Production of biodiesel from high-FFA neem oil and its performance, emission and combustion characterization in a decentralized power generating CI engine

Article · January 2011

CITATIONS
10

READS
450

3 authors, including:

Avinash Kumar Agarwal
Indian Institute of Technology Kanpur
580 PUBLICATIONS **23,005** CITATIONS

SEE PROFILE

Fuel Processing Technology 97 (2012) 118–129

Contents lists available at SciVerse ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Production of biodiesel from high-FFA neem oil and its performance, emission and combustion characterization in a single cylinder DICI engine

Atul Dhar [a], Roblet Kevin [b], Avinash Kumar Agarwal [a,*]

[a] Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur-208016, India
[b] Arts et Metiers, Paris Tech, France

ARTICLE INFO

Article history:
Received 20 October 2011
Received in revised form 4 January 2012
Accepted 12 January 2012
Available online 16 February 2012

Keywords:
FFA
Biodiesel
Neem oil
Transesterification
Combustion characteristics
Performance and emissions

ABSTRACT

Environment friendly alternative energy sources need to be developed in order to meet the burgeoning demand for fossil fuels for transportation. Utilization of vegetable oils as biodiesel is most accepted route. Yield and quality of biodiesel is dependent on feedstock quality specially moisture and free fatty acid (FFA) content. In this study, biodiesel was produced from high free fatty acid neem oil using a two step process i.e. esterification followed by transesterification. This biodiesel was characterized for its physical, chemical and thermal properties. Performance, emission and combustion characteristics of this biodiesel and its various blends with mineral diesel were compared with baseline data in a direct injection (DI) diesel engine. Brake specific fuel consumption for biodiesel and its blends was higher than mineral diesel and brake thermal efficiency of all biodiesel blends was found to be higher than mineral diesel. Brake specific CO and HC emissions for biodiesel fuelled engine were lower than mineral diesel but NO emissions were higher for biodiesel blends. Detailed combustion characterization revealed that combustion starts earlier for higher biodiesel blends however start of combustion was slightly delayed for lower blends of biodiesel in comparison with mineral diesel. Rate of heat release for all biodiesel blends were almost identical to mineral diesel. Combustion duration for biodiesel blends was found to be shorter than mineral diesel. Biodiesel produced from high FFA neem oil is found to be marginally inferior compared to mineral diesel.

1. Introduction

Depletion of fossil fuels and environmental concerns have encouraged the need to find alternatives to mineral diesel, which plays a main role in the transportation sector/industrial economy of every country in the world. Biomass based fuels such as vegetable oils and their derivatives are efficient potential solution at an international level to this burgeoning crisis. This reproducible, environmental friendly, non-toxic resource could be produced at small scale in rural areas and could provide clean and efficient fuel/energy in a decentralized manner in rural sector. The carbon emissions produced during the combustion of these oils are the ones, which are absorbed from the atmosphere by the plant in the process of photosynthesis; therefore the combustion of vegetable oils/derivatives does not increase the global balance of CO_2. It has been proven that these fuels emit far less harmful emissions and have significantly lower greenhouse gas potential compared to petroleum fuels.

Straight vegetable oils can be used in unmodified engines; however this leads to several operational problems in the engines on long-term usage. Three major drawbacks of vegetable oils adversely affect the performance of the engine. These are high viscosity, poor volatility and polyunsaturated character of vegetable oils [1-4]. High viscosity of vegetable oils leads to inefficient pumping and spray formation with large droplets. Therefore air and fuel are not optimally mixed and combustion remains incomplete in the engine. Low volatility of vegetable oils and their ability to polymerize (due to unsaturation) leads to formation of undesirable carbon deposits in the combustion chamber, injector coking and piston ring sticking issues. To eliminate these issues, different processes were developed to make these oils adapt modern engines. These processes (such as direct use by blending, micro-emulsion, pyrolysis, transesterification etc.) allow the vegetable oils to attain properties very similar to mineral diesel [5-7]. 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 (biodiesel) and glycerol [8]. Nevertheless, transesterification is not always possible. Oils, which have high free fatty acid (FFA) content can't be transesterified by this reaction. The process rather leads to saponification i.e. formation of soap. Formation of soap makes it very difficult to separate the layers of biodiesel and glycerol [9]. Many different thresholds of FFA contents are proposed in literature, but commonly, it is accepted that above 5% FFA level in the vegetable oils, it becomes very difficult to produce biodiesel by transesterification process [9-11].The FFA content of the oil influences the yield of

* Corresponding author.
E-mail address: akag@iitk.ac.in (A.K. Agarwal).

0378-3820/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.fuproc.2012.01.012

Table 1
Important properties of test fuels.

Blend composition (v/v)	Viscosity (cSt at 40 °C)	Density (g/ml)	Higher calorific value (MJ/kg)
Diesel	2.71	0.837	46.35
B5	2.92	0.840	46.00
B10	3.05	0.842	45.65
B20	3.21	0.848	44.98
B50	4.06	0.862	43.01
B100	6.17	0.891	39.87

Table 2
Specifications of the test engine.

Manufacturer	Kirloskar Oil Engine Ltd., India
Engine type	Vertical, 4-stroke, single cylinder, constant speed, direct injection, water cooled, compression ignition 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 at 1500 rpm	6.34 bar
IVO/IVC	4.5° before TDC/35.5° after BDC
EVO/EVC	35.5° before BDC/4.5° after TDC

biodiesel from this oil. Lower FFA results into easier production and higher yield of biodiesel. FFA content of vegetable oils is very sensitive to different parameters. From one single batch of oil seeds, oils with different FFA content could be produced depending on the process used to produce the oil, conditions of storage, moisture content and quality of the initial feedstock [11]. For producing low cost biodiesel, methods for utilization of low cost feedstock which generally have high FFA needs to be investigated [12]. Life cycle analysis of biodiesel production by Varanda et al. [13] showed that production of biodiesel from high FFA feedstocks are more economical and environment friendly.

Several experimental investigations have been carried out by researchers around the world to evaluate the engine performance of different biodiesel blends. Generally marginal loss in power and torque, and increased bsfc were observed in biodiesel fuelled engines. Altin et al. [14] 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 are also reported by Kaufman and Ziejewski [15] and Antolin et al. [16] for sunflower methyl ester; Clark et al. [17], McDonald et al. [18] for soybean esters; and Peterson et al. [19] for rapeseed oil biodiesel, Sinha et al. and Agarwal et al. for ricebran oil [20-22], Agarwal for linseed oil [23], and Ilkılıç et al. for safflower oil [24]. Carraretto et al. [25] carried out investigations on a six cylinders direct injection diesel engine using biodiesel blends. The increase of biodiesel percentage in the blend leads to a slight reduction in both power and torque over the entire speed range. B100 leads to 3% reduction in maximum power and 5% reduction in maximum torque. With B100, maximum torque was delivered at higher engine speed in this study. On the contrary, Al-widyan et al. reported slightly increased power and lower bsfc for waste oil biodiesel fuelled engine [26]. Raheman and Phadatare also reported average 6% higher brake power output for karanja oil biodiesel (up to B40) and with a further increase in biodiesel percentage in the blend, engine power reduced [27].

Raheman et al. evaluated the performance of biodiesel blends at different compression ratio and injection timings of the engine [28]. 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 advance in injection timing, this difference was reduced and the engine performance became comparable to diesel. This indicated towards the need to calibrate the engine fuel injection equipment for the new fuel in order to get the best performance. Nabi et al. investigated the performance and emission characteristics of neem oil biodiesel blends in a direct injection (DI) engine and reported reduction in smoke and CO emissions, while NOx emission increased with biodiesel blends [29]. Lower blends of tobacco seed oil methyl ester (TSOME) delivered slightly higher torque and power than mineral diesel at full load due to its slightly higher density and viscosity but at partial engine loads, slightly lower power output, torque and thermal efficiency was observed [30]. TSOME blending reduced CO and SO_2 emission but increased NOx emissions especially at full load. Canacki et al. reported identical brake thermal efficiency for soybean oil biodiesel (B100); diesel and B20 [31]. B100 produced significantly lower CO, HC, and smoke compared to diesel. Combination of earlier injection, shorter ignition delay and longer

