FUEL PROPERTIES OF JATROPHA METHYL ESTER AND ITS BLENDS WITH PETROLEUM DIESEL

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ABSTRACT

Jatropha curcas has drawn the attention of researchers in recent times as a high potential substrate for production of biodiesel. However, like many other substrates, fuel properties of its biodiesel vary with such factors as growing and climatic conditions. This paper presents experimental results for jatropha methyl ester of Botswana's semi-arid climatic conditions. Physicochemical properties, performance and emissions characteristics of jatropha methyl ester and its blends with petroleum diesel were investigated experimentally. The results showed that viscosity values for all fuels fall within specifications of American Standard Test Methods (ASTM), with a maximum variation of 21% observed between B0 and B100. Cold flow properties of cloud and pour points indicate that jatropha methyl ester and its blends can power the diesel engine without much difficulty in cold weather. The flash points of jatropha methyl ester and its blends were found to be lower than the ASTM specification of a minimum of 130°C, implying that the fuels are highly flammable and need extreme handling precaution during transportation. Biofuels depicted better engine performance when compared to petroleum diesel in terms of brake power, specific fuel consumption (SFC) and brake thermal efficiency (BTE). This is largely attributed to higher combustion efficiency due to extra inbound oxygen. Higher combustion efficiency of biofuels led to reduced production of hydrocarbons (HC), carbon monoxide (CO) and carbon dioxide (CO_2) emissions when compared with petroleum diesel. Petroleum diesel was also observed to produce the highest proportion of soot during combustion in the magnitude of approximately 3% per 3ml of fuel.

Keywords: Jatropha, fuel properties, blends, performance, emissions.

1. INTRODUCTION

The depletion of known petroleum reserves and the impact of emissions of petroleum diesel on the environment have invigorated research on alternative automotive fuels. Since the last few decades, researchers world over have been trying to find new alternative fuels that are available, technically feasible, economically viable and environmentally acceptable (Liaquat *et al.*, 2010). Biodiesel as an alternative fuel is one of the best alternatives among other sources due to its high potential to reduce levels of emissions such as HC, CO and smoke when used in engines, in addition to being renewable and biodegradable (Raheman *et al.*, 2004; Lee *et al.*, 2004). Carbon dioxide, the greenhouse gas that causes global warming, has been reported to be reduced by using biodiesel in diesel engines (Gumus *et al.*, 2010). The presence of oxygen molecules within the biofuels such as alcohol, vegetable oils, biomass or biogas promotes better oxidation and combustion (Agarwal, 2007; Math *et al.*, 2010).

Jatropha curcas plant grows on well-drained soils with good aeration and well adapted to marginal soil with low nutrient content (Atabani et al., 2013). The seed of jatropha is oval in shape, black in color, produces oil that is golden yellow and has high oil content (66%) (Rao, 2011). Investigations have been carried out by several researchers regarding engine performance, emission and combustion characteristics of diesel engine using biodiesel from edible oil source. Hasimoglu *et al*. (2008) studied the performance characteristics of a low heat rejection diesel engine at full load and different speeds using biodiesel from sunflower oil. They found a significant improvement in the SFC and BTE of the engine when biodiesel fuel (B100) was used. Combustion and emission characteristics of soybean oil methyl ester and diesel were studied by Canakci (2007). The author reported that the soybean oil biodiesel significantly reduced the unburnt HC, CO and particulate matter (PM). Nitrous oxides (NO_x) however increased by 11.2% compared to diesel fuel. Sahoo and Das (2009) compared combustion characteristics of biodiesel derived from jatropha, karanja and polanga in a small 6 kW air-cooled, single cylinder, four stroke diesel engine at different load conditions. The authors reported that pure polanga biodiesel was the optimal fuel blend as far as the peak cylinder pressure is concerned. They also reported that the ignition delay for pure jatropha biodiesel was shorter than for diesel fuel, varying between 5.9° and 4.2° crank angles. For pure karanja biodiesel, the ignition delay varied between 6.3° and 4.5° crank angles, and between 5.7° and 4.2° for pure polanga biodiesel. All these ignition delay periods were shorter than that of petroleum diesel. Chauhan *et al*. (2012) studied the performance and emission characteristics of Jatropha biodiesel and its blend in a single cylinder engine. They found that the performance of the engine is comparable to that using petroleum diesel. They also reported that Jatropha biodiesel and its blend emitted lower exhaust emissions except NO_x which compare to diesel fuel. This paper reports the effect of blending jatropha biodiesel with petroleum diesel on fuel properties. The fuel properties investigated are physico-chemical properties, performance and emissions characteristics of blended fuelled engine.

2. EXPERIMENTAL PROCEDURE

Jatropha seeds used in this study were harvested in Mmadinare village in Botswana. The village is located approximately 360 km north of Gaborone city. Seeds were extracted from dry and mature fruits. Oil extraction was performed using mechanical extraction device and the procedure for extraction is outlined in Gandure and Ketlogetswe (2013).

2.1. Biodiesel preparation

Jatropha biodiesel was produced through an alkali catalyzed transesterification process in the laboratory under strict observation and controlled conditions. Alkaline transesterification was preferred since the oil sample had free fatty acid content below 2% (Tesfa et al., 2010). One litre of crude jatropha oil was filtered and pre-heated to approximately 105°C to eliminate water. The oil was allowed to cool to approximately 58°C and then charged to a two litre transparent reaction vessel. A solution of methanol of 99.5% purity and 7.5g of potassium hydroxide pellets of 98% purity as catalyst was prepared and charged to the reaction vessel. The molar ratio of methanol to oil was fixed at 1:6, which is the optimal ratio for the transesterification of vegetable oils (Knothe *et al.*, 2005). The reaction vessel was tightly closed and contents agitated using a mechanical shaker for one hour. The reaction vessel was then set up-side down and allowed to cool for a further 3 hours. Two distinct layers were observed, the upper layer being the methyl ester (biodiesel) and the lower layer was glycerol (due to its higher specific gravity). Glycerol was drained off from the bottom of the reaction vessel until only biodiesel (and possibly traces of unreacted methanol) remained. The biodiesel was then washed twice with distilled water at room temperature to ensure removal of all traces of glycerol. The quantity of water used was approximately equal to the amount of biodiesel. A rotary vacuum evaporator was used to recover the unreacted alcohol from the biodiesel.

