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Performance, Emissions and Combustion Characterization of Biodiesel in a Generator Engine

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Abstract – *Alternative energy sources need to be developed in order to meet the increasing demand for fossil fuels. Furthermore, from environmental perspective, these new resources of energy must be environment friendly. Biomass, and particularly vegetable oils, fulfill these imperatives and is seen as a potential substitute for mineral diesel. Base catalysed transesterification is most acceptable process for biodiesel production. In this study, biodiesel produced from Neem oil with high free fatty acid content was characterised for its physical, chemical and thermal properties. Performance, emission and combustion characteristics of this biodiesel and its 20% blend (with mineral diesel) were compared with baseline data of mineral diesel in a direct injection (DI) engine. Brake specific fuel consumption for biodiesel was found to be marginally higher than mineral diesel however biodiesel also showed significant improvement in thermal efficiency at higher engine loads in comparison to mineral diesel. Brake specific CO and HC emissions for biodiesel were lower than mineral diesel at lower engine loads however NO emissions increased significantly in compassion to mineral diesel. Detailed combustion characterisation revealed that combustion starts earlier for biodiesel fuelled engine at all operating conditions but start of combustion was slightly delayed for 20% blend of biodiesel in comparison with mineral diesel. Combustion duration for biodiesel blends was shorter than mineral diesel.*

Keywords – biodiesel, combustion characterization, performance and emission test.

1. INTRODUCTION

Depletion of fossil fuels and environmental awareness has developed the need to find alternatives to diesel fuels which plays a major role in the industry and the economy of any country. Biomass and especially vegetable oils are seen to be efficient solution to the prevailing energy crisis. This non-toxic resource could be produced at small scale, which could provide energy in a decentralized manner, especially to rural areas. The carbon dioxide emissions produced during the combustion of these oils are the ones which were fixed by the plant, therefore vegetable oils don't increase the global balance of CO_2.

Nowadays great progress has been made to improve the way vegetable oils are used as engine fuels. Use of vegetable oils in an unmodified engine leads to many problems on their long-term usage. Three major typical characteristics of vegetable oils adversely affect the performance of the engine namely high viscosity, poor volatility and polyunsaturated character [1]-[4]. High viscosity of vegetable oils implies inefficient pumping and poor spray formation. Therefore, air and fuel are not optimally mixed and combustion remains incomplete. Furthermore, low volatility of vegetable oils and their ability to polymerize (due to unsaturation) leads to carbon deposit, injector coking and piston ring sticking.

To eliminate these issues, many different processes were developed to make these oils adapt modern engines. They allow the vegetable oils to attain properties very close to mineral diesel [5]-[7]. These processes include direct use by blending, micro-emulsion, pyrolysis, transesterification etc. Transesterification (alcoholysis) is a chemical reaction between triglycerides present in the vegetable oils and primary alcohols in the presence of a catalyst to produce mono-esters. The long and branched chain triglyceride molecules are transformed to monoesters and glycerine [8].

Several experimental investigations have been carried out by researchers around the world to evaluate the engine performance of different biodiesel blends. Generally a marginal power loss, reduction in torque and increased BSFC were observed in case of biodiesel fuelled engines. Altin *et al.* [9] studied the effect of sunflower oil, cottonseed oil, soyabean oil and their methyl esters in a single cylinder, four-stroke direct injection diesel engine. They observed slight reduction in the torque and power produced and increased BSFC in case of biodiesel fuelled engines. Similar results were also reported by Kaufman and Ziejewski [10] and Antolin *et al.* [11] for sunflower methyl ester; Clark *et al.* [12], McDonald *et al.* [13] for soybean esters; Peterson *et al.* [14] for rapeseed oil methyl ester etc.