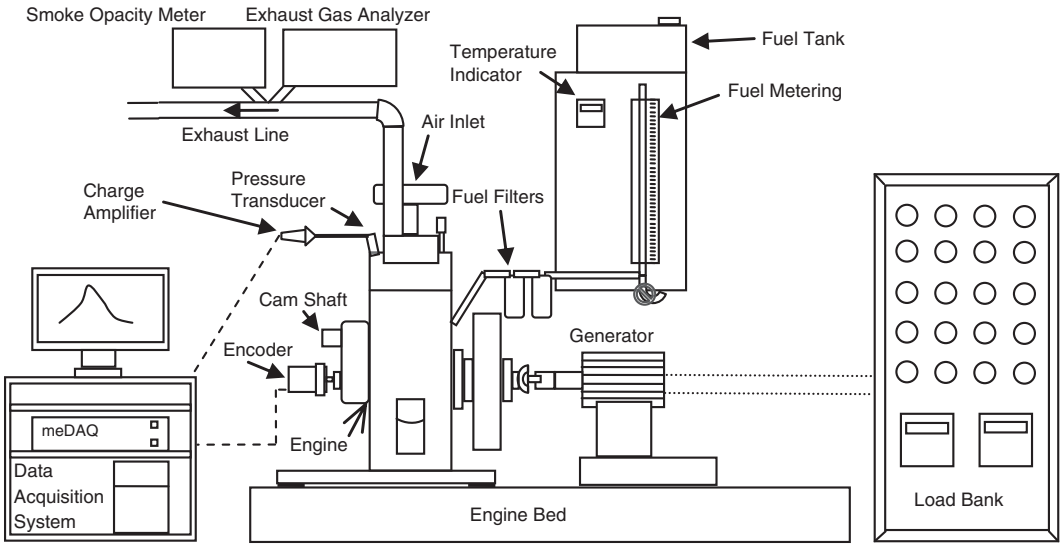


Fig. 1. Schematic of engine experimental setup.

combustion duration led to higher NOx emissions from biodiesel fueled engine [31,32]. NOx emissions from biodiesel fuelled engines were reduced by retarding the injection timing and low temperature combustion strategies [32-34].

Neem oil (Azadirachta indica) is non-edible oil available in huge surplus quantities in South Asia. Annual production of neem oil in India is estimated to be 30,000 tons [35].Traditionally; it has been used as fuel in lamps for lighting purpose in rural areas and is used on an industrial scale for manufacturing of soaps, cosmetics, pharmaceuticals and other non-edible products. 'Azardiratchi' is the main biochemical component of the Neem that is used for medicinal purposes [35]. Neem oil can be used for transesterification after the extraction of 'Azardiratchi'. The seed oil yield is 30–60% of the weight of the kernel [35-37]. However this oil suffers from the problem of high FFA therefore transesterification process cannot be used to efficiently convert it to biodiesel [36,37]. Ragit et al. has reported 83% ester yield of base catalyzed transesterification of neem oil with 6:1 alcohol ratio [37]. SatyaSelvabala et al. studied biodiesel production by using phosphoric acid modified mordenite (PMOR) as catalyst [38]. India has shortage of edible oils so its biodiesel programme is centered around non-edible vegetable oils like jatropha. For feedstock diversification and utilization of currently available local resources, non-edible sources like neem, karanja, mahua, sal etc. should be scientifically investigated for efficient biodiesel production and engine utilisation. Keeping this background in consideration, production of biodiesel from high FFA neem oil and its utilization as a potential alternative fuel for diesel engine has been investigated.

2. Experimental setup and procedure

Biodiesel was produced from high FFA neem oil and characteristed by measuring its viscosity, density, calorific value etc. This biodiesel and its blends were tested in a CIDI engine vis-à-vis mineral diesel for comparing their performance, emission and combustion characteristics with mineral diesel. Detailed experimental procedure is described in the following sub-sections.

2.1. Production of biodiesel

If biodiesel is seen as a possible alternative to provide energy in a decentralized manner, it seems imperative that processes used for biodiesel production need to be flexible enough to tolerate the variation in the quality of the feedstock oil, so that it meets the prevailing biodiesel specifications. For decentralized applications in countryside, expensive and complex installation to obtain high quality biofuels does not seem economically feasible. Furthermore, composition of vegetable oil itself could greatly change (fatty acid profile) because of the conditions of storage and local climatic conditions. The FFA content of the vegetable oils increases with duration of storage of seeds/oils and leads to degeneration of the quality of vegetable oils. To deal with these parameters, which have an adverse impact on the properties of the vegetable oils and biodiesel, solutions must be found to produce biodiesel even from low or medium quality vegetable oils, which have high FFA content. For such oils, one of the most frequently used pre-treatment step is to lower FFA content of the vegetable oils is 'esterification'. In the present study, FFA of neem oil was reduced (from 20.3%) by esterification reaction. This

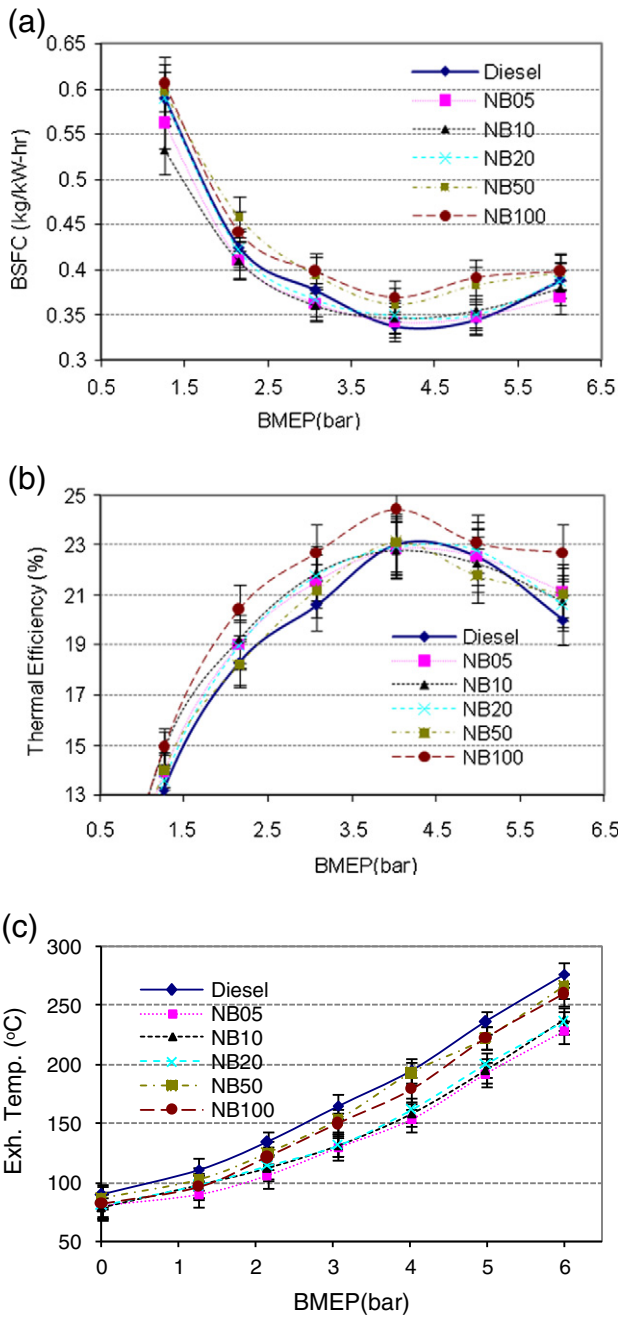


Fig. 2. Comparison of engine performance parameters with load (a) fuel consumption, (b) thermal efficiency, and (c) exhaust gas temperature.

reaction is traditionally catalyzed by acids such as sulphuric acid [9,10].

$$R-\underset{FFA}{COOH}+\underset{Alcohol}{R_4OH} \xleftrightarrow{Sulphuric\ Acid} \underset{Water}{H_2O}+R-CO-\underset{Ester}{OH_2C}-R_4$$

Main parameters ruling esterification are amount of catalyst (W/W_{oil}), molar ratio of alcohol to oil, temperature of reaction, time of reaction

Table 3
Range of percentage change in performance parameters w.r.t. mineral diesel.

