Fuel 88 (2009) 1698–1707

Contents lists available at ScienceDirect

Fuel

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

Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine

P.K. Sahoo [a], L.M. Das [a,*], M.K.G. Babu [a], P. Arora [b], V.P. Singh [b], N.R. Kumar [b], T.S. Varyani [b]

[a] *Centre for Energy Studies, Indian Institute of Technology Delhi, New Delhi 110016, India*
[b] *Escorts R&D Centre, Mathura Road, Faridabad, Haryana, India*

ARTICLE INFO

Article history:
Received 21 July 2008
Received in revised form 27 October 2008
Accepted 12 February 2009
Available online 4 March 2009

Keywords:
Biodiesel
Jatropha
Karanja
Polanga
Fuel economy

ABSTRACT

Non-edible jatropha (*Jatropha curcas*), karanja (*Pongamia pinnata*) and polanga (*Calophyllum inophyllum*) oil based methyl esters were produced and blended with conventional diesel having sulphur content less than 10 mg/kg. Ten fuel blends (Diesel, B20, B50 and B100) were tested for their use as substitute fuel for a water-cooled three cylinder tractor engine. Test data were generated under full/part throttle position for different engine speeds (1200, 1800 and 2200 rev/min). Change in exhaust emissions (Smoke, CO, HC, NO_x, and PM) were also analyzed for determining the optimum test fuel at various operating conditions. The maximum increase in power is observed for 50% jatropha biodiesel and diesel blend at rated speed. Brake specific fuel consumptions for all the biodiesel blends with diesel increases with blends and decreases with speed. There is a reduction in smoke for all the biodiesel and their blends when compared with diesel. Smoke emission reduces with blends and speeds during full throttle performance test.

1. Introduction

Energy is an essential input for economic growth, social development, human welfare and improving the quality of life. Since their exploration, the fossil fuels continued as the major conventional energy source. With increasing trend of modernization and industrialization, the world energy demand is also growing at a faster rate. Apart form their indigenous production, majority of developing countries import crude oil to cope up with their increasing energy demand. Thus, a major chunk of their hard earned export earnings is spent for purchase of petroleum products. India is also a net energy importer and almost 80% of the country's export earnings are directly spent for purchase of petroleum products [1]. There had been sharp increase in the consumption pattern of petroleum products in India. The transport and agriculture sectors are the major users of the conventional liquid fuels. It is estimated that the demand of diesel in the country would rise to 52.33 million tones by 2006–2007 and to 66.90 million tones by 2011–2012 with simultaneous increase in consumption by the agriculture sector.

2. Biodiesel as an appropriate substitute of diesel

The esters of vegetable oils are popularly known as biodiesel. It is the process of reacting triglyceride with an alcohol in presence of a catalyst to produce glycerol and fatty acid esters. In India, attempts are being made for using non-edible and under-exploited oils for production of esters. Blending conventional diesel fuel with esters (usually methyl esters) of vegetable oils is presently the most common form of biodiesel. There have been numerous reports indicating that significant emission reductions are achieved with these blends. Several studies [2] have shown that diesel and biodiesel blends reduce smoke opacity, particulates, un-burnt hydrocarbons, carbon dioxide and carbon monoxide emissions, but nitrous monoxide emissions have slightly increased.

It was [3] reported that the transesterification process has been proven worldwide as an effective means of biodiesel production and viscosity reduction of vegetable oils. Temperatures, catalyst type, concentration ratio of alcohol to fuel and stirring speed rate have been observed to influence the transesterification process to a greater extent. A brief study was conducted [4] on the use of biodiesel from coconut oil (50/50 blend), "B50" in motor coaches. This study revealed that it is a viable and a practical alternative fuel for older in-service engines. Particulate matter was almost negligible with the use of this fuel. Operators reported that the test vehicles had no noticeable drivability downsides. On the other hand it was observed the vehicles had some improved power performance while operating under city traffic conditions.

It was [5] also found that no significant engine problems were reported in large-scale tests with urban bus fleets running on B20. Fuel economy was comparable with diesel fuel and the fuel consumption of biodiesel blend being only 2–5% higher than that of conventional diesel. Ester blends have been reported to be stable

---

[*] Corresponding author. Tel.: +91 11 26591260; fax: +91 11 26581121.
E-mail address: lalitmdas@rediffmail.com (L.M. Das).

0016-2361/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.fuel.2009.02.015

and did not separate at room temperature over a period of 3 months. One limitation to the use of biodiesel is its tendency to crystallize at low temperatures below 0 °C. Such crystals can plug fuel lines and filters, causing problems in fuel pumping and engine operation. Wagner et al. [6] conducted 200 h engine tests with soybean oil ester fuel on John Deere (4239T Model) engine. It was reported that the engine performance with methyl, ethyl and butyl esters was nearly same as with diesel fuel. There was no difference in thermal efficiency resulting from use of the various fuels to power the engine. The esters showed slight power loss and increased fuel consumption, which was attributed to the lower gross heating values. Engine wear was normal. There was, however, increased carbon deposition on the pistons with the methyl and butyl esters. Emissions of oxides of nitrogen were significantly higher for the esters. They concluded that the esters could be used on a short-term basis and that further testing to be done for determining long-term ester fuel effects.

Keeping in view the need to reduce consumption of petroleum products and simultaneously address to stringent engine emission requirements for implementation of EURO III in all over the country by 2010, the Government of India has taken a major policy decision on use of biodiesel (prepared from non-edible oil seeds) as blends with diesel. The issue of present lower flash point specification for diesel in the country as compared to international standards is also likely to be solved through this process. A well defined road map has been put under implementation by the Government of India so that commercial use of biodiesel will be implemented in the mega cities and subsequently spread over the country.

Apart from the problem of diesel scarcity and higher fuel costs, there is the growing menace of vehicular pollution. To compensate for the shortages of diesel fuel, the adaptation of a selected alternative fuel to suit the diesel engine is considered more economically attractive in the short-term than engine modification to suit the fuel. For this purpose an alternative liquid fuel which will blend readily with diesel fuel is required. Such an alternative fuel should lend itself to local production in adequate and economic quantities. There should be little modifications to the existing engine. Engine performance and durability should not be affected significantly. Hence, there is a greater motivation to utilize biodiesel as a supplementary fuel for diesel in compression ignition engines[7–9].

In this experimentation, investigations have been undertaken to optimize the biodiesel production process and assess the comparative performance emission characteristics of a three cylinder tractor engine by using ten test fuels (100% neat diesel, JB20, JB50, JB100, KB20, KB50, KB100, PB20, PB50, and PB100) derived from jatropha, karanja and polanga oil.