Carraretto *et al.* [15] carried out investigations on six cylinders direct injection diesel engine. The increase of biodiesel percentage in the blend led to a slight decrease in both power and torque over the entire speed range. In particular, with pure biodiesel, there was a reduction of about 3% maximum power and about 5% of maximum torque. Moreover, with pure biodiesel, the maximum torque was found to have reached at higher

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engine speed. However, Al-widyan *et al.* [16] reported slightly increased power and lower BSFC for waste oil biodiesel fuelled engines. Raheman and Phadatre reported average 6% increased brake power output for a Karanja oil biodiesel up to 40% blend (B40) and with a further increase in the biodiesel percentage in the blend, engine power reduced [17].

Raheman *et al*. also evaluated the performance of biodiesel blends at different compression ratio and injection timings of the engine [18]. For the same operating conditions, performance of the engine reduced with increase in biodiesel percentage in the blend. However, with increase in compression ratio and advanced injection timings, this difference reduced and the engine performance became comparable to diesel. Nabi *et al*. investigated the performance and emission characteristics of Neem oil biodiesel blends in a DI engine and reported reduction in emissions including smoke and CO, while NOx emission was increased with diesel-NOME blends in comparison to conventional diesel fuel. With EGR, 15%, NOME-diesel blend showed better BTE and lower NOx in comparison to mineral diesel [19].

Increase in BSFC and slight reduction in BTE is observed by Gumus [20] for hazelnut kernel oil methyl ester. In this study, earlier start of combustion and longer combustion duration is reported with increasing percentage of biodiesel in the fuel blend. Qi *et al*. [21] evaluated the performance, emission and combustion characteristics of soyabean oil methyl ester. BSFC increased while BTE decreased with increasing fraction of biodiesel in the fuel. Peak pressure rise rate and peak heat release rate of biodiesel were higher than those of mineral diesel at low engine loads, however the trend was opposite at high engine loads. Jatropha, Karanja and Rice-bran oil biodiesel blends show shorter ignition delay with widening difference with increasing load [22]-[23] in comparison to mineral diesel.

2. CHARACTERISATION OF BIODIESEL

Important properties of Neem oil biodiesel blends used in the study are compared with mineral diesel in Table 1. Viscosity of 20% Neem oil biodiesel blend is within specified ASTM limit but viscosity of neat biodiesel was higher than specified ASTM limit of 6 cSt at 40°C. Calorific value of biodiesel and blend is lower than mineral diesel. Density of biodiesel and blend is close to mineral diesel.

Table 1. Fuel properties.

Blend Composition (v/v)	Viscosity (cSt at 40^{o}C)	Density (g/ml)	Calorific Value (MJ/kg)
Diesel	2.71	0.837	46.35
NB20	3.21	0.848	44.98
NB100	6.17	0.891	39.87

3. EXPERIMENTAL SETUP

Four-stroke, single cylinder, constant-speed, water-cooled, direct injection diesel engine (Make: Kirloskar Oil Engines Ltd. India; Model: DM-10) was used to study the effect of Neem oil biodiesel blends on engine performance and emissions. The detailed specifications of the engine are given in Table 2. The engine was operated at a constant speed of 1500 rpm. The inlet valve opens 4.5° before TDC and closes 35.5° after BDC. The exhaust valve opens 35.5° before BDC and closes 4.5° after TDC. The fuel injection pressure recommended by the manufacturer is 200-205 bars. This engine has a gravity-fed fuelling system with efficient filter paper element, force-feed lubrication system for main bearing, large-end bearings and camshaft bush; and thermo-siphon cooling system (Figure 1).