	B05	B10	B20	B50	B100
BSFC	− (1.5 to 4.8)	− (2.6 to 9.6)	+(3.2 to −2.6)	+ (1.3 to 11.1)	+ (2.3 to 13.5)
BTE	+ (5.8 to −0.8)	+ (12.2 to −1.2)	+ (5.7 to −0.3)	+ (6.1 to −3)	+ (2.4 to 13.5)

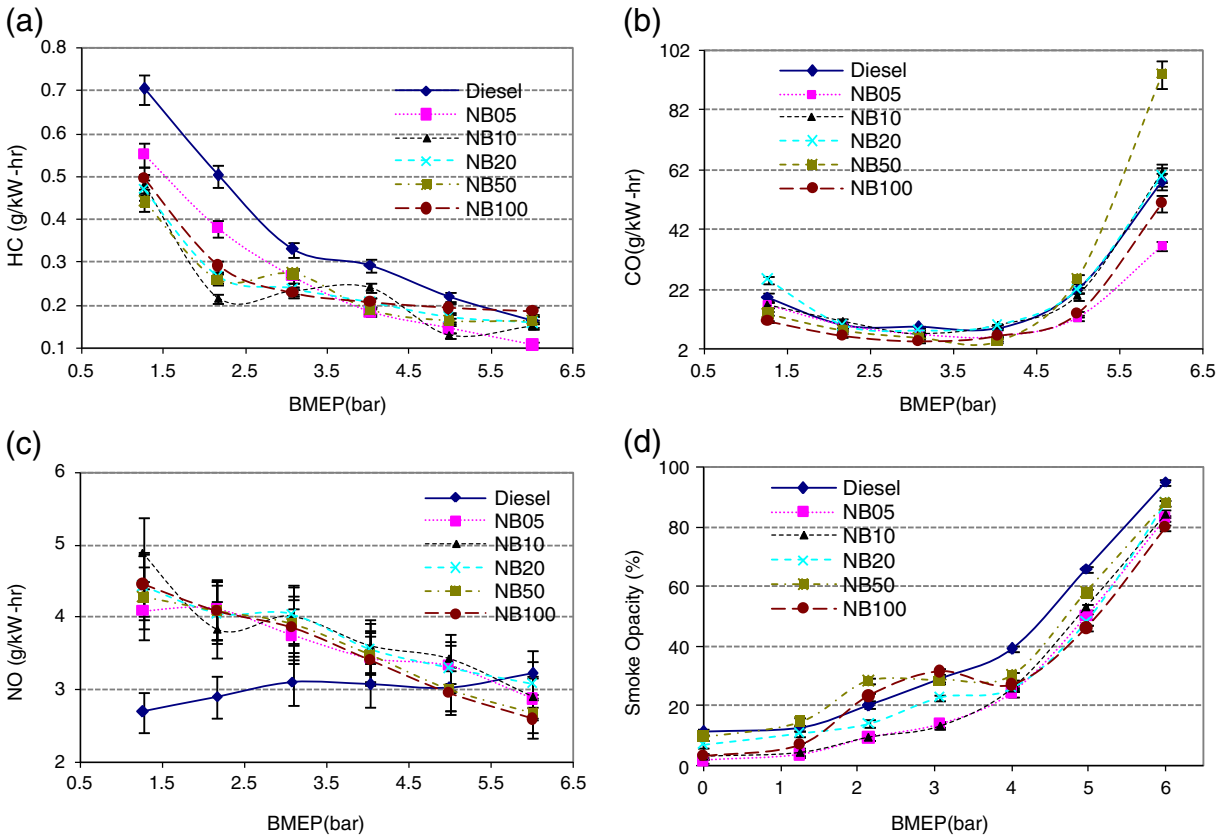
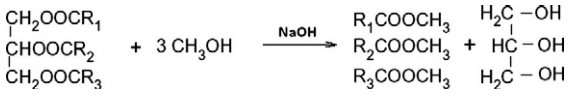


Fig. 3. Comparison of engine emission parameters with load (a) HC, (b) CO, (c) NO and (d) smoke opacity.

[9-11]. For our experiment, optimized process parameters for esterification reaction are: 4.5% catalyst, 6:1 alcohol to oil molar ratio, 90 min reaction time and 45 °C temperature. FFA content of the oil decreased from 20.0% to 3.6% in this esterification step. Further reduction in FFA takes place during the transesterification reaction. This is because of neutralization of FFA by the basic catalyst (NaOH). For this reason, a slightly higher amount of basic catalyst was taken for the transesterification in order to ensure presence of enough catalyst to catalyze the transesterification reaction even after this neutralization reaction for the FFA. Biodiesel was thus produced by transesterification step on this low FFA neem oil from esterification. Transesterification is the reaction of triglycerides present in the vegetable oils with primary alcohol (methanol, in this case) in the presence of a catalyst, to produce primary esters (biodiesel) and glycerol [1]. This reaction is given below:



Base-catalyzed transesterification used in this study has several advantages over other types of transesterification reactions such as low reaction temperatures and pressure, low cost material of construction and high process yield [1]. The main parameters governing this reaction are amount of catalyst (w/w_{oil}), molar ratio of alcohol to oil, reaction temperature, and reaction time, which needs to be optimized for every feedstock oil [1,9]. Optimum conditions for the present investigations were found to be 1% catalyst, 6:1 molar ratio of alcohol to oil, 60 min reaction time and 60 °C reaction temperature.

Preparation of neem oil methyl ester is done by mixing methanol and sulphuric acid for the esterification process step. Catalyst used for the process of esterification and transesterification steps are sulphuric acid (Merck 98% purity), and sodium hydroxide (RFCL, 97% Purity) respectively. Methanol used in both of these process steps was having density 0.791–0.792 kg/l with a purity of 99%. For the esterification process step, 6:1 molar ratio of alcohol to oil and 4.5% catalyst (w/w_{oil}) was used. The reactants are heated to 45 °C in a round bottom flask for 90 min, while stirring at 1300 rpm. After the completion of the reaction, the products are kept in a separating funnel for 5–6 h for gravity separation. The lower layer formed is dark brown, which mostly contains water while the upper layer contains reduced FFA neem oil. Lower layer is removed and upper layer is used for transesterification process step for conversion into biodiesel. For this, 6:1 molar ratio of alcohol to oil with 1% (w/w_{oil}) NaOH is mixed with reduced FFA neem oil. The reactants in the round bottom flask are heated at 60 °C at 1300 rpm stirring speed. After the completion of the reaction, products are again poured in a separating funnel for gravity separation of the products for 5 h. The

Table 4
Range of percentage change in performance parameters w.r.t. mineral diesel.

	B05	B10	B20	B50	B100
CO	− (0 to 43)	− (16 to 25)	− (12 to 28)	− (28 to 62)	− (13 to 50)
HC	− (19 to 35)	− (7 to 56)	− (4 to 33)	− (0 to 48)	− (12 to 42)
NO	+ (52 to −11)	+ (81 to −10)	+ (64 to −4)	+ (59 to −17)	+ (66 to −20)
Smoke opacity	− (24 to 83)	− (20 to 71)	− (15 to 36)	− (23 to 41)	− (15 to 72)