3. Experimental procedures

3.1. Biodiesel production

Initially, experiments were conducted in a laboratory set up which consists of heating mantle, reaction flask (made of glass) and mechanical stirrer. The working capacity of reaction flask is one litre. It consists of three necks for stirrer, condenser and inlet of reactant as well as for placing the thermocouple to observe the reaction temperature. The flask has a stopcock at the bottom for collection of the final product. Process parameters such as reaction temperature, reaction duration, stirring speed, amount of catalyst and volume of methanol were optimized in one litre per batch capacity biodiesel reactor. The optimized parameters were used for large quantity production of biodiesel in fifty litres capacity per batch biodiesel pilot plant for engine performance and emission. The physico-chemical properties of the jatropha, karanja and polanga oil based biodiesel and their various blends with diesel were evaluated as per the ASTM standards.

3.2. Experimental technology for performance and emission test

To evaluate the performance and emission characteristics, experiments were conducted on a big size water-cooled three cylinder tractor diesel engine fueled with prepared test fuels. The experimental set up is shown in Fig. 1. Engine systems equipped with automatic experimental technologies to measure the performance parameters like brake specific fuel consumption (BSFC), brake mean effective pressure (BMEP) and brake thermal efficiency (BTE) at full/part throttle position at various engine speeds. The experimental set up consists of a three cylinder diesel engine use for ESCORTS FARM TRAC model, eddy current dynamometer and electronic data acquisition and control with various automatic measuring systems.

3.2.1. Engine and dynamometer

The engine tested in this study is a 3-cylinder; AVL make compression ignition engine has 3.44 litre displacements with an 18:1 compression ratio. A wide range of normal farm tasks are performed by the engine installed in the tractor. The combustion chambers are of the open chamber, medium swirl design. At its rated speed of 2200 rpm the engine can develop 44.1 kW (60 hp), measured at the engine shaft. The fuel injection system incorporated a distributor-type injection pump which was rotated externally for adjustment of the injection timing. During the engine tests, loads were applied with eddy current dynamometer (AVL Alpha 160 model) coupled with tractor's engine. The torque was measured with the help of moment arm. The load was controlled by regulating the current in the electromagnet with the help of AVL PUMA 5 controller.

3.2.2. Instrumentation and the electronic data acquisition and control system (EDACS)

The instrument for evaluating performance and emission characteristics for the tractor engine consists of volumetric fuel meter, throttle actuator, air mass flow meter, blow meter, exhaust gas analyzer and smoke meter. An AVL PUMA 5 controller and electronic data acquisition and control system (EDACS) were employed for controlling the engine variables and data recording during the engine performance and emission tests. A schematic of the data acquisition and control system is shown in Fig. 2. All measurements of analog voltage signals were made with analog/digital conversion (A/D) converter. Appropriate linearization and conversion to engineering units was performed by the computer under software control.

Copper/constantan thermocouples were used to measure the engine coolant temperature, air intake temperature and fuel temperature. Exhaust temperature was measured with a chromel/alumel thermocouple installed in the engine's exhaust manifold. Torque and speed measurements were made with the EDACS data system connected to the computer through a computer controlled multiplexing interface designed specifically for this purpose. The torque and speed transducers were mounted on the engine shaft between the engine and dynamometer. Fuel consumption was measured with a positive displacement volumetric AVL fuel mass flow meter (model 735 with 0.12% accuracy) which displayed cumulative fuel consumption (cc) and elapsed time on its front panel, LED displays. The AVL fuel mass flow meter features high reliability and ease of application to the latest diesel injection systems. This is achieved through the use of a specially developed pressure control system that makes vehicle-like conditions possible on the test bed, and prevents undesirable pressure build-up in the measurement circuit. The measurement of any return flow avoids

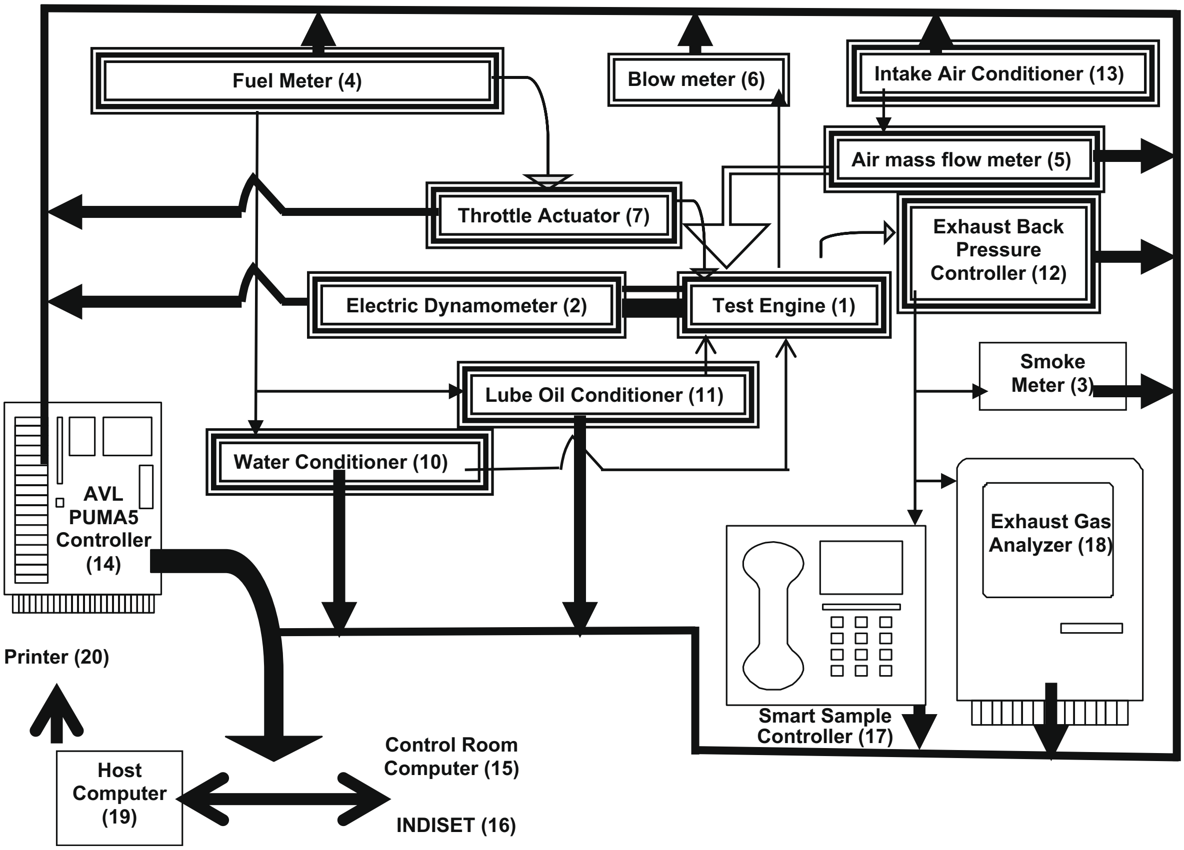

Fig. 1. Schematic diagram of test set up for a three cylinder DI diesel engine.