A piezoelectric pressure transducer (Make: Kistler Instruments, Switzerland; Model: 6613CQ09-01) was installed in the engine cylinder head to acquire the combustion pressure–crank angle history. Machining for installation of pressure transducer was done in the cylinder head and the engine's main shaft was coupled with a precision shaft encoder (Make: Encoder India Limited, Faridabad; Model: EN 58/6-720AB). Change signals from the pressure transducer were amplified and converted to voltage signal by using a charge amplifier. The high-precision shaft encoder used for delivering signals of crank angle had a resolution of 0.5° crank angle. A TDC marker was used to locate the top dead center position in every cycle of the engine. The signals from the charge amplifier, TDC marker and shaft encoder were acquired using a high-speed data acquisition system (Make: Hi-Techniques, USA; Model: meDAQ). Engine tests are done at 1500±3 RPM, for 200 bar fuel injector pressure for diesel, 100% Neem oil biodiesel (NB100) and 20% blend of Neem oil biodiesel with mineral diesel (NB20).

The cylinder pressure data were acquired for 50 consecutive cycles and then averaged in order to eliminate the effect of cycle-to-cycle variations. All tests were carried out after thermal stabilization of the engine.

Exhaust gas opacity was measured using smoke opacimeter (Make: AVL Austria, Model: 437). The exhaust gas composition was measured using exhaust gas analyzer (Make: AVL India, Model: DIGAS 444). It measures CO_2, CO, HC, NO and O_2 concentrations in the exhaust gas. The basic principle for measurement of CO_2, CO, and HC emissions is non-diffractive infrared radiation (NDIR) and electrochemical method for NO emission.

Table 2. Specifications of the engine used.

Manufacturer	Kirloskar Oil Engine Ltd., India
Engine type	Vertical, 4-stroke, single cylinder, constant speed, direct injection, water cooled, compression ignition engine
Engine model	DM-10
Rated power	7.4 kW at 1500 rpm
Bore/stroke	102/ 116 (mm)
Displacement volume	0.948 L
Compression ratio	17.5
Start of fuel injection	26° BTDC
Nozzle opening pressure	200– 205 bar
BMEP at1500 rpm	6.34 bar

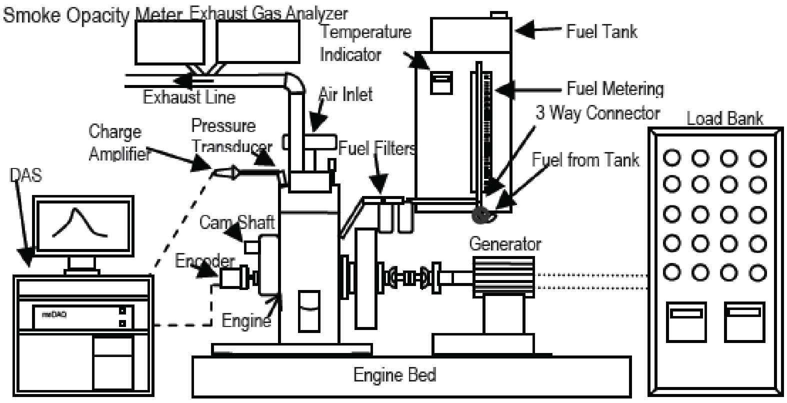


Fig. 1. Schematic of experimental setup.

Table 3. Specification of exhaust gas analyser.

Measured Gas	Accuracy	
CO	<0.6% vol: >0.6% vol:	±0.03% vol ±5%
HC	< 200ppm vol: >200 ppm vol:	±10 ppm ±5%
NO	< 500 ppm >500 ppm	±50 ±10%

4. RESULTS AND DISCUSSIONS

i. Performance Tests

Experiments were conducted at 200 bars fuel injection pressure to compare the performance of 20% and 100% biodiesel blends with mineral diesel. BSFC for NB100 and NB 20 was higher than mineral diesel (Figure 2(a)). BSFC increased by 2.4% for NB100 in comparison with mineral diesel at full load. BSFC was observed to have increased with increasing proportion of biodiesel in the fuel. Brake thermal efficiency of pure biodiesel was highest among the fuels used. Improvement in thermal efficiency for NB20 and NB100 is 3% and 13% respectively with respect to mineral diesel at full load. NB100 and NB20 both showed higher thermal efficiency than mineral diesel at all engine loads (Figure 2(b)). Increase of the BSFC for the biodiesel and its blend is due to lower calorific value of biodiesel in comparison with mineral diesel. Presence of oxygen in the biodiesel molecule improves the combustion of biodiesel hence its brake thermal efficiency increases with respect to mineral diesel.