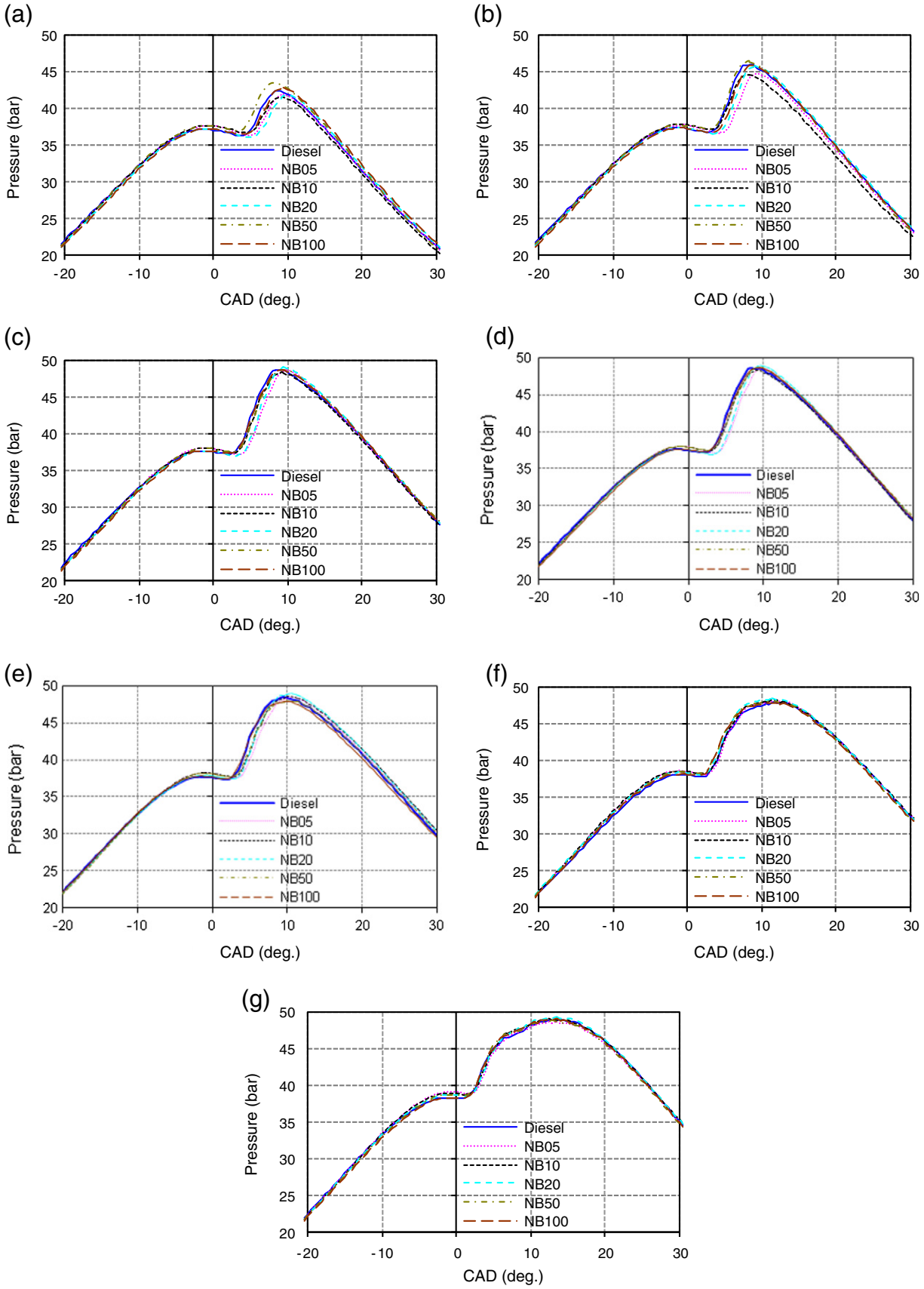


Fig. 4. Comparison of in-cylinder pressure at: (a) 0, (b) 1.3, (c) 2.2, (d) 3, (e) 4, (f) 5, and (g) 6 bar BMEP.

lower layer formed is deep dark brown and mainly contains glycerol while the upper layer is biodiesel, which also contains traces of catalyst. Traces of the catalyst are removed by water washing the biodiesel. However before washing the biodiesel, it is necessary to remove the methanol content in biodiesel in order to avoid soap formation. Since the boiling point temperature of methanol is 64.5 °C, it can be easily removed by heating biodiesel up to 75 °C. Biodiesel is heated and kept at this temperature for 5 min and then the biodiesel is mixed with 10% (v/v) warm water and kept in separating funnel for few hours. The lower layer contains water with traced of catalyst and this layer is removed. The pH of biodiesel is checked. If it is more than 7, water washing step is repeated. The upper layer is biodiesel, which is again heated at 105 °C for 5–10 min so as to remove the traces of moisture before final storage.

2.2. Characterization of biodiesel

Various blends of biodiesel such as B5, B10, B20, B50 and B100 were used for engine studies and they were compared with the baseline data from the mineral diesel. Important properties of these neem oil biodiesel blends used in this study, such as viscosity, density and calorific value of these test fuels were measured in the laboratory and are compared vis-à-vis baseline data of mineral diesel (Table 1).

It can be seen from this table that the viscosity of neem oil biodiesel blends (upto B50) is within ASTM specification limits (upto 6 cSt at 40 °C) whereas B100 is marginally out of specifications. Calorific value of biodiesel blends is lower than mineral diesel because biodiesel (B100) is having approximately 12% lower calorific value compared to mineral diesel. Density of biodiesel (B100) is observed to be higher than mineral diesel. Cetane number of the neem oil biodiesel and mineral diesel were 51 and 48 respectively.

These test fuels are used in the engine for performance, emission and combustion characteristics vis-à-vis baseline data from mineral diesel.

2.3. Test engine setup

A four-stroke, single cylinder, constant-speed, water-cooled, direct injection diesel engines (Make: Kirloskar Oil Engines Ltd. India; Model: DM-10) was used to experimentally investigate different neem oil biodiesel blends for engine performance, emissions and combustion. The detailed specifications of the engine used are given in Table 2. The engine is operated at a constant speed of 1500 rpm. The fuel injection pressure is in the range of 200–205 bars. Fresh lubricating oil was filled in oil sump before beginning the experiment. This engine had gravity-fed fuelling system having an efficient paper element fuel filter, force-feed lubrication for main bearing, large-end bearings and camshaft bush; run-through or thermo-siphon cooling system (Fig. 1). Similar engines are also used in low end automotive applications.

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. The engine shaft was coupled with a shaft encoder (Make: Encoder India Limited). Signals from the pressure transducer were amplified using a charge amplifier. Shaft encoder was used for delivering signals of crank angle with a resolution of 0.5° crank angle. A TDC marker was used to locate the top dead center position of the piston 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 carried out at 1500 ± 3 rpm, at 200 bar fuel injector pressure for diesel (D), B05, B10, B20, B50, and B100. The cylinder pressure data were acquired for 50 consecutive cycles and then averaged in order to eliminate the effect of cycle-to-cycle variations of the cylinder pressure data. 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.

3. Results and discussion

Performance, emission and combustion characteristics of B05, B10, B20, B50 biodiesel blends and B100 with mineral diesel are investigated in a CI engine and are discussed in the following subsections.

3.1. Engine performance

Experiments were conducted at 200 bar fuel injection pressure to compare the performance of B05, B10, B20, B50 biodiesel blends and B100 with mineral diesel.

Table 3 shows the range of percentage change in performance parameters for all biodiesel blends with respect to mineral diesel for the entire operating load range of the engine. BSFC for all the biodiesel blends is higher than mineral diesel (Fig. 2(a)). BSFC was observed to have increased with increasing proportion of biodiesel in the fuel. Brake thermal efficiency (Fig. 2(b)) of B100 was highest among all the test fuels. All blends showed higher thermal efficiency than mineral diesel. Fig. 2(c) compares the exhaust gas temperature of various biodiesel blends with mineral diesel. BSFC for the biodiesel and its blend increases due to lower calorific value of biodiesel in comparison with mineral diesel. Presence of oxygen in the biodiesel molecules improve the combustion efficiency of biodiesel hence its brake thermal efficiency increases with respect to mineral diesel. Exhaust gas

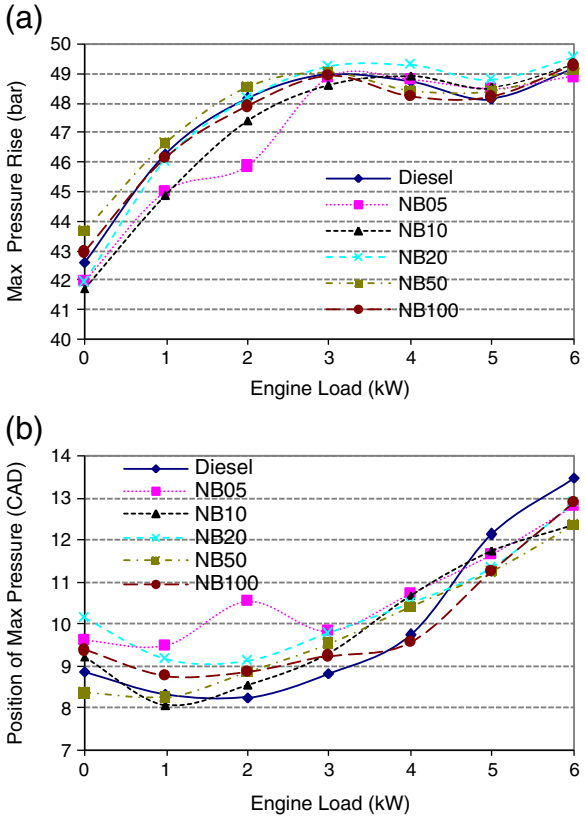


Fig. 5. Variation of (a) maximum cylinder pressure and, (b) maximum pressure crank angle.

