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Technical Note

Experimental investigation of control of NO_x emissions in biodiesel-fueled compression ignition engine

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Abstract

Biodiesel is an alternative fuel consisting of the alkyl esters of fatty acids from vegetable oils or animal fats. Vegetable oils are produced from numerous oil seed crops (edible and non-edible), e.g., rapeseed oil, linseed oil, rice bran oil, soybean oil, etc. Research has shown that biodiesel-fueled engines produce less carbon monoxide (CO), unburned hydrocarbon (HC), and particulate emissions compared to mineral diesel fuel but higher NO_x emissions. Exhaust gas recirculation (EGR) is effective to reduce NO_x from diesel engines because it lowers the flame temperature and the oxygen concentration in the combustion chamber. However, EGR results in higher particulate matter (PM) emissions. Thus, the drawback of higher NO_x emissions while using biodiesel may be overcome by employing EGR. The objective of current research work is to investigate the usage of biodiesel and EGR simultaneously in order to reduce the emissions of all regulated pollutants from diesel engines. A two-cylinder, air-cooled, constant speed direct injection diesel engine was used for experiments. HCs, NO_x, CO, and opacity of the exhaust gas were measured to estimate the emissions. Various engine performance parameters such as thermal efficiency, brake specific fuel consumption (BSFC), and brake specific energy consumption (BSEC), etc. were calculated from the acquired data. Application of EGR with biodiesel blends resulted in reductions in NO_x emissions without any significant penalty in PM emissions or BSEC.

Keywords: Biodiesel; EGR; Transesterification; Exhaust emissions

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1. Introduction

Diesel engines are main workhorses for heavy-duty vehicles because of their good fuel economy and durability. They have higher thermal efficiency, resulting from high compression ratio and lean fuel combustion. Diesel engines operate with an excess air ratio (λ) = 1.5–1.8 on full load and higher λ values at lower loads [1]. Diesel engine combustion generates large amounts of NO_x because of high flame temperatures in presence of abundant oxygen and nitrogen in the combustion chamber.

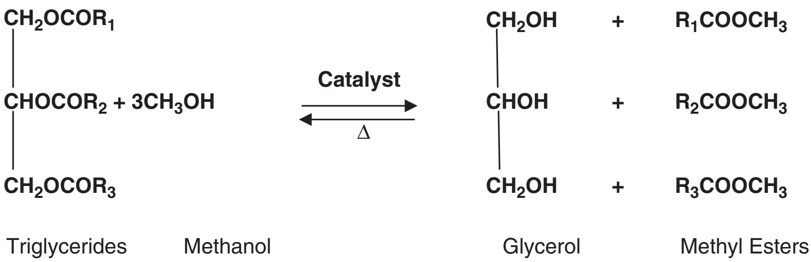
Increased environmental concerns and tougher emission norms have led to the development of advanced engine technologies to reduce NO_x and particulate matter (PM) emissions. Ever increasing emission reduction demands present a continuing challenge to engine designers because of NO_x–PM trade-off associated with most of the emission reduction strategies. Recent engine work focuses on improvements or incorporation of new technologies to power cylinder, air delivery, fuel management, and electronic systems [2]. Very low emissions from engines can be achieved with exhaust gas after treatment and optimized combustion processes [3]. Modification of diesel engines and fuel to reduce emissions has been a subject of numerous studies over the years. Many such studies have previously focused on fuel changes, such as reduced aromatic content (higher cetane number), reduced fuel sulfur, increased fuel volatility, and decreased fuel density. Oxygenated diesel fuel studies have focused primarily on the possibility of significant emissions reductions.

2. Biodiesel

Though the amount of CO_2 emissions by mankind is relatively small as compared to the nature's CO_2 emissions, this anthropogenic part is classified as climatically relevant. Therefore, the KYOTO Treaty demands a considerable reduction of greenhouse gases. Oxygenated diesel fuels can be obtained either by blending oxygenates to diesel or using bio-fuels [4,5]. Recent surge in petroleum prices have regenerated interest in bio-fuels. The development of biomass-based diesel substitutes is an attractive proposition, as it helps to improve diesel fuel quality. The fuels of bio-origin may be alcohol, vegetable oils, biomass, and biogas. Some of these fuels can be used directly in the engine, while others need to be formulated to bring the relevant properties close to conventional fuels.