Exhaust gas temperature for biodiesel blends is lower than mineral diesel (Figure 2(c)). But depression in exhaust gas temperature is not proportional to quantity of biodiesel in the fuel. Lower exhaust gas temperature is caused by better thermal efficiency.

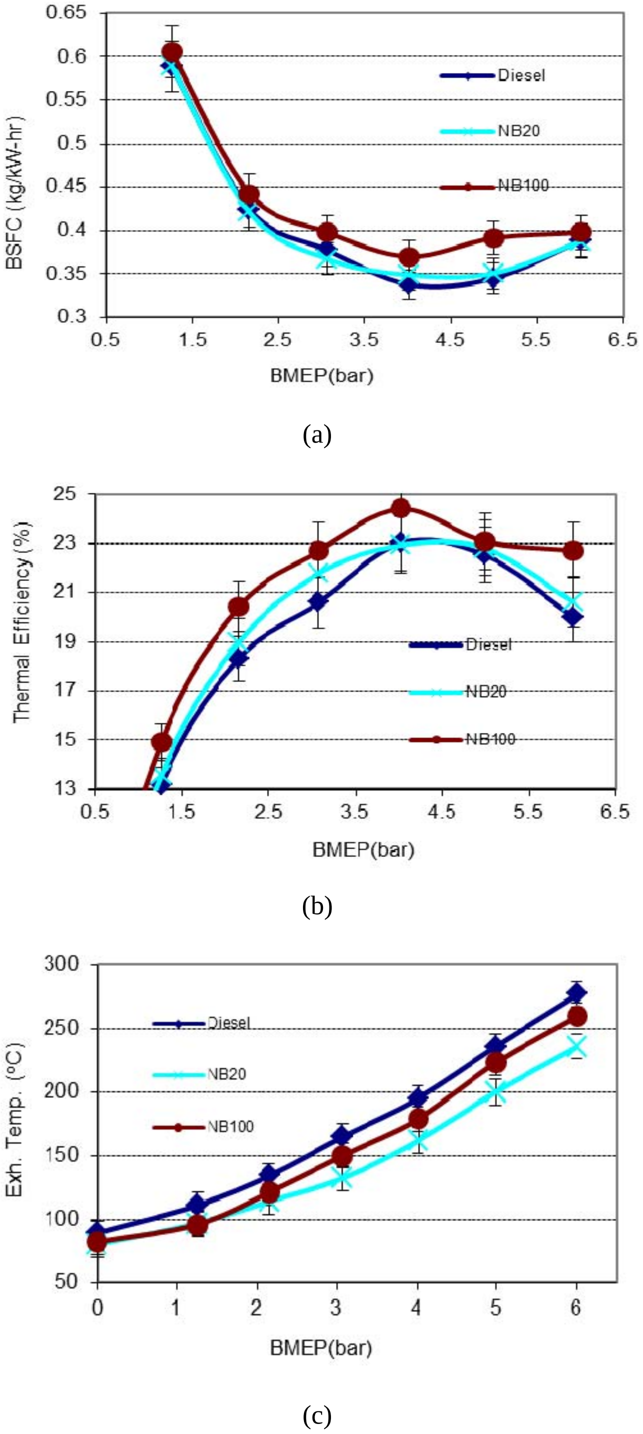
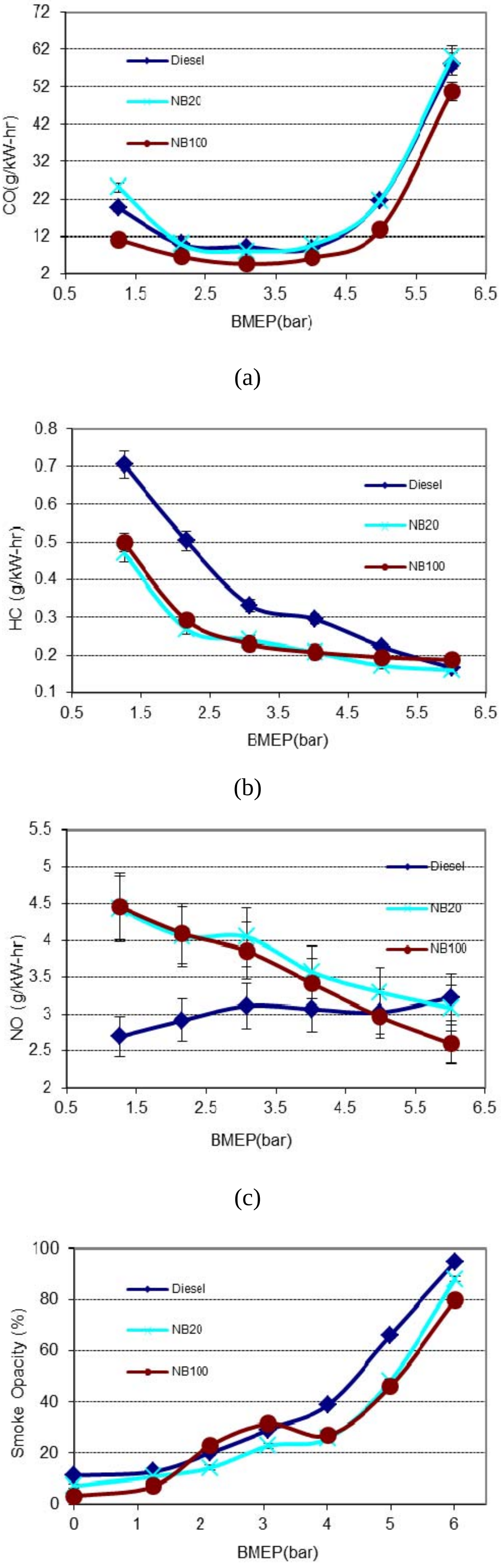


