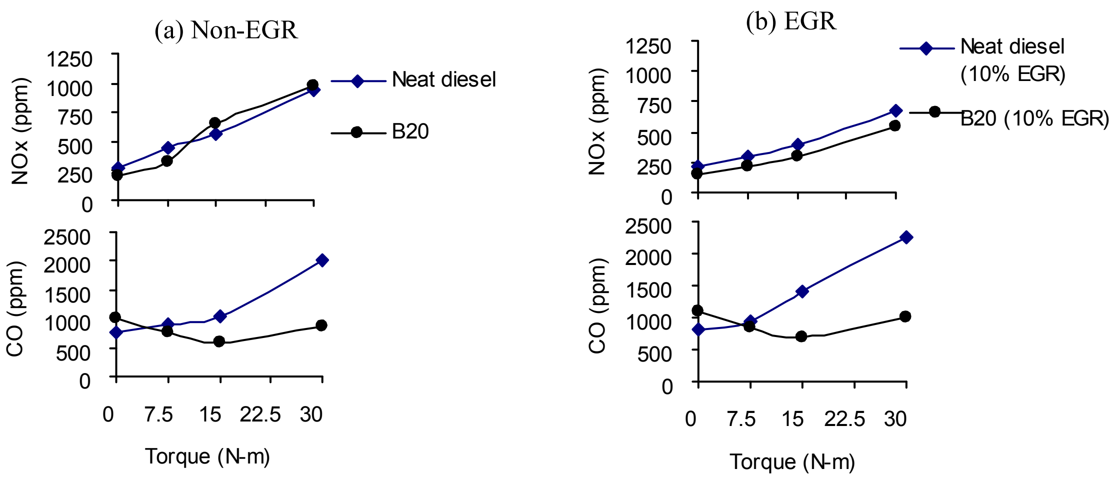

Fig. 7: CO and NOx emissions with diesel and B20 without and with EGR condition at 1200 rpm.

At no load condition, CO with B20 is slightly higher than that of neat diesel, and with increasing load CO is always lower than diesel fuel without and with EGR condition. Here also NOx reduction with B20 is higher than neat diesel fuel. From experimental results it is understood that biodiesel combustion at low temperature condition deteriorates combustion quality and produces higher CO without or with low percentage of EGR due to higher viscosity of biodiesel and improper mixture formation. With EGR operation biodiesel reduced higher NOx than diesel due to higher specific heat of biodiesel exhaust, for which recirculated exhaust gas at EGR absorb higher amount of combustion heat.

Figure 7 shows PM emissions at different engine speeds and loads for various fuels. At 650 rpm, PM emission at no load with diesel fuel is about 45 mg/m3 of exhaust gas. It increased to about 175 mg/m3 at full load operation, about four times than no load condition. B20 showed the PM about 20% and B100 about 30% less than diesel throughout the operation range. At 950 rpm, PM emission at no load with diesel fuel is about 93 mg/m3 of exhaust gas. It increased to about 266 mg/m3 at full load operation,

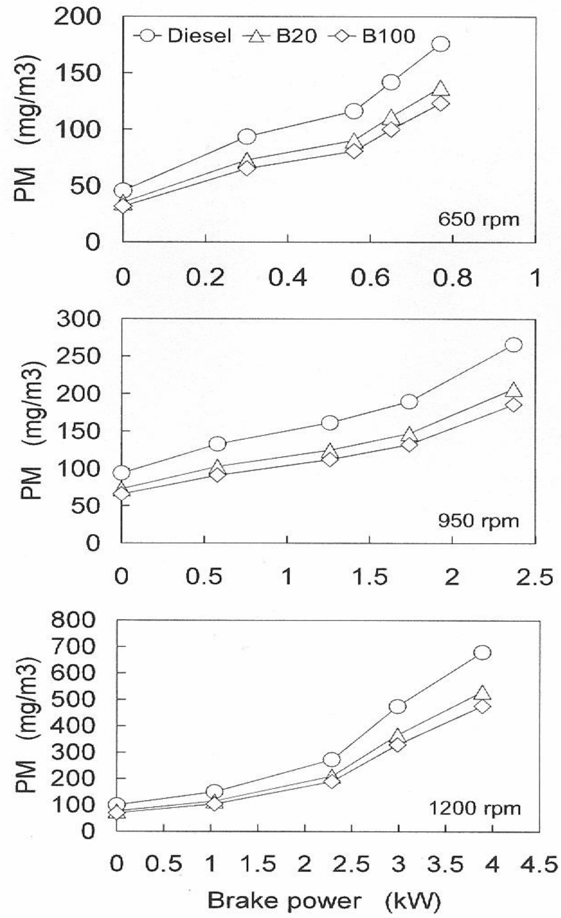

Figure 10: PM emissions with various fuels at different engine speeds and loads

about three times than no load condition. B20 showed the PM about 20% and B100 about 30% less than diesel throughout the operation range. At 1200 rpm, PM emission at no load with diesel fuel is about 100 mg/m3 of exhaust gas. It increased to about 680 mg/m3 at full load operation, about seven times than no load condition. Again B20 showed the PM about 20% and B100 about 30% less than diesel throughout the operation range. Shobokshy (1984) and Sharmaet al. (2005) have reported that particulate concentration increases with increased engine load; the same trend is obtained in present study. Particles are mainly 406 formed during diffusion combustion, and most of the combustion process is diffusive at high load. Therefore, high levels of PM were exhausted at full load operations at different engine speeds. The oxygen content of biodiesel helped in reducing PM. Higher reduction was expected at higher load operations, but the reduction throughout the engine load was almost constant. The other reason of reduction in PM with biodiesel and blend is attributed to near absence of aromatic compounds and sulphur in biodiesel.

4. CONCLUSION

The following conclusions can be drawn from the experimental investigation.

1. B20 showed very similar thermal efficiency to that of the level of diesel without and with low EGR conditions.
2. The bsfc of B20 is about 1-4% higher than that of diesel without or with EGR.
3. At no load or low load conditions, B20 produced higher CO than diesel, but at high load condition B20 produced significantly lower CO than diesel without or with EGR condition.
4. At no load or low load condition without EGR, B20 produced lower NOx than the neat diesel, but at higher load condition NOx emission with B20 is higher than diesel. With 10% EGR condition, B20 always produced lower NOx than that of diesel at all engine speed and load conditions.
5. The oxygen content of biodiesel helped in reducing PM. This might be due to lower sulphur and aromatic content of biodiesel. B20 showed the PM about 20% and B100 about 30% less than diesel at all operating conditions.

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