Vegetable oils have almost similar energy density, cetane number, heat of vaporization, and stoichiometric air/fuel ratio compared to mineral diesel fuel [6]. However, straight vegetable oils cannot be used directly in engines. Straight vegetable oils or their blends with diesel pose various long-term operational and durability problems in compression ignition engines, e.g., poor fuel atomization, piston ring-sticking, fuel injector coking and deposits, fuel pump failure, and lubricating oil dilution, etc. [7]. The properties of vegetable oils responsible for these problems are high viscosity, low volatility, and polyunsaturated character. Several techniques are proposed to reduce the viscosity of vegetable oils such as blending, pyrolysis, micro-emulsion, and transesterification, etc. Heating and blending of vegetable oils reduce the viscosity but its molecular structure remains unchanged hence polyunsaturated character and low volatility problems exist. It has been reported that transesterification is an effective process to overcome all these problems associated with vegetable oils [6,7].

Biodiesel is the name of a clean burning mono-alkyl ester-based oxygenated fuel made from natural, renewable sources such as vegetable oils and animal fats. Biodiesel has similar physical and thermal properties compared to conventional diesel fuel. Biodiesel is compatible with conventional diesel and can be blended in any proportion with petroleum diesel to produce a stable blend. Vegetable oil esters have superior fuel properties compared to straight vegetable oils. They have lower viscosity, higher volatility, and lower un-saturation. Glycerin is a valuable by-product of transesterification process, which is used in pharmaceutical and cosmetic industries. Transesterification is a reversible reaction of fat or oil (triglyceride) with a primary alcohol to form esters and glycerol. Alcohol combines with the triglycerides to form glycerol and esters. The reaction is shown below.



A catalyst is usually used to improve the reaction rate and yield. Alkalies, acids, and enzymes can catalyze this reaction. Alkali-catalyzed transesterification is much faster than acid-catalyzed transesterification and is most often used commercially. Effect of different parameters like temperature, molar ratio of alcohol to oil, catalyst, reaction time have been investigated by several researchers and it was found that for base catalyzed transesterification at atmospheric pressure, 55–60 °C temperature, 45 min to 1 h reaction time and 6:1 molar ratio of alcohol to oil the yield is optimum [6–14].

Biodiesel is a renewable fuel which is free from sulfur and aromatic compounds. Biodiesel does not overburden the environment with CO_2 emission as CO_2 from the atmosphere is absorbed by the vegetable oil crop during the photosynthesis process, while the plant is growing. Hence biodiesel offers net CO_2 advantage over conventional fuels [15,16]. The use of biodiesel in diesel engines does not require any hardware modification. Biodiesel gives considerably lower emissions of PM, carbon monoxide (CO) and hydrocarbon (HC) without any fuel consumption or engine performance penalties. Biodiesel's particulate reducing effect could be attributed to its lower aromatic and short-chain paraffin HC and higher oxygen content [17]. It has been observed that carbon deposits on the cylinder head, piston top, piston ring grooves, and injector of biodiesel-fueled engine are substantially lower compared to the diesel-fueled engine. Also, the wear of vital moving parts of biodiesel-operated engine is substantially lower compared to the diesel-operated engine due to its inherent lubricity properties [7]. However, researchers found increased NO_x emissions with biodiesel compared to diesel [6,18]. To achieve reductions in NO_x emissions, Exhaust Gas Recirculation (EGR) can be used with biodiesel.

3. Exhaust gas recirculation (EGR)

Controlling the NO_x emissions primarily requires reduction of in-cylinder temperatures. EGR is an effective technique of reducing NO_x emissions from the diesel engine exhaust

[1,5,19–27]. EGR has been used by several researchers including Abd-Alla [20], Baret [21], Ladommatos [22,23]. EGR involves replacement of oxygen and nitrogen of fresh air entering in the combustion chamber with the carbon dioxide and water vapor from the engine exhaust. The recirculation of part of exhaust gases into the engine intake air increases the specific heat capacity of the mixture and reduces the oxygen concentration of the intake mixture. These two factors combined lead to significant reduction in NO_x emissions. EGR (%) is defined as the mass percent of the recirculated exhaust (M_{EGR}) in total intake mixture (M_i) [20],