Fig. 2. Comparison of engine performance parameters with load (a) fuel consumption, (b) thermal efficiency, and (c) exhaust gas temperature.

ii. Engine Emissions

The emissions of CO increase with increasing load (Figure 3 (a)). Higher the load, richer fuel–air mixture is burned, and thus more CO is produced due to lack of oxygen. For NB20, CO emissions are close to mineral diesel. NB100 shows 12% to 48% reduction in CO emissions in comparison to mineral diesel. Biodiesel blends exhibit about 30% reduction in HC emissions at lower loads compared to mineral diesel but at higher loads HC emissions for biodiesel blends and mineral diesel were comparable (Figure 3(b)). This may be due to better combustion of biodiesel blends due to presence of oxygen. About 30% increase in the emission of NO was observed in comparison with mineral diesel for the biodiesel fueled engines (Figure 3(c)) at lower engine loads. At higher engine load NO emission reduced by 4 and 19% for NB20 and NB100 respectively with respect to mineral diesel. The smoke opacity NB20 and NB100 fueled engines was lower by 35 and 71% respectively than mineral diesel at lower loads. At higher loads reduction of 7 and 16% in smoke opacity was observed for NB20 and NB100 respectively in comparison with mineral diesel (Figure 3(d)).



(a)

(b)

(c)

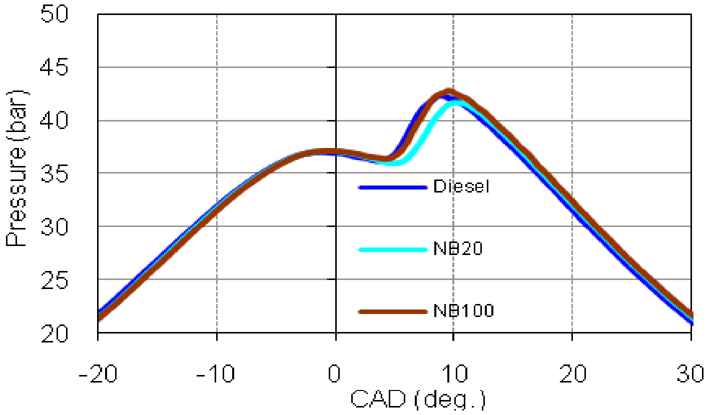
(d)