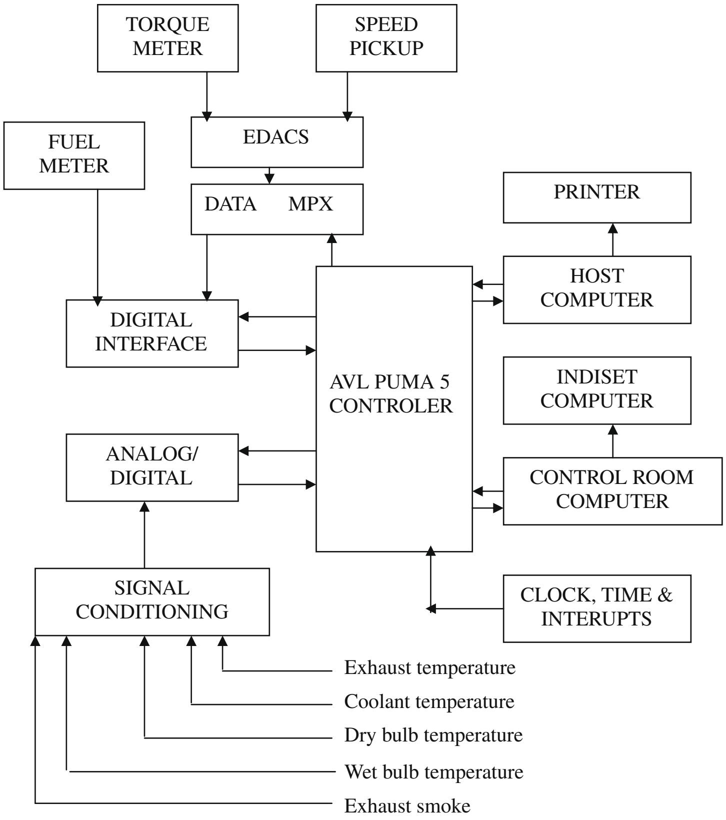

Fig. 2. Schematic representation of electronic data acquisation and control system (EDACS).

errors in the total value (e.g. cycle consumption). Fuel rate measurements were made by using the computer to time the consumption of a predetermined volume of fuel.

The AVL Throttle Actuator FVG 9400 EC was used for the adjustment of the throttle valve or injection pump on diesel engine. The throttle of the engine was maintained with the help of throttle actuator to regulate the fuel flow rate to the injection pump of the engine. The experiments were conducted at full throttle as well as part throttle (50% throttle position) to analyze several performance and emission parameters at different speeds. In view of the increased complexity and power of modern engines, high demands are nowadays, also placed on blow-by meters. The measurement method used by the AVL blow-by meter (model 442) in the present study was based on the orifice measurement principle, which permitted the blow-by gas to be measured in both directions of flow. This made possible the determination of the gas even in heavily pulsating flows and when there was partial vacuum in the crankcase. Blow-by gases were measured accurately by blow-by meter and the amount of blow-by gases was indicated digitally in the host computer.

The mass flow meter was an air consumption mass measurement system working on a hot film anemometer principle. This well-established measurement method was based on a system whereby heat was extracted from a heated body by the gas flowing around it. In mass flow meter, flow-dependent cooling was used as a measuring effect. New measurement methods and demands for increased test bed efficiency have resulted in a clear trend toward continuous fuel consumption measurement. Air mass flow meter was used to measure the mass of air directly required by the engine with the help of EDACS. The intake air was filtered and conditioned before entering the air mass flow meter with the help of intake air conditioner. Water and lubricating oil conditioner were used for maintaining the quality of the cooling water and lubricating oil, respectively.

Exhaust smoke opacity was measured with an AVL make model smoke meter which provides a low level voltage signal proportional to the attenuation of a focused light beam passing through the exhaust gas stream. The meter was calibrated under control of the computer prior to each test sequence. The AVL CEB II Advanced Emissions Analysis System is a highly sophisticated and innovative exhaust gas measurement device was used for recording CO, HC, NO_x, particulate matter during the 8 mode emission test cycle. Local barometric pressure was recorded prior to each test run for later use in correcting test data to standard conditions. Upon completion of the recording period, data were stored in an INDISET computer for subsequent correction to standard conditions and data analysis.

Tests were conducted with diesel fuel oil to establish a performance baseline at the manufacturer's recommended standards. Ten types of fuels employed including base line diesel in this test program. Tests were then made with fuel mixtures containing diesel and biodiesel from jatropha, karanja and polanga oil at various proportions. For each fuel blend, data were collected at full throttle and part throttle with respect to different speeds. Prior to each test with a new fuel blend the engine was allowed to warm up for 20 min to ensure any fuel remaining in the fuel line or fuel filters would be consumed. Data collection during any test was not begun until the torque, speed, exhaust temperature and coolant temperature had stabilized i.e. when no upward or downward trend in these parameters was detected. During the data collection period, data were recorded at 60 s intervals. It was found that six data scans per test were sufficient. Continual minor adjustments of engine speed and dynamometer load setting were necessary to obtain consistent data with all fuels and loads at full and part throttle performance by accounting the correction factor of 0.12%. The objective of such a study was to compare the suitability of these fuels for engine application and to determine the optimum fuel blend for this 3-cylinder diesel engine.

4. Results and discussion

4.1. Test fuel standardization

The properties of biodiesel and their blends are compared with ASTM biodiesel standards. The tested properties of methyl esters of jatropha, karanja and polanga oil are found to be reasonable agreement with ASTM 6751. It is observed from Table 1 that the typical combustion characteristics of jatropha biodiesel (JB), karanja biodiesel (KB) and polanga biodiesel (PB) are in the close range of the requirement of the engine. The calorific values of all the biodiesel and their blends are lower than that of diesel because of their oxygen content. The presence of oxygen in the biodiesel helps for complete combustion of fuel in the engine. The flash point of all the biodiesel and their blends is lowered by transesterification but it is still higher than that of diesel. Addition of a small quantity of biodiesel with diesel increases the flash point of diesel. Hence, it is safer to store biodiesel–diesel blends as compared to diesel alone.