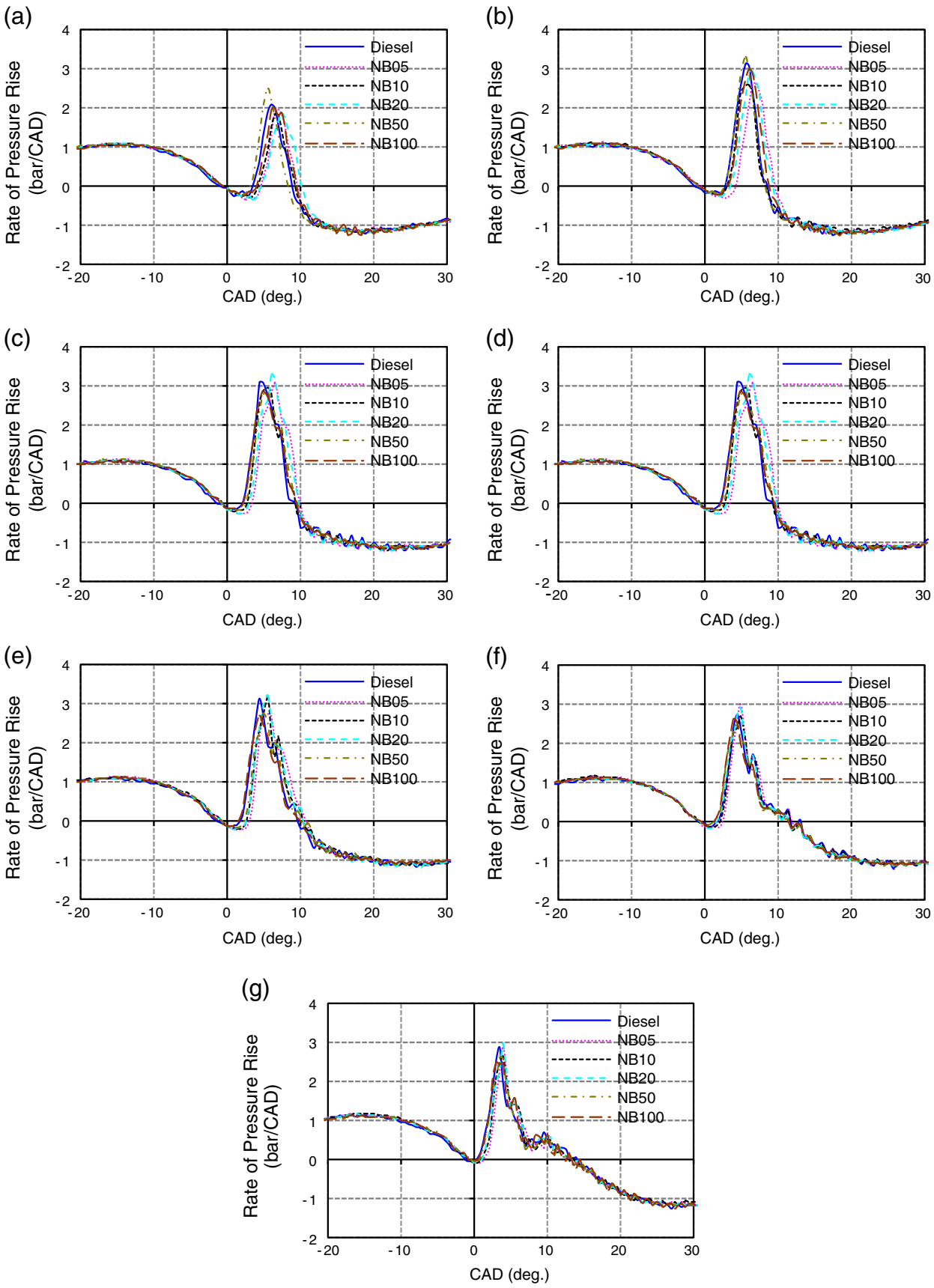


Fig. 6. Comparison of in-cylinder pressure rise rate at: (a) 0, (b) 1.3, (c) 2.2, (d) 3, (e) 4, (f) 5, and (g) 6 bar BMEP.

temperature for all biodiesel blends is lower than mineral diesel. Combustion of higher biodiesel blends starts relatively earlier and their combustion ends earlier also compared to lower biodiesel blends (Fig. 10), therefore one can observe relatively higher exhaust gas temperature compared to lower biodiesel blends. Lowest exhaust gas temperature was shown by B5. Lower exhaust gas temperatures resulting due to shorter combustion duration for biodiesel blends (Fig. 10), reduced CO and HC emissions (Fig. 3) are causing better thermal efficiency for biodiesel blends.

3.2. Engine emissions

The raw emissions of different regulated gases were recorded for various test fuels and biodiesel. These raw emissions are converted to mass emission and the results are presented in Fig. 3.

Table 4 shows the range of percentage change in emission parameters for all biodiesel blends with respect to mineral diesel for the entire load range of the engine. All biodiesel blends exhibit lower HC emissions compared to mineral diesel (Fig. 3(a)). This may be due to better combustion of biodiesel blends due to presence of oxygen. HC emission actually reduced with increasing engine load. The emissions of CO increases with increasing load (Fig. 3 (b)). Higher the load, richer fuel–air mixture is burnt, and thus more CO is produced due to lack of oxygen. At lower engine loads, CO emissions for all biodiesel blends are close to mineral diesel. At higher engine loads, all the biodiesel blends except 50% blend show significant reduction in CO emissions. Reduction in CO emission is caused by the presence of oxygen molecules in the biodiesel blends, which facilitates the reburning of CO formed in the cylinder. Increase in the emission of NO was observed in comparison with mineral diesel for all biodiesel fueled engines (Fig. 3(c)). NO formation is dependent on the temperature inside the cylinder and the concentration of oxygen available for reacting with nitrogen. Higher oxygen content of biodiesel blends increases NOx emissions. It is evident from combustion analysis that combustion duration for biodiesel blends is shorter than mineral diesel. This shorter combustion duration results in higher in-cylinder temperature. At lower engine loads, maximum rate of heat release is slightly higher for biodiesel blends but at higher engine loads, there is not much difference in combustion characteristics of biodiesel blends and diesel. Difference in NOx emission is also higher at lower engine loads but there is not much difference in NOx emission at higher loads. Szybist et al. [39] in their investigation on NOx formation concluded that NOx formation is insensitive to the maximum cylinder temperature and the maximum rate of heat release, but is sensitive to the timing or crank angle at which these temperature maxima occur. If heat release starts earlier then conditions are conducive for NOx formation because of longer time availability. There is no significant difference in magnitude of heat release traces (Fig. 8) but start and completion of combustion is earlier (Fig. 10) for biodiesel with respect to mineral diesel so more NOx is expected from biodiesel blend combustion. The smoke opacity for lower biodiesel blends was lower than mineral diesel at all loads (Fig. 3(d)). Larger fraction of fuel molecules are converted into CO rather than soot with the increase in oxygen concentration and simultaneously smoke opacity for biodiesel blends is reduced. At lower engine loads, B50 and B100 have shown higher smoke opacity compared to mineral diesel. Emission characteristics essentially do not follow linear trend w.r.t. concentration of biodiesel in the blended fuel. This is because biodiesel has higher viscosity compared to mineral diesel and addition of even smaller quantities of biodiesel in mineral diesel leads to an increase in blend viscosity, which potentially affects the fuel atomization and spray pattern, leading to different performance characteristics. This is a possible explanation however this needs further scientific investigations.

3.3. Combustion characteristics

Detailed combustion characterization investigations of biodiesel fuelled engine were carried out and various parameters such as pressure-crank angle history, rate of cylinder pressure rise, heat release rate, cumulative heat release, mass fraction burned etc. were analyzed for different test fuels at various engine loads to compare the combustion performance of the engine with new test fuels.

3.3.1. In cylinder pressure vs. crank angle diagram

The variations in the in-cylinder pressure with crank angle for B05, B10, B20 and B50 biodiesel blends and B100 at different engine operating conditions with a baseline data of mineral diesel are shown in Fig. 4(a)–(g).