$$\text{EGR}\ (\%) = \frac{M_{\text{EGR}}}{M_{\text{i}}} \times 100.$$

However, the application of EGR results in higher fuel consumption and emission penalties. EGR increases HC, CO, and PM emissions along with slightly higher specific fuel consumption. In heavy-duty engines, the NO_x produced during high load operation is substantially high. Applying EGR at or near full load tends to increase the smoke emissions since the engine operates near stoichiometric air-fuel ratio. This not only increases the particulate emission but may also necessitate de-rating of the engine to maintain acceptable smoke levels. The application of EGR can also adversely affect the lubricating oil and engine durability [28,29]. It is widely accepted that sulfur oxides present in exhaust gas accelerates wear. Without applying EGR, energy-efficient diesel engines normally produce an exhaust that contains oxygen from around 5% at full load to around 20% during idling [1]. As the excessive exhaust oxygen decreases with increase in engine load, the specific heat of the exhaust rises because of increase in CO_2 concentration. Thus, the effectiveness of NO_x reduction by EGR also varies with load. Test results indicate that high EGR rates need to be applied at low load and low EGR rates are sufficient for high load [1]. Also, as load increases, diesel engines tend to generate more smoke because of reduced oxygen. Therefore, EGR, although effective to reduce NO_x, further increases the smoke and PM emissions [1]. Engine operation with oxygenated fuel and EGR results in NO_x reductions without deteriorating brake specific fuel consumption (BSFC) and emissions [5,19].

4. Experimental setup and methodology

Rice bran oil (RBO) was converted into its methyl esters through base-catalyzed transesterification. Methyl alcohol (Merck) of 99.5% purity having density of 0.791–0.792 kg/l and sodium hydroxide is used for this process. Experimental setup for transesterification in laboratory is shown in Fig. 1. The biodiesel prepared, neat vegetable oil, and mineral diesel were tested for viscosity at different temperatures between 40 and 100 °C on Setavis kinemetic viscometer as per ASTM D445 and Flash point are evaluated experimentally as per standard test method ASTM D93. Viscosity decreases drastically after transesterification as shown in Figs. 2 and 3. The process of transesterification brings down specific gravity of the rice bran oil as shown in Fig. 4. The biodiesel so developed is completely miscible with mineral diesel oil. The flash point of rice bran oil gets lowered drastically on transesterification as shown in Fig. 5, but it was still higher than mineral diesel. Thus, biodiesel is an extremely safe fuel in handling compared to diesel. The ester (biodiesel) was blended with mineral diesel in various concentrations ranging from 10% to

Fig. 1. Experimental setup for transesterification process.

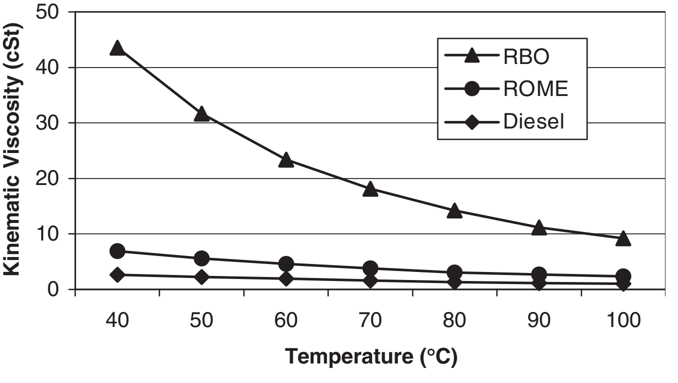


Fig. 2. Viscosity vs. temperature for rice bran oil, ROME, and diesel.

50%. These biodiesel blends were used as a fuel in the CI engine for conducting various experiments.

A constant speed, two-cylinder, four-stroke, air-cooled, direct injection diesel engine generator set of 9 kW rating (Indec PH2 model) was chosen for this study (Table 1). For recirculation of the exhaust gas, appropriate piping was done. The schematic diagram of the EGR setup is shown in Fig. 6. The quantity of EGR can be regulated by a control valve, which is installed in the EGR loop. An air box was provided in EGR loop to

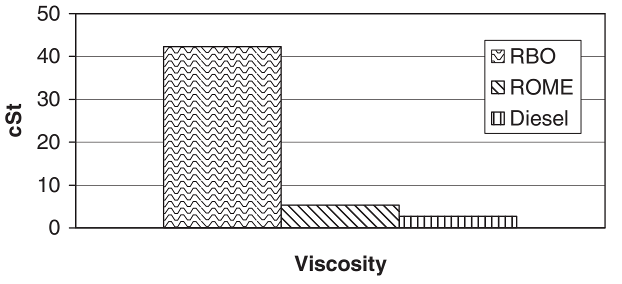


Fig. 3. Viscosity (@40 °C) for rice bran oil, ROME, and diesel.