4.2. Performance analysis

Performance parameters such as change in BSFC, BSEC, power and smoke with respect to speed are evaluated for all the test fuels and are compared to diesel under full throttle conditions. The part throttle performance data such as BSFC, BSEC and smoke are also evaluated with respect to BMEP at various engine speeds. In the final phase of testing under this study, all three cylinders of the engine were operated over the AVL 8 mode test conditions and engine-out emissions were sampled. Measured emissions were compared with emissions from the same engine operated with base line diesel. The results obtained in this study with neat diesel,

Table 1
Properties of test fuels.

SN	Fuel blend	Density (kg/m^3)	CV (kJ/kg)	Viscosity (cSt)	Flash point (°C)	Cloud point (°C)	Pour point (°C)
1	Diesel	850	44000	2.87	76	6.5	3.1
2	JB20	852	43759.5	3.02	88	6.9	3.3
3	JB50	857	43323	3.59	113	7.3	3.4
4	JB100	873	42673	4.23	148	10.2	4.2
5	KB20	851	43690	3.04	96	8.9	3.1
6	KB50	856	43307	3.62	106	11.2	4.2
7	KB100	883	42133	4.37	163	14.6	5.1
8	PB20	852	43109	2.98	86	7.8	2.9
9	PB50	857	42542	3.42	93	8.7	2.9
10	PB100	869	41397	3.99	140	13.2	4.3

neat biodiesel and different blends are discussed with respect to engine performance and emissions; and are shown in the figures (Fig. 3 through Fig. 5).

4.2.1. Effect of speed and blending ratio on power at full throttle performance (FTP)

Significant change in power is not observed in Fig. 3a at lower speed of 1200 and 1400 rpm for all the biodiesel blends. However, slight reduction in power is observed at all the speeds with biodiesel blends of KB20, KB100, JB100, PB20 and PB100. There is no significant change in power up to 1200 rpm with JB20 and JB50. The improvement in power is observed for JB20 and JB50 above 1200 rpm. The maximum increase in power is observed for JB50 at 2000 and 2100 rpm.

Under full throttle conditions, the use of 20% karanja biodiesel in diesel (KB20) caused a reduction in power in the range of 0.44–1.93%. Similarly, reduction in power is also observed for KB100 in the range of 1.2–2.55% during the higher speed engine operation. But there is an improvement of power for KB50 during the entire range of engine operation. The maximum increase in power (0.88% higher than that of diesel) is observed at 2200 rpm for 50% karanja biodiesel in diesel.

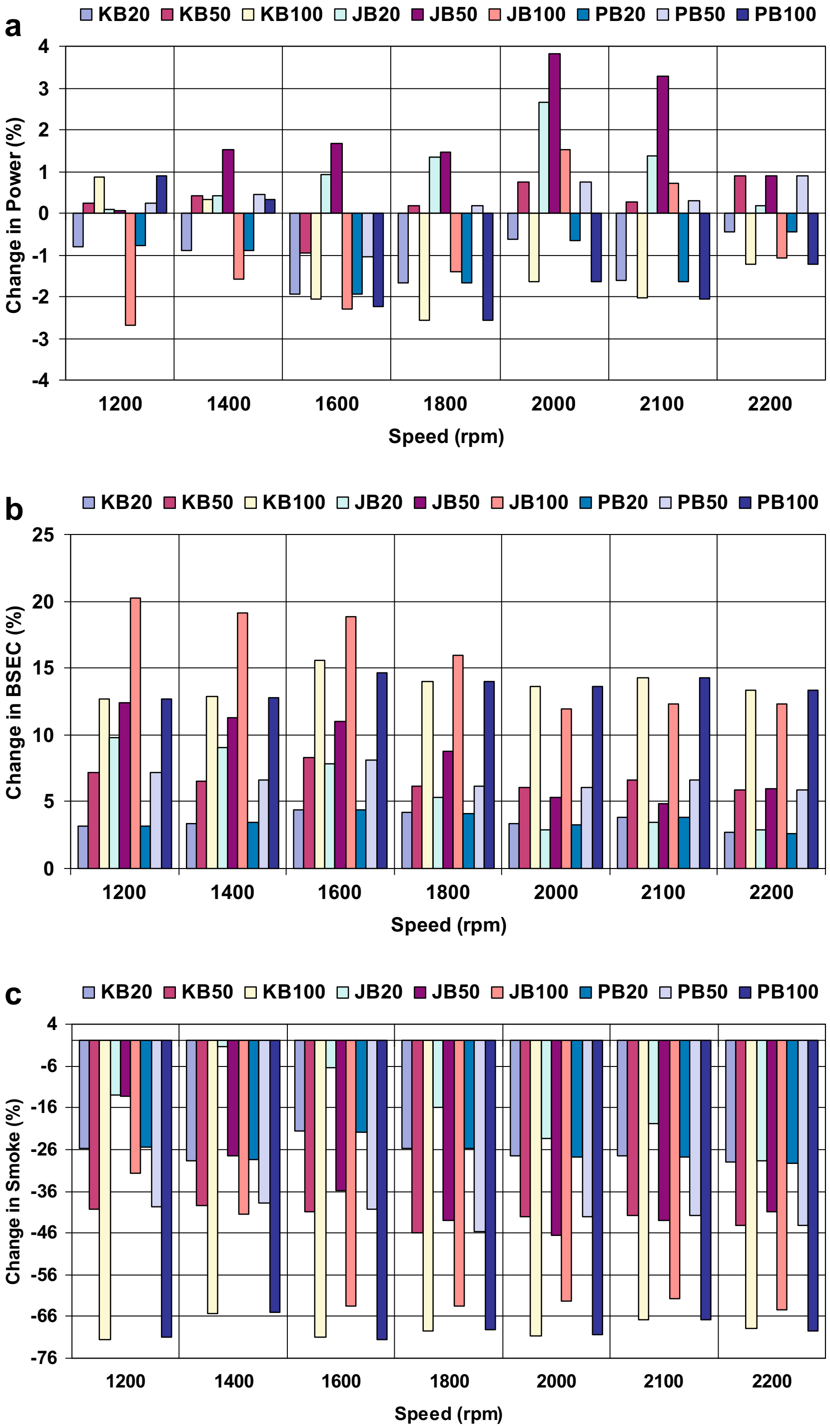

Fig. 3. (a) Change in power (%) with respect to speed and blends (FTP), (b) Change in BSEC (%) with respect to speed (FTP), (c) Change in smoke (%) with respect to speed (FTP).

The use of 20 and 50% jatropha biodiesel in diesel (JB20 and JB50) results in an improvement in power in the range 0.09–2.64% and 0.05%–3.8%, respectively. But there is a substantial reduction in power observed in case of neat jatropha biodiesel. The maximum decrease in power (2.68% lower than that of diesel) is observed at a speed of 1200 rpm for neat jatropha biodiesel (JB100).