From these figures, it can be noticed that at higher engine loads, pressure trends are almost similar for all test fuels. Lower biodiesel blends show delayed pressure rise w.r.t. mineral diesel at lower engine loads due to longer physical ignition delay period (because of higher boiling range of biodiesel). For higher blends, start of pressure rise for biodiesel blends is comparable with mineral diesel. B20 always shows higher peak pressure in comparison with mineral diesel indicating optimum conditions for combustion exhibited by mixture of two fuels. Presence of oxygen in biodiesel helps in combustion and lower viscosity of mineral diesel ensures adequate air-fuel mixing. At all engine loads, combustion starts earlier for higher biodiesel blends than mineral diesel while for lower blends, start of combustion gets delayed w.r.t. to mineral diesel. Ignition delay for all fuels decreases as the engine load increases because the in-cylinder gas temperature is higher at high engine loads, therefore it reduces the physical ignition delay period. The start of combustion reflects the variation in ignition delay because fuel pump and injector settings were kept identical for all fuels.

Fig. 5(a) shows the maximum cylinder pressure at different loads for these biodiesel blends. It shows that at all engine loads, the peak pressure for B20 is higher than mineral diesel. Peak pressure for B05 and B10 is significantly lower than mineral diesel. The peak pressure for B20 is higher because of the shorter ignition delay and fast burning of the accumulated fuel as a consequence of optimum oxygen content in the fuel and comparatively lower viscosity due to small concentration of biodiesel in the fuel. Fig. 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 from this figure that with increasing engine load, peak cylinder pressure shifts away from TDC. Peak cylinder pressure occurs closer to TDC for biodiesel blends due to earlier start of combustion for them due to their higher cetane number.

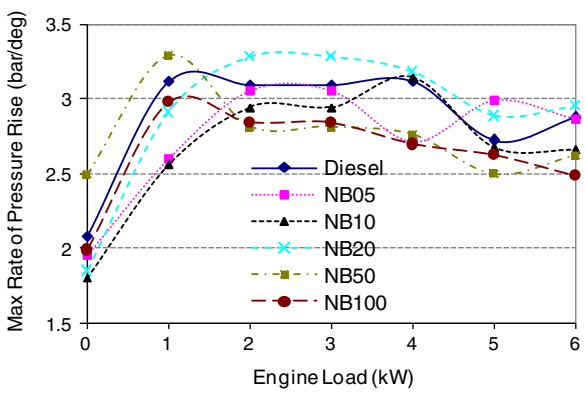


Fig. 7. Max pressure rate for rated load.

3.3.2. Rate of cylinder pressure rise vs. crank angle diagram

Fig. 6 (a)–(g) shows the variation in the rate of pressure rise (dP/dθ) with crank angle degrees at different loads for all test fuels.

The maximum rate of pressure rise varies from 1.7 bar/deg at lower engine loads to 3.5 bar/deg at higher engine loads. The maximum rate of pressure rise for lower biodiesel blends is comparable with mineral diesel but for higher blends, it is lower than mineral diesel at all engine loads (Fig. 7). Lower rate of pressure rise for higher blends is a consequence of earlier start of combustion for biodiesel blends, which results in lesser fuel accumulation during premixed combustion.

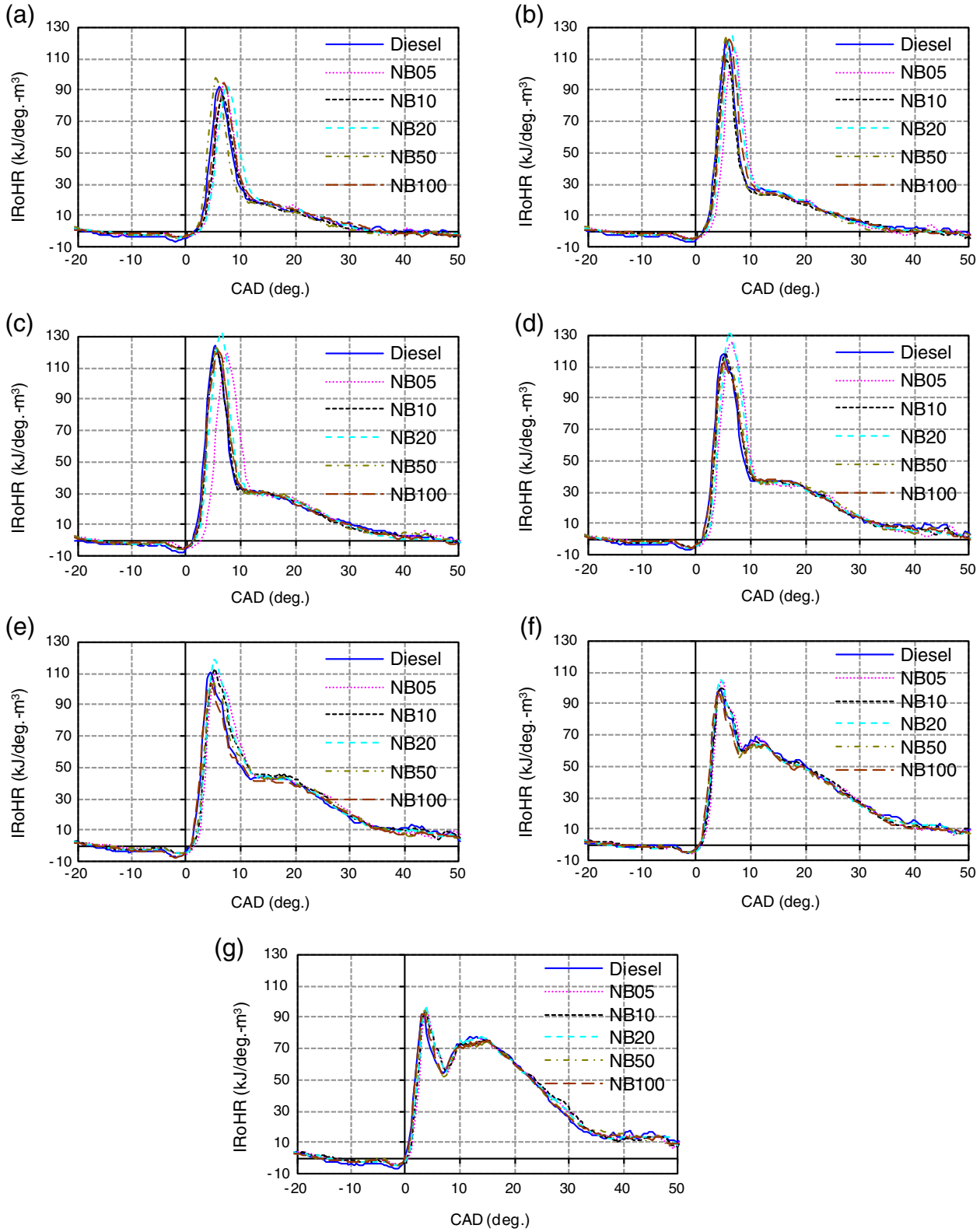


Fig. 8. Comparison of heat release rate at: (a) 0, (b) 1.3, (c) 2.2, (d) 3, (e) 4, (f) 5, and (g) 6 bar BMEP.