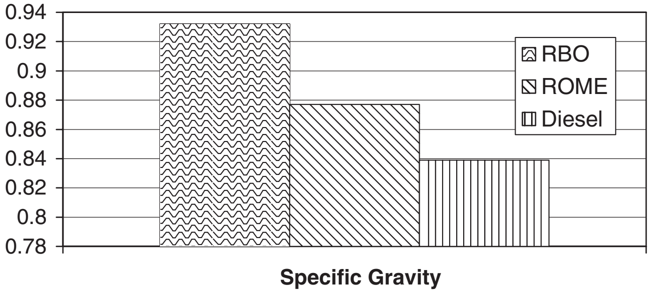


Fig. 4. Specific gravity (@30 °C) for rice bran oil, ROME, and diesel.

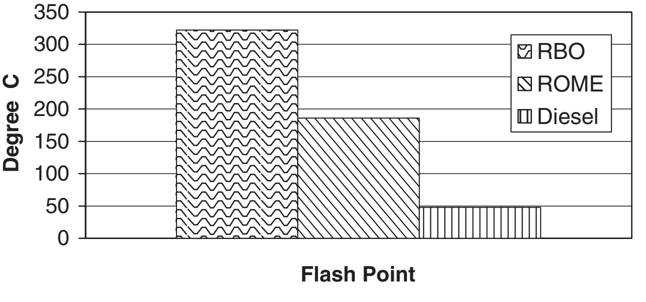


Fig. 5. Flash point for rice bran oil, ROME, and diesel.

dampen the fluctuations of recirculated exhaust. An orifice was installed in the EGR loop after the air box in order to measure the flow rate of recirculated exhaust. To measure the airflow accurately, a laminar flow equipment (LFE) (Cussons, Model: 7025) was installed before the intake manifold.

Suitable instrumentation for temperature measurement at several locations was provided. Volumetric fuel consumption measurement was done. Exhaust gas emission measurements were done by exhaust gas analyzer (EXSA-1500 Horiba, Japan). It measures O_2, CO, and CO_2 by Non-Dispersive Infrared Analyzer (NDIR), THC by

Table 1
Engine specifications

Model	Indec PH2 diesel engine
Engine type	Two cylinder, direct injection, air cooled
Bore/stroke	87.3/110 mm
Rated power	9 kW
Compression ratio	16.5:1
Total displacement volume	1318 L
Fuel injection release pressure	210 bar
Rated speed	1500 rpm
Inlet valve opens/inlet valve closes	4.5° BTDC/35.5° ABDC
Exhaust valve opens/exhaust valve closes	35.5° BBDC/4.5° ATDC

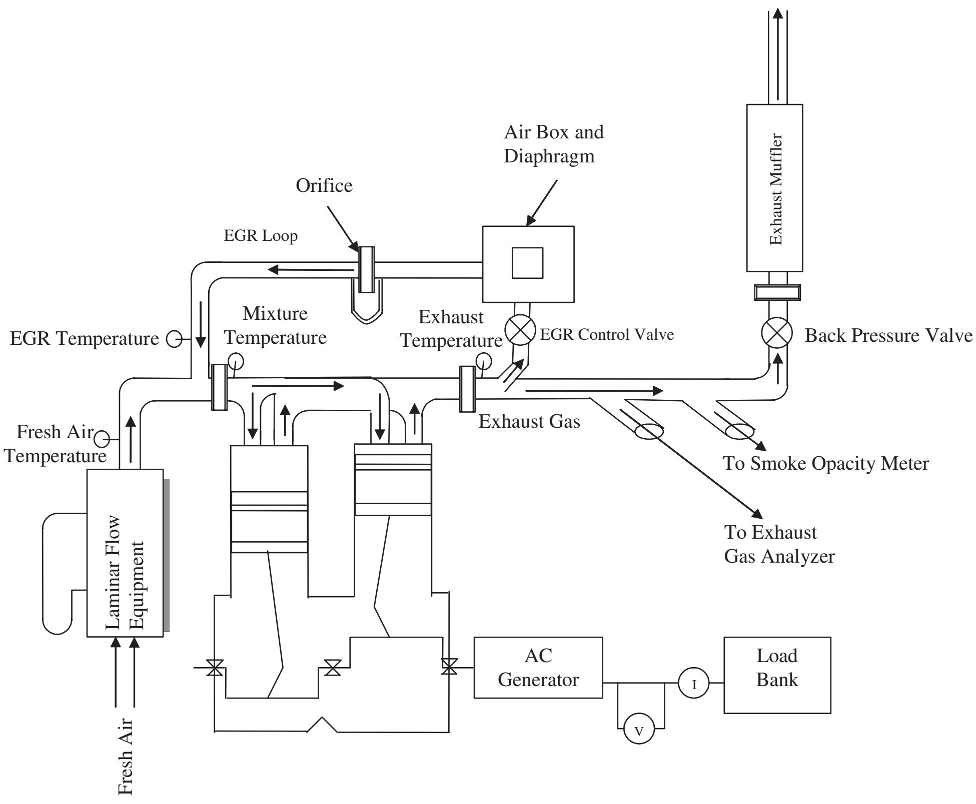


Fig. 6. Schematic diagram of engine setup using EGR.