Fig. 3. Comparison of brake specific mass emission parameters with load for (a) CO (b) HC (c) NO emissions, and (d) smoke opacity.

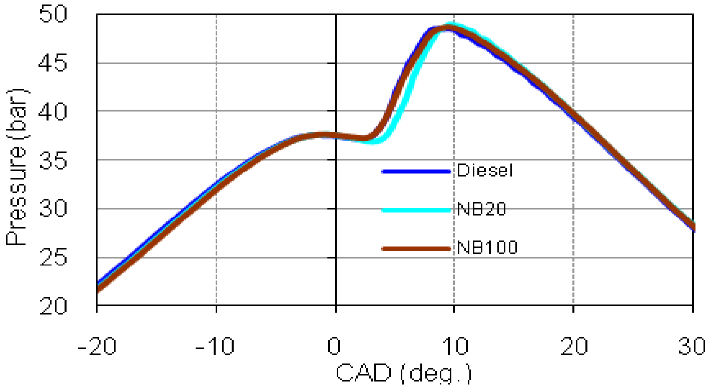
iii. Combustion Characteristics

a. In cylinder pressure vs. crank angle diagram

The variations in the in-cylinder pressure with crank angle for 20% and 100% biodiesel blends at different engine operating conditions with a baseline data of mineral diesel are shown in Figures 4(a)-(c). From these figures, it can be noticed that at higher engine loads, pressure trends are almost similar for all the fuels. 20% biodiesel blend shows slightly delayed pressure rise w.r.t. mineral diesel at lower loads. For 100% biodiesel, start of pressure rise is comparable with mineral diesel. At all engine loads, combustion starts marginally earlier for 100% biodiesel than mineral diesel while for 20% biodiesel blend, start of combustion is delayed w.r.t. to mineral diesel. Ignition delay for all fuels decreases as the engine load increases because the gas temperature inside the cylinder is higher at high engine loads, thus it reduces the physical ignition delay. The start of combustion reflects the variation in ignition delay because fuel pump and injector settings were kept identical for all fuels.



(a)



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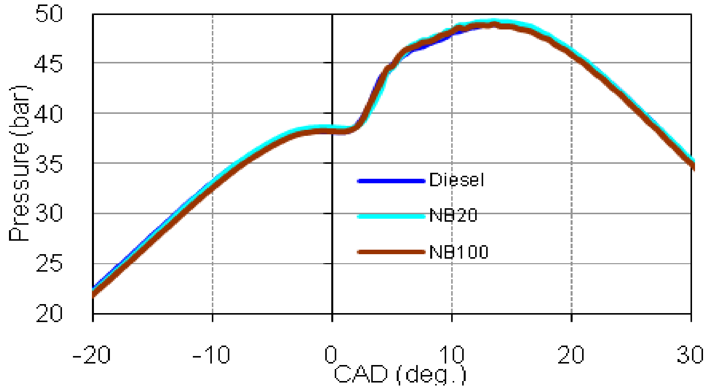
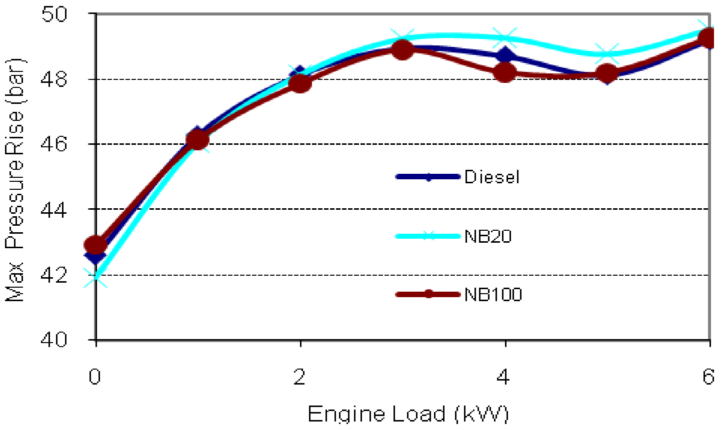