Reduction in power is observed for PB20 over the entire range of speeds and the maximum decrease in power (1.93% lower than that of diesel) is seen at 1600 rpm. Similarly, there is an improvement in power ranges from 0.19% to 0.88% is observed for PB50 during the entire range of engine operation. But PB100 does not show any particular trend for power variations. There is a reduction of power in higher speeds and increase in power at lower speeds for PB100.

4.2.2. Effect of speed and blending ratio on BSEC at full throttle performance (FTP)

The increase in the brake specific energy consumption (BSEC) for all the biodiesel blends with diesel is seen in Fig. 3b. It is observed from these figures that BSEC increases with blends and decreases with speed. The maximum increase in BSEC (20.21% higher than that of diesel) is observed in case of JB100 at 1200 rpm. The use of KB20, KB50 and KB100 caused an increase in BSEC in the range of 2.68%, 5.84% and 13.31% with respect to diesel at rated rpm (2200), respectively. Similarly, change in BSEC for JB20, JB50, JB100, PB20, PB50 and PB100 are 2.86%, 6.0%, 12.37%, 2.59%, 5.84% and 13.31% at rated speed, respectively. Best BSEC is observed with PB20 fuel. With biodiesel blends having higher proportions of biodiesel, the BSEC tends to increase. This is attributed to lower gross heat values of these blends than that of reference fuel. It can be seen from the Fig. 3b for JB100, there is significant increase in BSEC while minimum increase in BSEC is for PB20. Therefore, It is concluded that PB20 is the optimum fuel blend as compared to all the test fuels as BSEC deterioration is minimum (2.59%) at rated speed of the engine.

4.2.3. Effect of speed and blending ratio on smoke emission at full throttle performance (FTP)

In addition to the change in power and BSEC, smoke percentage in engine exhaust is also analyzed. It is seen from the Fig. 3c that there is a reduction in smoke for all the biodiesel and their blends when compared with diesel. Smoke emission reduces with blends and speeds. The use of KB20, KB50 and KB100 caused a reduction in smoke in the range of 28.96%, 44.15% and 68.83% with respect to diesel at a rated speed of 2200 rev/min, respectively. Similarly, decrease in smoke for JB20, JB50, JB100, PB20, PB50 and PB100 are 28.57%, 40.9%, 64.28%, 29.22%, 44.15% and 69.48% was observed at the rated speed, respectively. It is observed that the minimum reduction in smoke of at least 1.29% for JB20 for lower engine speed (1200–1600 rpm) and 15.84% for higher speeds (1800–2200 rpm). The maximum reduction (above 65%) is seen in case of KB100 and PB100 followed by JB100 (above 60%) for all the ranges of speed.

The improvement of smoke emission in case of KB100, PB100 and JB100 can be explained by the enrichment of oxygen owing to biodiesel. This is reasonable since more fuels are supplied for the higher load and shorter time is available for the preparation of air/fuel mixture at high speeds results in less smoke than diesel. Therefore, the reduction of smoke percentage is due to the excess oxygen atom in the biodiesel helps in complete combustion of fuel.

4.2.4. Effect of BMEP and blending ratio on BSEC at different speeds at part throttle performance (PTP)

The part throttle performance data of biodiesel and their blends with diesel as compared with neat diesel are given in Fig. 4a through Fig. 4c. Fuel economy in terms of gms/BHP-hr with different fuels in part throttle test mode is analyzed. Fuel economy for diesel is 235, 176, 162, 164, 165 and 166 gms/BHP-hr at 1.8, 3.6, 5.4, 6.5, 7.0 and 7.2 bar BMEP, respectively during the rated speed of 2200 rpm. Similarly, BSFC of 220, 169, 159, 158, 159, 160 gms/BHP-hr are observed at 1.8, 3.9, 5.9, 7.1, 7.6, 7.8 bar, respectively at 1800 rpm. When the engine is operated at 1200 rpm, BSFC of 205, 162, 153, 155, 157, 158 gms/BHP-hr resulted at BMEP of 2.1, 4.4, 6.4, 7.8, 8.4, 8.6 bar, respectively.

When percentage change in BSEC is plotted with respect to BMEP, it is observed from the graphs that the BSEC deterioration at the rated speed of 2200 rpm is more pronounced as compared to the BSEC deterioration at lower speeds of 1800 rpm and 1200 rpm. The average fuel economy at rated speed measured with KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50, PB100 are of the order of 181.85, 185.45, 193.03, 181.63, 184.56, 191.28, 180.55, 181.15, 189.97 gms/BHP-hr. It is observed that there is an improvement in fuel economy with JB20, PB20 and PB50 when compared with reference fuel. The brake specific energy consumption improvement is observed with JB20. Biodiesel proportion of more than 20% in the blend tends to decrease BSEC. The energy content of the fuel tends to decrease by increasing biodiesel proportion from B20 to B100. This consequently affects the fuel economy.

4.2.5. Effect of BMEP and blending ratio on smoke at different speeds at part throttle performance (PTP)

Smoke in exhaust at part throttle performance test is also analyzed and interpreted graphically in the Figs. 5(a)–(c). Smoke emissions in terms of Bosch unit for diesel is 0.2, 0.6, 1.6, 2.3, 2.6 and 2.7 at 1.8, 3.6, 5.4, 6.5, 7.0 and 7.2 bar BMEP, respectively during the rated speed of 2200 rpm. Similarly, smoke of 0.1, 0.5, 1.8, 2.4, 2.9, 3.1 Bosch are observed at 1.8, 3.9, 5.9, 7.1, 7.6, 7.8 bar, respectively at 1800 rpm. When the engine is operated at 1200 rpm, smoke of 0.1, 0.8, 1.1, 2.3, 3.1, 3.4 Bosch units resulted at BMEP of 2.1, 4.4, 6.4, 7.8, 8.4, 8.6 bar, respectively. It is seen in these figures that during part throttle test mode, blends with higher percentage of biodiesel in diesel, tend to decrease the exhaust smoke. When percentage change in smoke is plotted with respect to BMEP, it is observed from the graphs that the smoke reduction at rated speed of 2200 rpm is more pronounced as compared to the smoke reduction at lower speeds of 1800 rpm and 1200 rpm. The average smoke emission at rated speed measured with KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50, PB100 are of the order of 1.20, 0.92, 0.45, 0.64, 0.66, 0.40, 1.19, 1.04, 1.32 Bosch, respectively.