Heated Flame Ionization Analyzer (hot FID) and NO_x by Chemiluminescence Analyzer. Exhaust gas opacity was measured by smoke opacity meter (AVL 437, Austria).

Experiments were conducted on diesel engine for various EGR rates and it was found that 15% EGR rate gives maximum NO_x reduction. To achieve the objectives of this study, the engine was run with mineral diesel and different blends of biodiesel at 15% EGR rate. The engine was also run with diesel and no EGR to generate baseline data. The data for HC, NO_x, CO, smoke opacity, exhaust gas temperature, fuel consumption were collected. Then, engine performance and emission pattern were compared.

5. Results and discussion

Initially, a series of engine tests were carried out using diesel at 1500 rpm and different EGR rates in order to show the effect of EGR on the smoke opacity and NO_x concentration in the exhaust. The smoke opacity of the exhaust gas is measured to quantify the PM present in the exhaust gas. Fig. 7 shows the smoke opacity at different EGR rates. Higher smoke opacity of the exhaust is observed when the engine is operated with EGR compared to without EGR. Smoke opacity increases with increasing EGR rates and increasing engine load. The variation in smoke opacity level at high loads was higher compared to lower loads. EGR reduces availability of oxygen for combustion of fuel, which results in relatively incomplete combustion and increased formation of PM.

Fig. 8 shows the well-established benefit of EGR in reducing NO_x emissions from diesel engine. When EGR is applied, NO_x is decreased with increasing EGR rates. The degree of

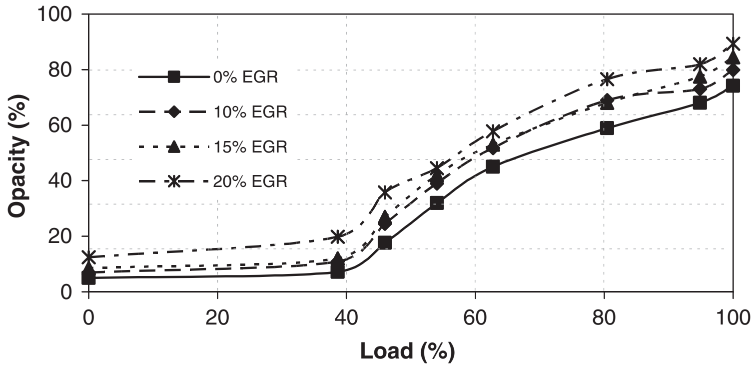


Fig. 7. Smoke opacity for different EGR rates.

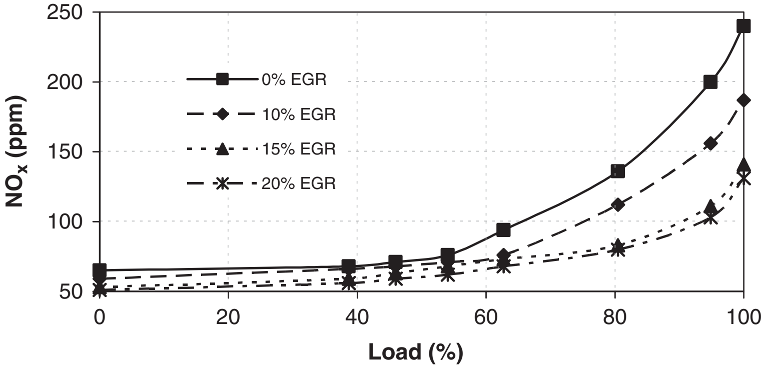


Fig. 8. NO_x for different EGR rates.

reduction in NO_x at higher loads is higher. The reasons for reduction in NO_x emissions using EGR in diesel engines are reduced oxygen concentration and decreased flame temperatures.

Therefore, it can be observed that when EGR is applied to diesel engine, NO_x is reduced but smoke opacity is increased. This is a well-known trade-off between NO_x and PM. On the other hand, if biodiesel is used in diesel engine, smoke opacity is decreased but NO_x is increased. Thus, biodiesel with EGR can be used to reduce NO_x and smoke opacity simultaneously. A series of exhaustive engine test were carried out using 15% EGR rate and different concentration of biodiesel to evaluate the performance and emission pattern of the engine. The performance and emission data were analyzed for thermal efficiency, BSFC, BSEC, exhaust gas temperature, HC, CO, NO_x emissions, and smoke opacity.