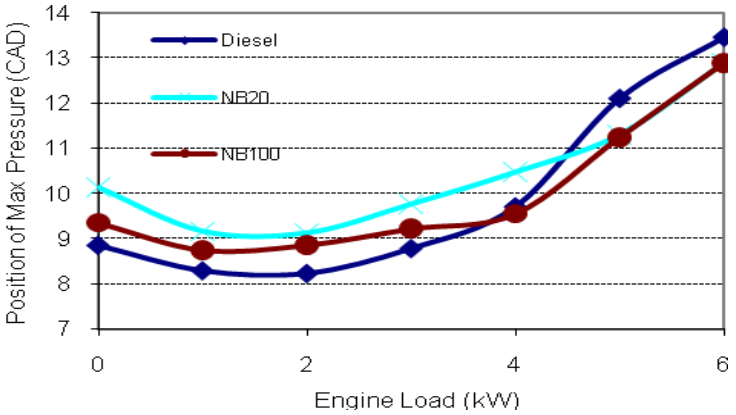
(c)

Fig. 4. Comparison of in-cylinder pressure at: (a) 0, (b) 3, (c) 6 bar BMEP.

Figure 5(a) shows the maximum cylinder pressure at different loads for different blends. It shows that, at all engine loads, the peak pressure for 20% biodiesel blend is higher than mineral diesel. The peak pressure for 20% biodiesel is higher because of the shorter ignition delay and fast burning of the accumulated fuel. Figure 5(b) shows the crank angle, at which the peak cylinder pressure is attained for all fuels at different engine operating conditions. It can be observed that with increasing engine load, peak cylinder pressure shifts away from TDC (Figure 5(b)).



(a)