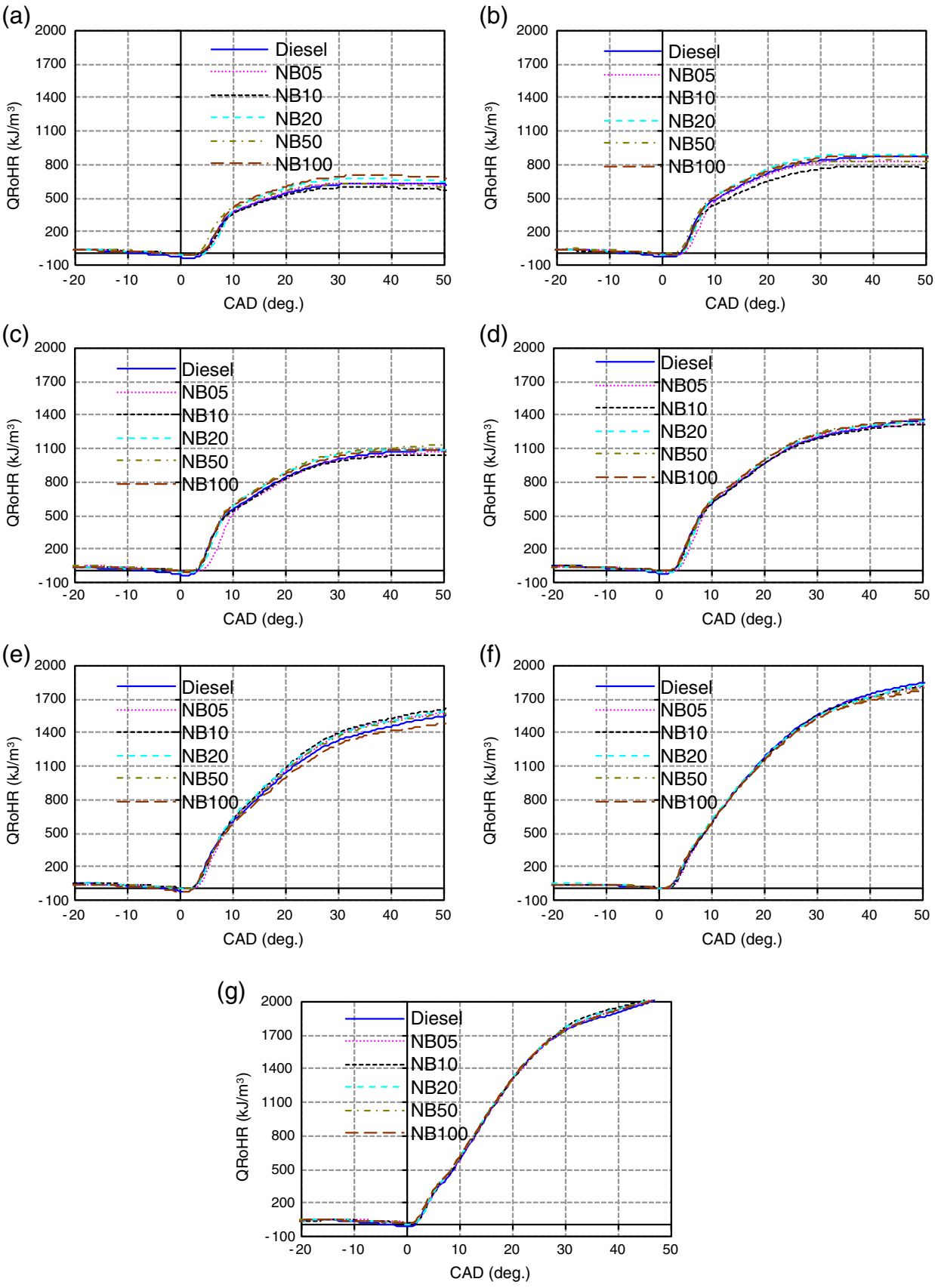


Fig. 9. Comparison of cumulative heat release at: (a) 0, (b) 1.3, (c) 2.2, (d) 3, (e) 4, (f) 5, and (g) 6 bar BMEP.

3.3.3. Heat release rate vs. crank angle diagram

Fig. 8(a)–(g) shows the heat release rate diagrams for biodiesel blends vis-à-vis mineral diesel at different engine operating conditions. Because of the vaporization of the fuel accumulated during ignition delay, in the beginning a negative heat release is observed and after combustion is initiated, heat release becomes positive.

Biodiesel blends show identical combustion stages for all loads as mineral diesel. After the ignition delay, premixed fuel-air mixture burns rapidly. The premixed combustion heat release start is delayed for lower biodiesel blends (B05, B10 and B20) because lower concentration of biodiesel in the fuel does not have significant effect on cetane number however it affects the air fuel mixture formation due to change in fuel viscosity and evaporation characteristics of the fuel. Premixed combustion heat release rate is higher for lower biodiesel blends at all engine loads owing to optimum conditions for mixture formation and improved combustibility of mixture due to presence of oxygen in the fuel. At higher engine loads, heat release during mixing control combustion phase increases for all test fuels due to increasing fuel quantity injected.

Fig. 9(a)–(g) shows the cumulative heat release diagrams for biodiesel blends vis-à-vis mineral diesel at different engine operating conditions. Biodiesel blends show very close pattern of cumulative heat release for all loads in comparison to mineral diesel. Cumulative heat release increases with increasing engine load for all the fuels as mass of fuel burning in the combustion chamber increases with increasing load.

3.3.4. Crank angle for mass fraction burn

Fig. 10(a) shows the crank angle for 5% mass fraction burned. This figure shows that 5% fuel burns earlier for higher blends of biodiesel. This is due to the earlier start of combustion for higher biodiesel blends, as observed earlier. For all blends, start of combustion is advanced with increasing engine load. Lower biodiesel blends show delayed start of combustion w.r.t. mineral diesel, which indicates delay in the start of combustion possibly due to relatively higher viscosity of biodiesel. For higher biodiesel blends, delay due to higher viscosity is compensated by increased cetane number of biodiesel. Largest delay in start of combustion was observed for B05 at lower loads possibly due to increase in the viscosity of the blend and insignificant effect of small concentration of biodiesel to change the chemical properties of the fuel. Fig. 10(b) shows the crank angle degree for 50% mass fraction burned at different engine load conditions. Biodiesel blends take lesser time for 50% combustion as compared to mineral diesel. Fig. 10(c) shows the crank angle degree for 90% mass fraction burned at different engine load conditions. Here also, it is observed that biodiesel blends take lesser time for 90% combustion as compared to mineral diesel.

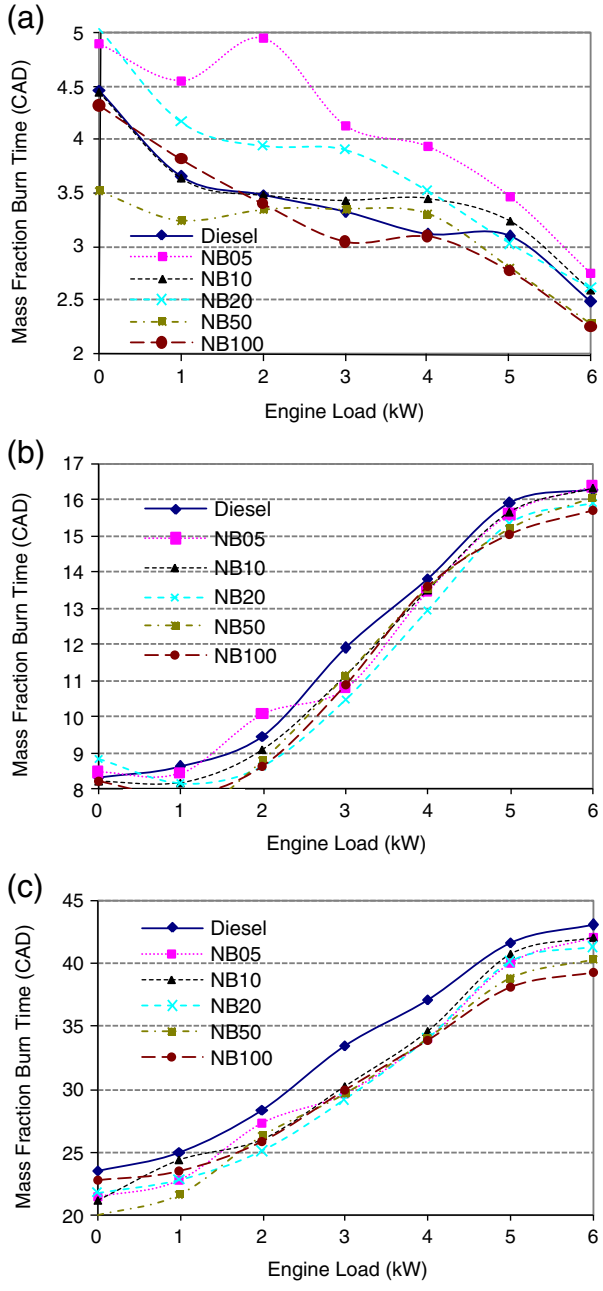


Fig. 10. Crank Angle for (a) 5%, (b) 50% and, (c) 90% mass fraction burn.

4. Conclusions

Biodiesel was produced by two step process of esterification followed by transesterification of high FFA Neem oil (Feedstock FFA: 20%). For esterification, optimum reaction conditions were: molar ratio of alcohol to oil 6:1, 4.5% catalyst, 45 °C temperature, and stirring speed 1300 rpm. For transesterification, optimum reaction conditions were: molar ratio of alcohol to oil of 6:1, 1% catalyst (NaOH), 60 °C temperature, and stirring speed 1300 rpm. Density, viscosity and calorific values of this biodiesel and its blends were measured for the characterization of biodiesel and found to be within the ASTM specification.