The exhaust gas temperature profile is shown in Fig. 9. It can be observed that with increase in load, exhaust gas temperature also increases. Temperature of the exhaust gas was found to be lower in case of EGR-operated engine. The possible reason for this temperature reduction may be relatively lower availability of oxygen for combustion and higher specific heat of intake air mixture. However, blends of biodiesel with application of EGR give lower exhaust gas temperature than baseline diesel data without EGR.

The trends of the thermal efficiency are shown in Fig. 10. Thermal efficiency is found to be slightly increased with EGR at lower engine loads. The possible reason may be

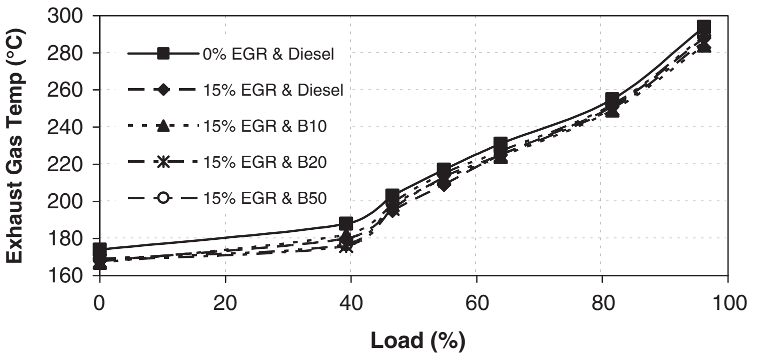


Fig. 9. Exhaust gas temperature for EGR and different blends of biodiesel.

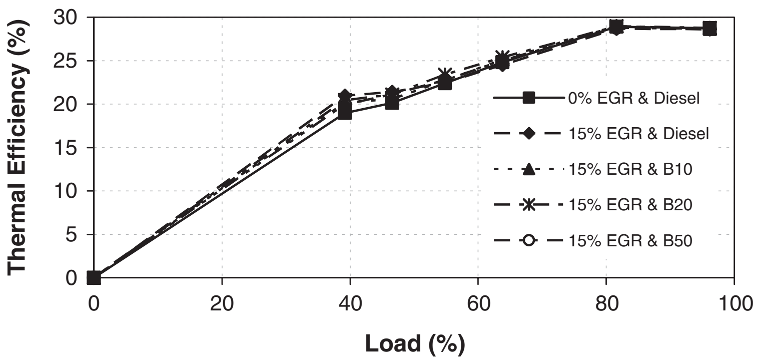


Fig. 10. Thermal efficiency for EGR and different blends of biodiesel.

re-burning of HCs that enter the combustion chamber with the recirculated exhaust gases. At higher engine loads, thermal efficiency remains unaffected by EGR. When engine was operated on biodiesel blends with EGR, thermal efficiency improved with increasing concentration of biodiesel in the blend. This may be possibly due to improved thermal efficiency observed with oxygenated fuels. An important observation is that all biodiesel blends have higher thermal efficiency than the baseline data.

Fig. 11 represents comparison of BSFC for all biodiesel blends using EGR with baseline data. For diesel, BSFC is lower at lower loads for engine operated with EGR compared to without EGR. However, at higher engine loads, BSFC with EGR is almost similar to that of without EGR. When engine was operated on biodiesel blends with EGR, BSFC increased with increasing concentration of biodiesel in blends. This increase in BSFC was due to lower calorific value of biodiesel compared to diesel. However, BSFC was found minimum at 20% blend when only biodiesel blends were compared. The possible reason may be highest thermal efficiency for this blend [6].

However, BSFC is not a very reliable parameter to compare fuels of different calorific values and densities. Here, BSEC is a more reliable parameter for comparison. Fig. 12 represents BSEC results for this set of experiments. It can be observed that BSEC was

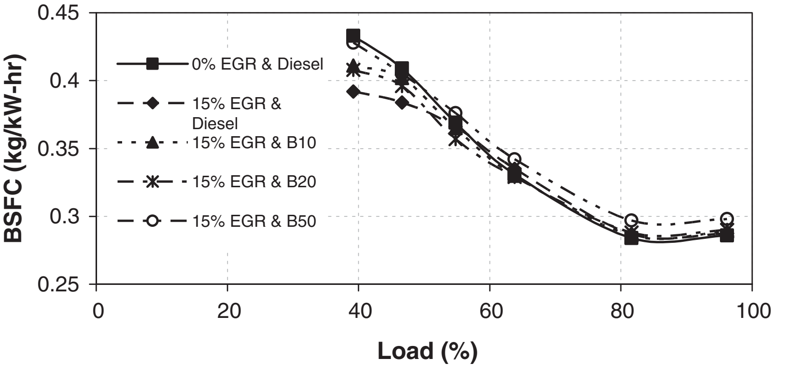


Fig. 11. Brake specific fuel consumption for EGR and different blends of biodiesel.