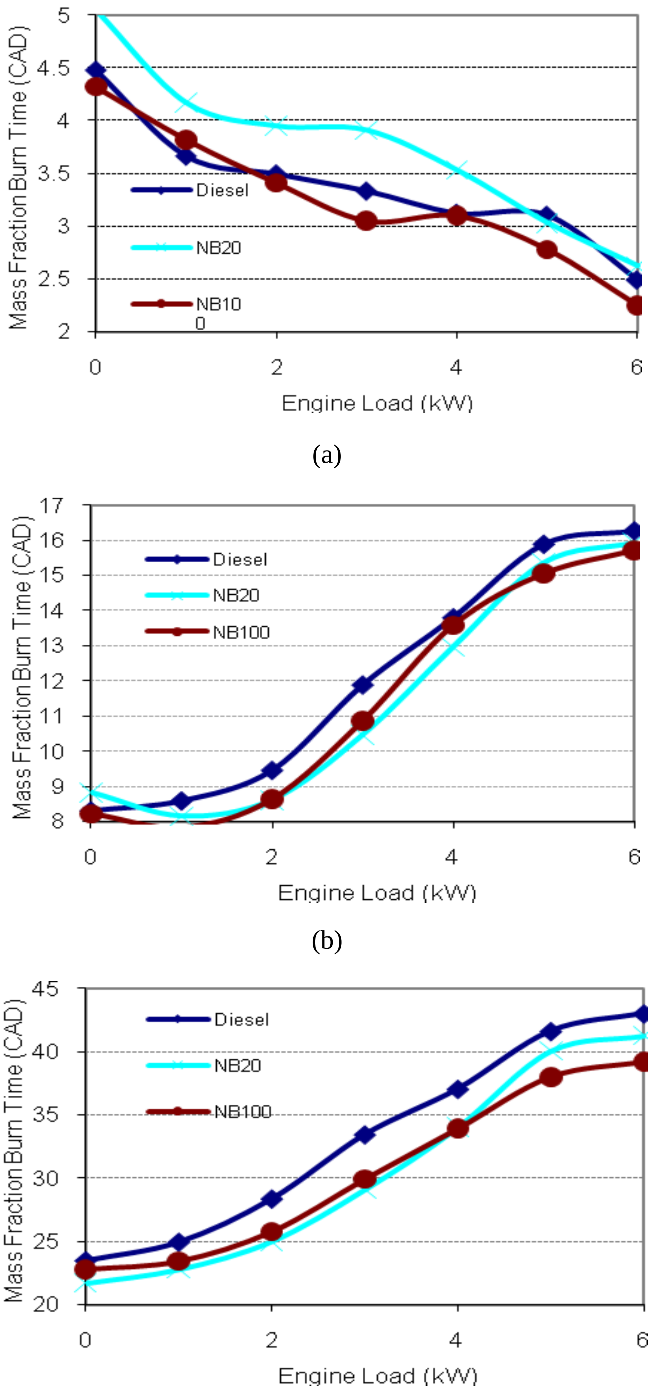
(b)

Fig. 5. Variation of (a) Maximum cylinder pressure and, (b) Max pressure crank angle for rated load.

b. Crank Angle for Mass Fraction Burn

Figure 6(a) shows the crank angle for 5 percent mass fraction burned. This figure shows that 5 percent fuel burns earlier for 100% biodiesel. This is due to the earlier start of combustion for biodiesel, as suggested earlier. 20% biodiesel blend shows delayed start of combustion w.r.t. to mineral diesel which indicates delay in the start of combustion due to higher viscosity of biodiesel.

For 100% biodiesel delay due to higher viscosity is compensated by higher cetane number of biodiesel. Figure 6(b) shows the crank angle degree for 50 percent mass fraction burned at different engine load conditions. Biodiesel blends takes less time for 50% combustion as compared to mineral diesel. Figure 6(c) shows the crank angle degree for 90 percent mass fraction burned at different engine load conditions. Biodiesel blends takes less time for 90% combustion as compared to mineral diesel.



(a)

(b)

(c)

Fig. 6. Crank Angle for (a) 5%, (b) 50% and, (c) 90% mass fraction burn.

5. CONCLUSION

Neem oil biodiesel and its blends were characterized by measuring its density, viscosity and calorific value. Performance, emission and combustion characteristics of this biodiesel and its blends were measured in a constant speed direct injection engine. Brake specific fuel consumption for biodiesel was 2.4% higher than mineral diesel but brake thermal efficiency of biodiesel also showed 13% improvement at higher load in comparison with mineral diesel. Brake specific CO emission was 12-48% lower than mineral diesel at lower loads but at higher loads there was no significant reduction. Brake specific hydrocarbon emissions for biodiesel fuelled engine operation were lower than mineral diesel by 30% at lower loads. About 30% increase in NO emissions were observed for biodiesel blends at lower loads but at higher engine loads NO emissions reduced in compassion with mineral diesel. Combustion started earlier for higher biodiesel blend fuelled operating conditions but start of combustion was slightly delayed for lower blends of biodiesel in comparison with mineral diesel. Combustion duration for biodiesel blends was shorter than mineral diesel.

Overall, the biodiesel prepared from Neem oil proves to be a suitable candidate for partial replacement of mineral diesel in a decentralized power generator.

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