It is observed that there is a substantial improvement in smoke emission with KB100, JB100 and PB100 when compared with reference fuel. It is also observed that the exhaust smoke with KB100, JB100 and PB100 fuel is less than 1/9th of that of diesel in part throttle mode. The least level of smoke emission is observed in case of JB100. Biodiesel proportion of more than 20% in the blend tends to decrease smoke emission. Increase of biodiesel proportion from B20 to B100, tends to decrease the smoke emission level.

4.3. Engine emission studies

The new generation vehicle is optimized for meeting EURO II emission norms and therefore the emission test is essential for recommending the best fuel. The engine 8 mode test cycle of ISO 8178 Type C1 is adopted for the engine emission test. The results of the emission levels for CO, NO_x, HC, PM and HC, and NO_x emissions for all the three types of biodiesel and their blends are shown in Fig. 6. The cumulative CO emission for different fuel blends during 8 mode cycle tests is of the order of 1.29, 1.25, 1.21, 1.23, 1.77, 1.49, 1.38, 1.75, 1.32 and 1.12 gm/kWh for diesel, KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50 and PB100, respectively. There is an improvement in CO emission for KB20, KB50, KB100 and PB100 whose value is 2.93%, 5.87%, 5.13% and 12.96% less than

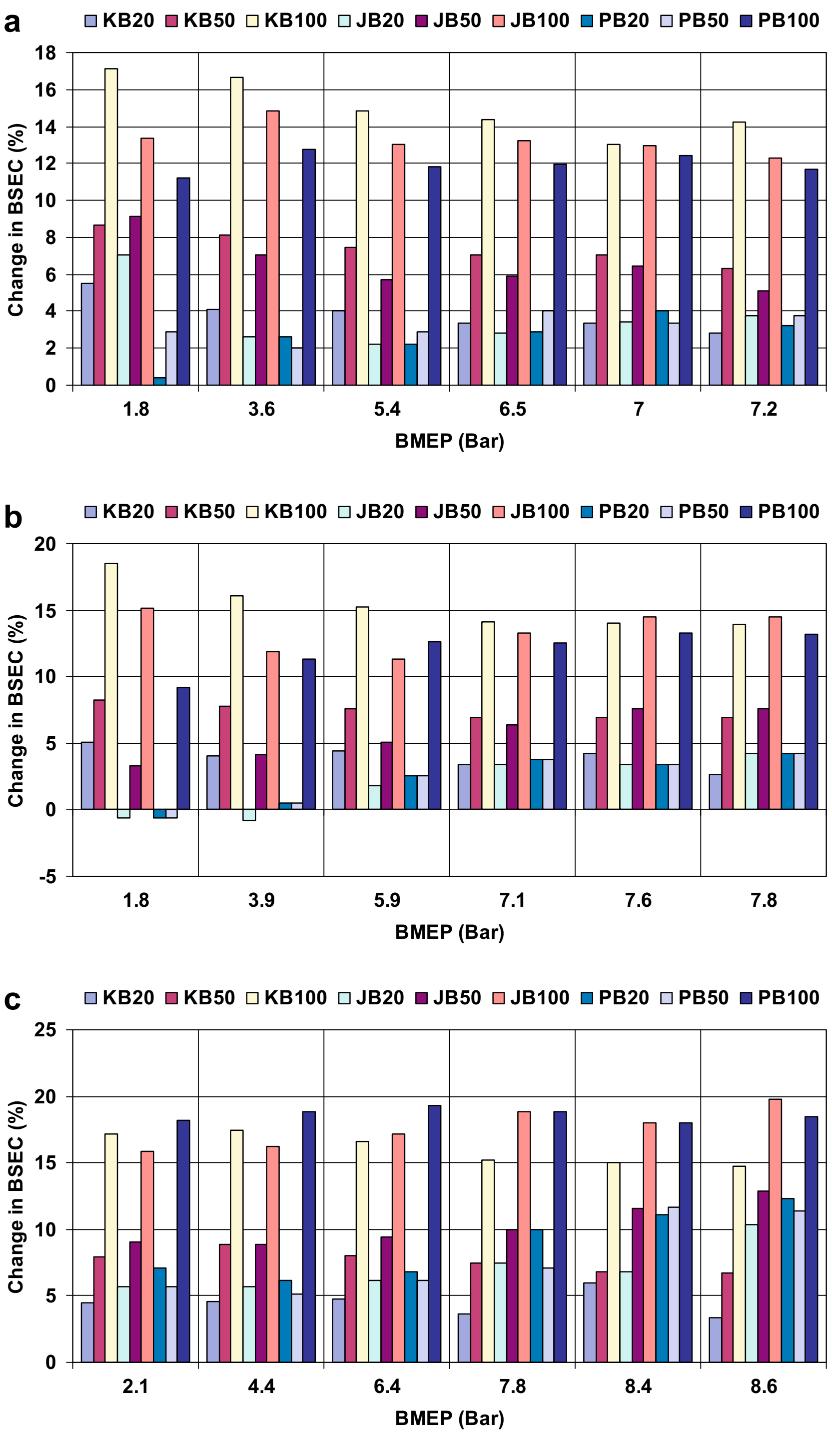

Fig. 4. (a) Change in BSEC (%) with respect to BMEP at 2200 rpm (PTP), (b) change in BSEC (%) with respect to BMEP at 1800 rpm (PTP), (c) change in BSEC (%) with respect to BMEP at 1200 rpm (PTP).

that of diesel during the 8 mode test cycle. Increase in CO emission for JB20, JB50, JB100, PB20 and PB100 is of the order of 35.21%, 14.67%, 5.57%, 34.24% and 2.59% as compared to diesel, respectively. Factors causing combustion deterioration (such as high latent heat of evaporation) could be responsible for the increased CO emission. It is also found from the figure that CO emission increases gradually with blending of higher concentration of biodiesel to diesel. This may be due to increase in viscosity with blending leading to less homogenous mixtures. It is observed from the graph that the emission of CO is least in case of PB100. Therefore, PB100 is the optimum fuel blend for CO emission.