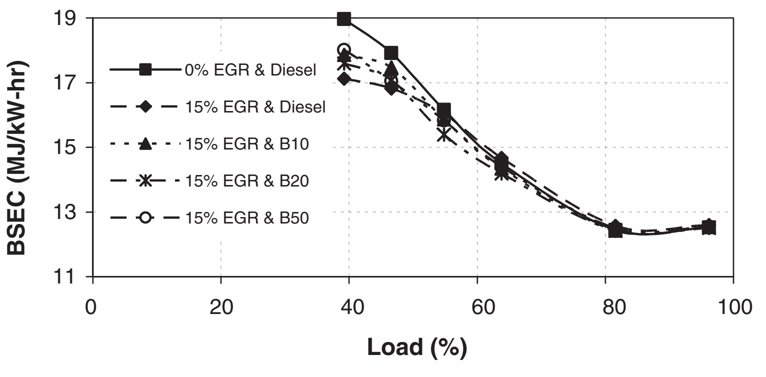


Fig. 12. Brake specific energy consumption for EGR and different blends of biodiesel.

lower for diesel with EGR compared to baseline data at lower loads. But at higher loads BSEC with and without EGR follows the same trend. When engine was operated on biodiesel blends, BSEC reduced with increasing concentration of biodiesel. The possible reason for lower BSEC may be better thermal efficiency. 20% biodiesel blend gave lowest BSEC with EGR. At higher loads, the engine followed almost similar BSEC trend for all data sets.

The smoke opacity is shown in Fig. 13. Higher smoke opacity of the exhaust is observed when the engine is operated with EGR compared to without EGR on diesel. EGR reduces availability of oxygen for combustion of fuel, which results in incomplete combustion and increased formation of PM. Smoke opacity for biodiesel blends 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 improved combustion and thus lower smoke. It is observed that 20% biodiesel blend gives lowest smoke opacity for all data sets with EGR.

Fig. 14 shows the well-established benefit of EGR in reducing NO_x emissions from diesel engine. The degree of reduction in NO_x at higher loads is higher. The reasons for reduction

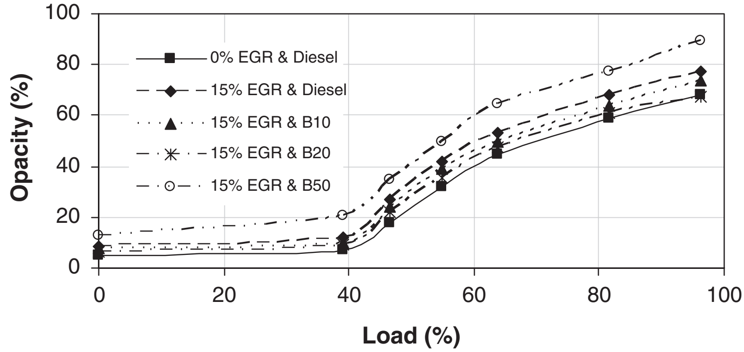


Fig. 13. Smoke opacity for EGR and different blends of biodiesel.

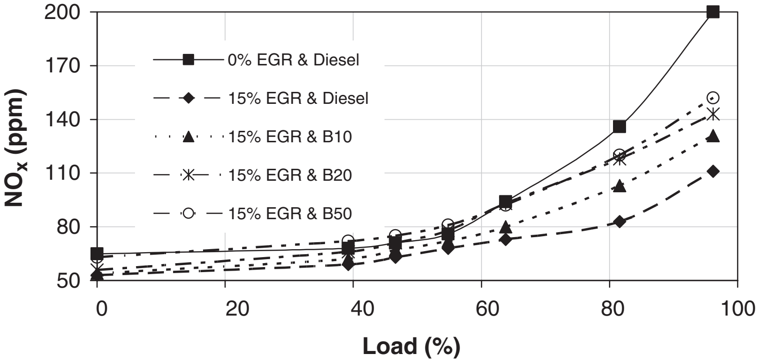


Fig. 14. NO_x for EGR and different blends of biodiesel.

in NO_x emissions using EGR in diesel engines are reduced oxygen concentration and decreased flame temperatures. However, NO_x emissions in case of biodiesel blends are higher than diesel due to higher temperatures prevalent in the combustion chamber. An important observation is that all biodiesel blends have lower NO_x emissions than the baseline data for diesel without EGR.