Performance, emission and combustion characteristics of this biodiesel were evaluated in a constant speed direct injection compression ignition engine. Brake specific fuel consumption for biodiesel and its blends were higher than mineral diesel however brake thermal efficiency of all biodiesel blends was also higher than mineral diesel. BSCO and BSHC emissions for biodiesel fuelled engine operation were lower than mineral diesel however BSNOx emissions were higher for biodiesel blends. Combustion started earlier for higher biodiesel blends however start of combustion was slightly delayed for lower biodiesel blends in comparison to mineral diesel. Rate of heat release trends for all the biodiesel blends were almost identical to mineral diesel. Combustion duration for biodiesel blends was shorter than mineral diesel. This indicates that lower blends of biodiesel (upto B20) can be used in unmodified CI engines without any compromise in engine performance and emission characteristics.

References

[1] A.K. Agarwal, Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines, Progress in Energy and Combustion Science 33 (2007) 233–271.

[2] C.L. Peterson, D.L. Auld, Technical overview of vegetable oil as a transportation fuel, Fact — solid fuel conversion for the transportation sector, 12, ASME, 1991, pp. 45–54, 1991.
[3] Vellguth, G Performance of vegetable oils and their monoesters as fuels for Diesel engine. SAE 831358, 1983.
[4] C.L. Peterson, G.L. Wagner, D.L. Auld, Vegetable oil substitution for diesel fuel, Transactions of ASAE 26 (1983) 322–327.
[5] F. Staat, P. Gateau, The effects of rapeseed oil methyl ester on diesel engine performance exhaust emissions and long-term behavior – a summary of three years of experimentation. SAE 950053, 1985.
[6] J.M. Desantes, J. Arregle, S. Ruiz, A. Delage, Characterization of the injection–combustion process in a D.I. diesel engine running with rape oil methyl ester. SAE 1999-01-1497, 1999.
[7] R. Altõn, S. Cetinkaya, H.S. Yucesu, The potential of using vegetable oil fuels as fuel for diesel engines, Energy Conversion and Management 42 (2001) 529–538.
[8] F. Ma, A.H. Milford, Biodiesel production: a review, Bioresource Technology 70 (1999) 1–15.
[9] A.S. Ramadhas, S. Jayaraj, C. Muraleedharan, Biodiesel production from high FFA rubber seed oil, Fuel 84 (2005) 335–340.
[10] J.M. Marchetti, V.U. Miguel, A.F. Errazu, Heterogeneous esterification of oil with high amount of free fatty acids, Fuel 86 (2007) 906–910.
[11] M. Naik, L.C. Meher, S.N. Naik, L.M. Das, Production of biodiesel from high free fatty acid Karanja (*Pongamia pinnata*) oil, Biomass and Bioenergy 32 (2008) 354–357.
[12] Z. Helwani, M.R. Othman, N. Aziz, W.J.N. Fernando, J. Kim, Technologies for production of biodiesel focusing on green catalytic techniques: a review, Fuel Processing Technology 90 (2009) 1502–1514.
[13] M.G. Varanda, G. Pinto, F. Martins, Life cycle analysis of biodiesel production, Fuel Processing Technology 92 (2011) 1087–1094.
[14] R. Altin, S. Cetinkaya, H.S. Yucesu, The potential of using vegetable oil fuels as fuel for diesel engine, Energy Conversion and Management 42 (1991) 529–538.
[15] K.R. Kaufman, M. Ziejewski, Sunflower methyl esters for direct injected diesel engines, Transactions of ASAE 27 (6) (1984) 1626–1633.
[16] G. Antolin, Optimisation of biodiesel production by sunflower oil transesterification, Bioresource Technology 83 (2002) 111–114.
[17] S.J. Clark, L. Wagner, M.D. Schrock, P.G. Piennaar, Methyl and ethyl soybean esters as renewable fuels for diesel engines, JAOCS 61 (10) (1984) 1632–1638.
[18] J.F. McDonald, D.L. Purcell, B.T. McClure, D.B. Kittelson, Emission characteristics of soy methyl ester fuels in an IDI compression ignition engine, Transactions of SAE, 1995 SAE 950400.
[19] C.L.D. Peterson, L. Reece, J.C. Thompson, S.M. Beck, C. Chases, Ethyl ester of rapeseed used as a biodiesel fuel — a case study, Biomass and Bioenergy 10 (5/6) (1996) 331–336.
[20] S. Sinha, A.K. Agarwal, Experimental investigation of the combustion characteristics of biodiesel (rice bran oil methyl ester) fuelled direct injection transportation diesel engine, Journal of Automobile Engineering, Proceedings of IMechE, Part-D. 221 (8) (2007) 921–932.
[21] S. Sinha, A.K. Agarwal, Ricebran oil biodiesel's performance, emission and endurance test on a CIDI transport engine, International Journal of Vehicle Design 50 (1/2/3/4) (2009) 248–270.
[22] A.K. Agarwal, A. Dhar, Comparative performance, emission and combustion characteristics of rice-bran oil and it's biodiesel in a transportation diesel engine, Journal of Engineering for Gas Turbine and Power, Transactions of ASME 132 (6) (2010) 064503-1-4.
[23] A.K. Agarwal, Lubrication oil tribology of a biodiesel-fuelled CI engine, Journal of Automobile Engineering Proceedings of IMechE, Part-D 219 (5) (2005) 703–714.
[24] C. Ilkılıç, S. Aydın, R. Behcet, H. Aydin, Biodiesel from safflower oil and its application in a diesel engine, Fuel Processing Technology 92 (2011) 356–362.
[25] C. Carraretto, A. Macor, A. Mirandola, A. Stoppato, S. Tonon, Biodiesel as alternative fuel: experimental analysis and energetic evaluations, Energy 29 (2004) 2195–2211.
[26] M.I. Al-Widyan, G. Tashtoush, M. Abu-Qudais, Utilization of ethyl ester of waste vegetable oils as fuel in diesel engines, Fuel Processing Technology 76 (2002) 91–103.
[27] H. Raheman, A.G. Phadatare, Diesel engine emissions and performance from blends of karanja methyl ester and diesel, Biomass and Bioenergy 27 (2004) 393–397.
[28] H. Raheman, S.V. Ghadge, Performance of diesel engine with biodiesel at varying compression ratio and ignition timing, Fuel 87 (2008) 2659–2666.
[29] M.N. Nabi, M.S. Akhter, M.M.Z. Shahadat, Improvement of engine emissions with conventional diesel fuel and diesel–biodiesel blends, Bioresource Technology 97 (2006) 372–378.
[30] N. Usta, An experimental study on performance and exhaust emissions of a diesel engine fuelled with tobacco seed oil methyl ester, Energy Conversion and Management 46 (2005) 2373–2386.
[31] M. Canakci, Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel, Bioresource Technology 98 (2007) 1167–1175.
[32] X. Lu, D. Han, Z. Huang, Fuel design and management for the control of advanced compression-ignition combustion modes, Progress in Energy and Combustion Science 37 (2011) 741–783.
[33] T. Fang, C.F. Lee, Bio-diesel effects on combustion processes in an HSDI diesel engine using advanced injection strategies, Proceedings of the Combustion Institute 32 (2009) 2785–2792.
[34] M. Zheng, M.C. Mulenga, G.T. Reader, M. Wang, D.S.-K. Ting, J. Tjomg, Biodiesel engine performance and emissions in low temperature combustion, Fuel 87 (2008) 714–722.
[35] A. Karmakar, S. Karmakar, S. Mukherjee, Biodiesel production from neem towards feedstock diversification: Indian perspective, Renewable and Sustainable Energy Reviews 16 (2012) 1050–1060.
[36] O. Koul, M.B. Isman, C.M. Ketkar, Properties and uses of neem, *Azadirachta indica*, Canadian Journal of Botany 68 (1) (1990) 1–11.
[37] S.S. Ragit, S.K. Mohapatra, K. Kundu, P. Gill, Optimization of neem methyl ester from transesterification process and fuel characterization as a diesel substitute, Biomass and Bioenergy 35 (2011) 1138–1144.
[38] V.S. SatyaSelvabala, T.K. Varathachary, D.K. Selvaraj, V. Ponnusamy, S. Subramanian, Removal of free fatty acid in *Azadirachta indica* (Neem) seed oil using phosphoric acid modified mordenite for biodiesel production, Bioresource Technology 101 (2010) 5897–5902.
[39] J.P. Szybist, L.B. Andre´, J.D. Taylor, L. Robert, R.L. McCormick, Evaluation of formulation strategies to eliminate the biodiesel NOx effect, Fuel Processing Technology 86 (2005) 1109–1126.