The increase in NO_x emission are the tune of 4.15%, 6.94%, 14.18%, 20.54%, 15.65%, 18.39%, 14.87%, 17.31% and 22.5% for KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50 and PB100, respectively as compared to diesel. The cumulative NO_x emission of different fuel blends during 8 mode cycle tests is of the order of 9.02, 9.37, 9.65, 10.29, 10.87, 10.43, 10.68, 10.42, 10.58 and 11.06 gm/kWh for diesel, KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50 and PB100, respectively. The presence of oxygen molecule in biodiesel causes an increase in combustion gas temperature resulting in a marginal increase in NO_x emissions. At elevated flame temperature, this oxygen reacts with nitrogen and tends to

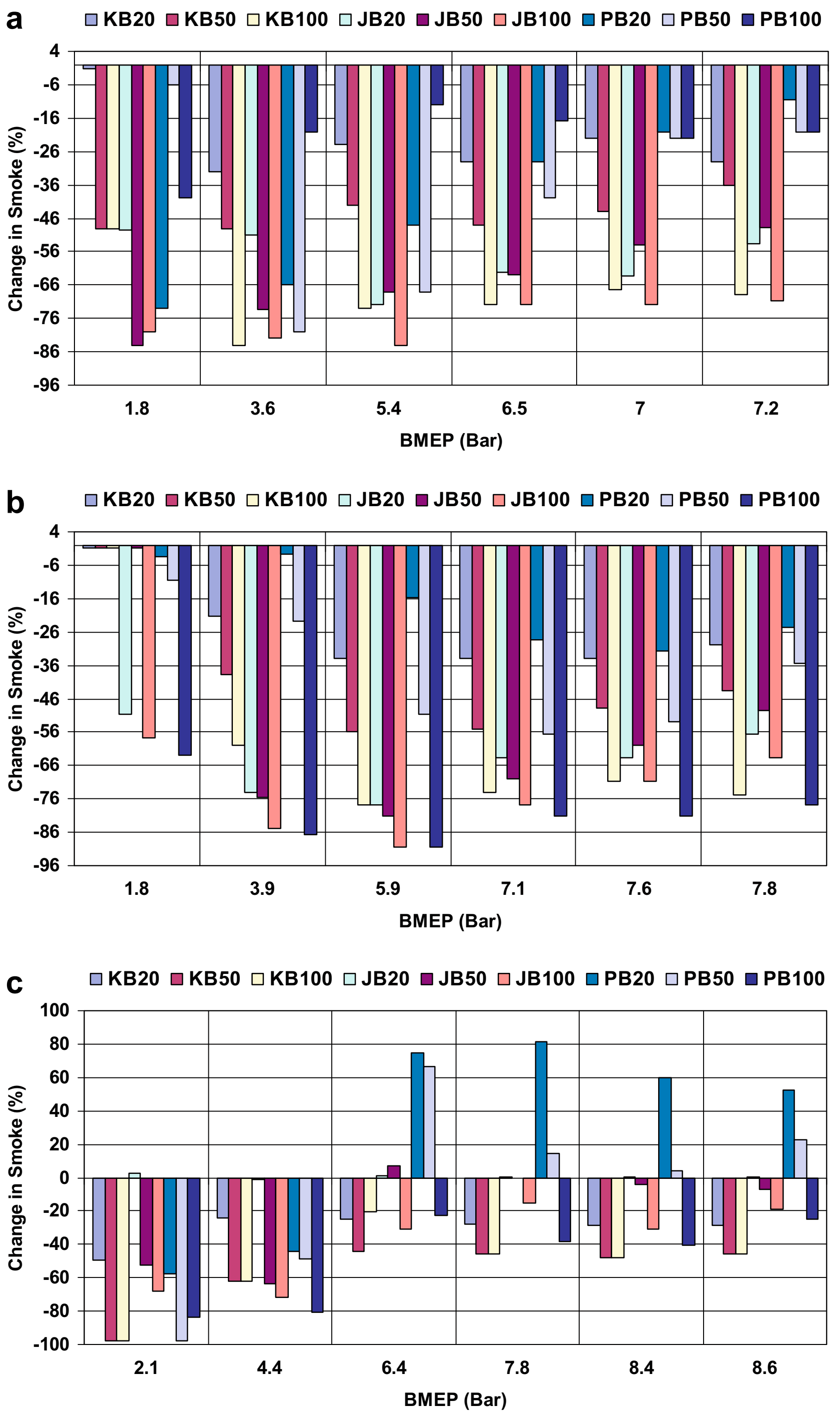

Fig. 5. (a) Change in Smoke (%) with respect to BMEP at 2200 rpm (PTP), (b) change in Smoke (%) with respect to BMEP at 1800 rpm (PTP), (c) change in Smoke (%) with respect to BMEP at 1200 rpm (PTP).

form NO_x. When HC emissions are compared with diesel, a noticeable improvement is observed for all the test fuel blends of biodiesel except PB20. Total HC emission of different fuel blends during 8 mode cycle tests is of the order of 0.43, 0.41, 0.40, 0.33, 0.29, 0.35, 0.33, 0.46, 0.43, and 0.40 gm/kWh for diesel, KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50 and PB100, respectively. The reduction of total HC is of the order of 4.30%, 6.84%, 20.64%, 32.28%, 18.19%, 20.73%, −6.84%, −2.73% and 6.75% for KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50 and PB100, respectively. The best improvement is seen in case of JB20 followed by KB100 and JB100. The reduction in HC is mainly due to the result of improved combustion of biodiesel blends within the combustion period due to the presence of excess oxygen atom in biodiesel.

It is observed from this 8 mode test cycle study that use of biodiesel in diesel engine reduces HC and increases NO_x. But when the combined effect of HC and NO_x (i.e. HC + NOx) is analyzed, the results show an increasing trend for all the biodiesel and their blends with diesel. The increase in the combined effect of HC and NO_x is of the order of 3.81%, 6.65%, 12.71%, 18.0%, 13.69%, 16.48%, 14.67%, 16.48% and 21.03% for KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50 and PB100, respectively. Total HC + NO_x emissions of different fuel blends during 8 mode cycle tests are 9.45, 9.78,