Effect of EGR and biodiesel on unburned HCs and CO are shown in Figs. 15 and 16. These graphs show that HC and CO emissions increase with EGR and load. The possible reason may be lower excess oxygen available for combustion. Lower excess oxygen concentration results in rich air-fuel mixtures at different locations inside the combustion chamber. This heterogeneous mixture does not combust properly and results in higher HC emissions. Similarly, with EGR, the air-fuel ratio decreases, and CO eventually increases. Adding biodiesel to diesel decreases the oxygen required for combustion because of presence of molecular oxygen in fuel. This results in lower HC and CO emission. It can be observed from Fig. 15 and 16 that HC and CO emissions are lower for biodiesel blends than with diesel when the engine was operated employing EGR. However, HC and CO emissions for 20% biodiesel blends are almost same or lower compared to baseline data of diesel without EGR.

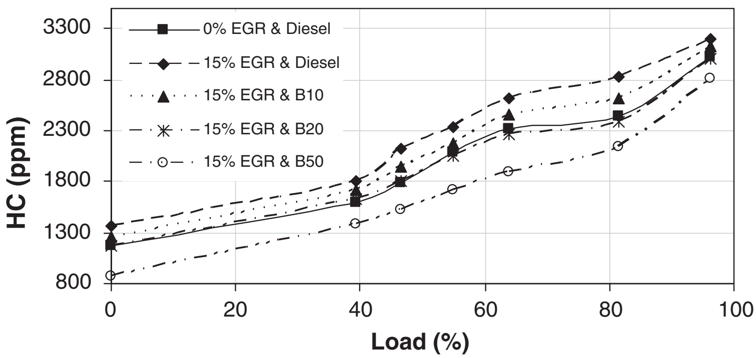


Fig. 15. Hydrocarbons for EGR and different blends of biodiesel.

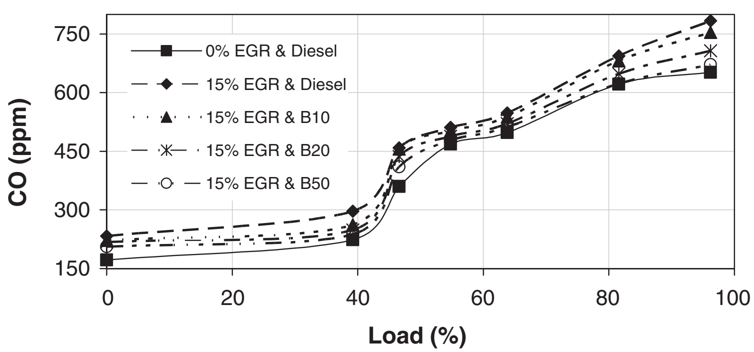


Fig. 16. Carbon monoxide for EGR and different blends of biodiesel.

6. Conclusions

Transesterification is an effective way to reduce the viscosity of the rice bran oil. Viscosity, flash point and specific gravity of the oil reduce after transesterification.

Based on the exhaustive engine tests, it can be concluded that biodiesel and EGR both can be employed together in CI engines to obtain simultaneous reduction of NO_x and smoke. Other emissions such as HC and CO are also found to have decreased. A 20% biodiesel blend with 15% EGR is found to be optimum concentration for biodiesel, which improves the thermal efficiency, reduces the exhaust emissions and the BSEC.

Biodiesel is an oxygenated fuel and it undergoes improved combustion in the engine due to the presence of molecular oxygen which also leads to higher NO_x emissions. This higher NO_x emission can be effectively controlled by employing EGR. Recycled exhaust gas lowers the oxygen concentration in the combustion chamber and increases the specific heat of intake charge which results in lower flame temperature. Reduced oxygen and flame temperature leads to lower NO_x formation. However, application of EGR also resulted in some penalties. EGR increases the HC and CO emissions. Also, higher BSFC and particulate emissions were observed. The application of EGR can also adversely affect lubricating oil quality and engine durability. Thus, EGR with biodiesel can be applied to reduce NO_x emissions without increasing smoke emissions. In summary, engine operation with biodiesel while employing EGR results in NO_x reductions without compromising engine performance and emissions.

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