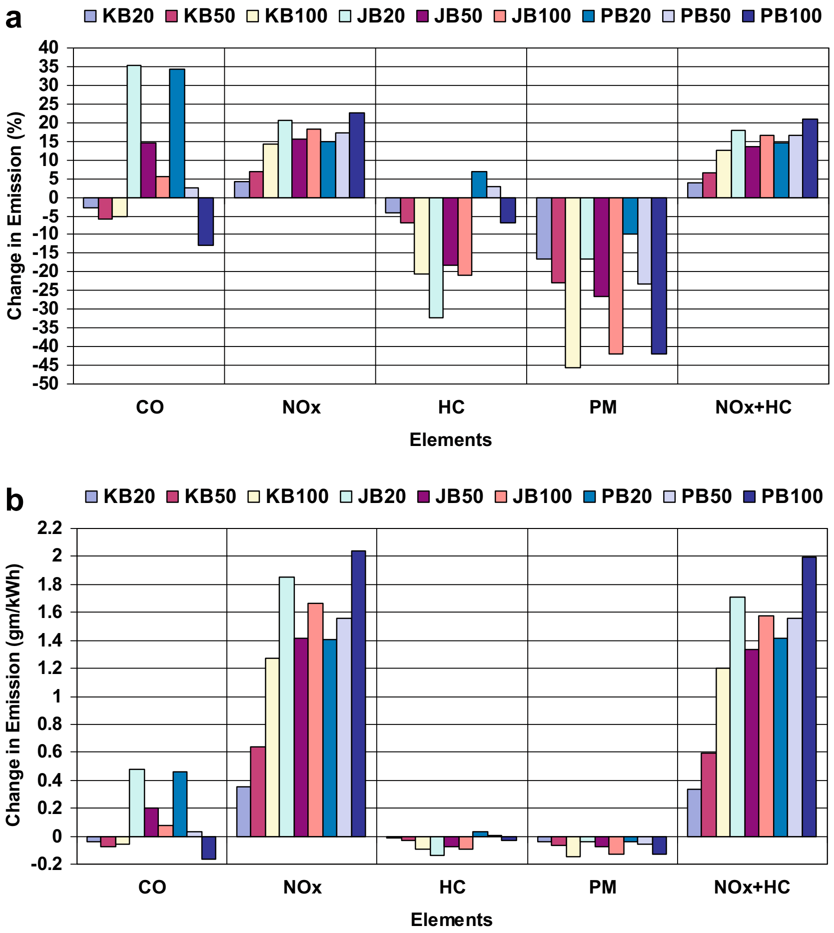

Fig. 6. (a) Change in emission in percentage during 8 mode cycle test, (b) change in mass emissions during 8 mode cycle test.

10.04, 10.65, 11.16, 10.78, 11.02, 10.86, 11.01 and 11.44 gm/kWh for diesel, KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50 and PB100, respectively. It is seen from the figure that HC + NO_x increase with biodiesel addition in diesel. This is due to higher rate of combustion of fuel leading to higher combustion temperature.

The most significant factor is observed during this investigation is that reduction in particulate matter (PM) for all the blends of biodiesel with diesel. The reduction of total PM is of the order of 16.43%, 22.98%, 45.48%, 16.53%, 26.60%, 42.06%, 9.88%, 23.08% and 42.06% for KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50 and PB100, respectively. Total PM emissions of different fuel blends during 8 mode cycle tests is of the tune of 0.30, 0.256, 0.233, 0.155, 0.256, 0.227, 0.169, 0.283, 0.239 and 0.169 gm/kWh for diesel, KB20, KB50, KB100, JB20, JB50, JB100, PB20, PB50 and PB100, respectively. This reduction in particulate matter in case of all the biodiesel test fuels is due to the absence of sulphur, aromatic and presence of oxygen which plays a vital role for complete combustion of fuel.

In summary, the use of biodiesel results in reduction in hydro carbon (HC) and particulate matter (PM) as seen with biodiesel and their blends. However, there is a slight increase in carbon monoxide (CO), oxides of nitrogen (NO_x) and combine HC and NO_x.

5. Conclusion

The fuel properties of biodiesel and their blends in comparison with that of diesel are comparable to those of diesel. The present results obtained show that, the transesterification process improved the fuel properties of the oil with respect to density (kg/m^3), calorific value (kJ/kg), viscosity (cSt), flash point (°C), cloud point (°C) and pour point (°C). The comparison of these properties with diesel shows that the methyl esters of jatropha, karanja and polanga oil have relatively closer fuel property values to that of diesel. Hence, no hardware modifications are required for handling these fuels (biodiesel and their blends) in the existing engine. The addition of biodiesel to diesel fuel changes the physico-chemical properties of the blends. With the increase of biodiesel concentration in diesel–biodiesel blends density, kinematic viscosity, cetane number, high heat value, flash and fire point of the blends increase.

During full throttle engine performance test, significant change in power is not observed for the three cylinder tractor engine at lower speeds of 1200 and 1400 rpm for all the biodiesel blends. However, slight reduction in power is observed at all the speeds with biodiesel blends of KB20, KB100, JB100, PB20 and PB100. The maximum increase in power is observed for JB50 at 2000 and 2100 rpm. Brake specific fuel consumptions for all the biodiesel blends with diesel increases with blends and decreases with speed. There is a reduction in smoke for all the biodiesel and their blends when compared with diesel. Smoke emission reduces with blends and speeds during full throttle performance test.

During part throttle performance test, it is observed that there is an improvement in fuel economy with JB20, PB20 and PB50 when compared with reference fuel. The best brake specific fuel consumption improvement is observed with JB20. Biodiesel proportion of more than 20% in the blend tends to decrease BSFC. It is seen that during part throttle test mode, blends with higher percentage of biodiesel in diesel, tends to decrease the exhaust smoke substantially. Noticeable reduction in hydro carbon (HC) and particulate matter (PM) is seen with biodiesel and their blends. However, there is a slight increase in carbon monoxide (CO), oxides of nitrogen (NO_x) and combine HC and NO_x.

References

[1] Sahoo PK, Naik SN, Das LM. Studies on biodiesel production technology from *Jatropha curcas* and its performance in a CI engine. J Agri Eng, Indian Soc Agri Eng (ISAE) 2005;42(2):18–24.

[2] Agarwal AK, Das LM. Biodiesel development and characterization for use as a fuel in compression ignition engines. Am Soc Mech Engrs J Eng, Gas Turb Power 2000;123:440–7.

[3] Peterson CL, Reece DL, Hammond DL, Cruz R, Thompson J. A comparison of ethyl and methyl esters of vegetable oils as diesel fuel substitute. In: Proceedings of alternate energy conference, ASAE; 1992. p. 99–110.

[4] Masjuki HH, Kalam MA, Maleque MA, Kubo A, Nonaka T. Performance, emissions and wear characteristics of an indirect injection diesel engine using coconut oil blended fuel. Proc Instn Mech Engrs 2000;215(Part D):393–404.

[5] Ramadhas AS, Muraleedharan C, Jayaraj S. Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. Renew Energ 2005;20:1–12.

[6] Wagner LE, Clark SJ, Scrock MD. Effects of soybean oil esters on the performance, lubricating oil and wear of diesel engines. Paper No. 841385, SAE; 1984.

[7] Ghadge SV, Raheman H. Biodiesel production from mahua (*Madhumica indica*) oil having high free fatty acids. Biomass Bioenerg 2005;28:601–5.

[8] Barsic NJ, Humke AL. Performance and emissions characteristics of a naturally aspirated diesel engine with vegetable oil fuels. Paper No. 810262, SAE; 1981.

[9] Sahoo PK, Naik SN, Babu MKG, Das LM. Biodiesel development from high acid value polanga seed oil and performance in a CI Engine. Fuel 2007;86(3):448–54.