The petroleum diesel used for blending was purchased from a local Shell Petrol Station and had properties including density of 831 kg/m^3, viscosity of 2.3 mm^2/s at 40°C, acidity of 0.2 mgKOH/g, calorific value of 46.5 MJ/kg, flash point of 79°C, cloud point of 2°C and pour point of -12°C. Blended fuel samples were prepared by mixing jatropha methyl-ester with petroleum diesel, at 10 - 100%, with 10% increment by volume.

2.2. Viscosity analysis

Jatropha biodiesel and its blends with petroleum diesel were analyzed using a Fungilab Premium Series (PREL 401024) viscometer coupled to a Thermo Fisher Scientific heating bath circulator. The heating bath circulator was three-quarter (¾) filled with distilled water. 3ml of fuel samples were weighed in order to determine their densities. The viscometer was set-up with the appropriate spindle and heating jacket. The Low Centi Poise (LCP) spindle was selected for these experiments since low viscosity fluids were analyzed. The spindle was connected and the machine calibrated with the density of the fuel sample to be tested and the appropriate speed for the spindle. After appropriately assembling the apparatus, the sample to be tested was charged in such a way that the spindle was completely immersed. The instrument was then run, with the heating bath set to 95°C. The spindle speed (rpm) could be varied based on the torque values, with the ideal range being 60-95%. Sample viscosity readings were then recorded at temperature intervals of 5°C from room temperature to 60°C as hot water was circulating between the heating bath and the heating jacket of the viscometer. The Data logger application software was used to download the experiment data from the viscometer to a personal computer for storage and analysis.

2.3. Flash point measurement

The flash points of jatropha biodiesel and blends with petroleum diesel were determined using an automated Pensky-Martens Closed Cup Tester, APM-7 model, according to the ASTM D93 test method. A brass test cup (of specified dimensions) was filled to the inside mark with fuel test specimen and fitted with a cover (of specified dimensions). Settings of expected flash point value, sample name and procedure selection were made for each test to complete the instrument setup. Procedure A was used for petroleum diesel and biodiesel blends while procedure C was used for 100% biodiesel (B100). Each procedure has two modes, the search (special) mode used for novel specimens whose flash point ranges are unknown, and the normal mode used for specimens whose flash point ranges are known. The experiment was run and the test cup heated while the specimen was agitated by a stirrer at a pre-determined rate according to the specified procedure. An ignition source was directed into the test cup at regular intervals with simultaneous interruption of the stirring, until a flash was detected. Each test sample was first analyzed using the search procedure since flash points of the samples were unknown. The normal mode of the procedure was then used to validate the results.

2.4. Cloud and pour point analyses

The cloud and pour points of the fuels were tested using the Normalab cloud and pour point tester, NTE 450 model. The instrument is coupled to a cooling bath which uses methanol as the cooling medium. Cold methanol is pumped and circulated between the cooling bath and the instrument to lower the temperature of the test specimen to its cloud and pour points. The cooling bath was allowed to cool to a temperature of -60°C before specimen testing could commence. The coupled instrument is intended for the treatment of samples according to ASTM D97 and D2500, IP15 and IP215, ISO3015 and ISO3016 standards. For all the fuel samples, the test specimen (fuel sample) was charged into the sample test tube in an amount that filled to a specified mark, which in turn was mounted onto the motorised measurement head. After settings were made which included sample name, start temperatures for testing cloud and pour points, and minimum temperature (set to -60°C), the instrument was run to commence the test. The total test times ranged between 1 hour 15 minutes and 1 hour 40 minutes for jatropha biodiesel and blends with petroleum diesel.

2.5. Acid value determination

Acid value measurements of fuel sample extracts were carried out by titration technique according to ASTM D664 standard test method (Mac Farne, 2010). Based on the same standard 125 ml of solvent, consisting of 50% isopropyl alcohol and 50% toluene was prepared in a 600 ml beaker. A sample weighing 5g was then added to the beaker, followed by 2 ml of phenolphthalein indicator. The solution was titrated with 0.1M KOH to the first permanent pink colour. Three titrations were carried out for each of the two fuel sample extracts and the average titration values determined. The acid values were determined using equation (1) and percentage of free fatty acids using equation (2).

$$\text{Acid value, AV} = \frac{56.1 \times N}{W} \times \textit{Average Titration Value} \quad (1)$$

Where

56.1 = molecular weight of KOH
N = molarity of the base
W = weight of sample in grams

$$\text{Free Fatty Acids (\%)} = 0.5 \times AV \quad (2)$$

2.6. Energy content

The calorific values of jatropha biodiesel and its blends with petroleum diesel were determined using the IKA C200 Calorimeter system whose main components include the basic device, decomposition vessel, ignition adapter, combustion crucible and oxygen filling point. The system has automatic data acquisition through the CalWin calorimeter software which handles calculations for the calorific values of samples.

2.6.1. Calorimeter conditions

To determine the heating (calorific) values of the fuel samples, 3ml of sample extract were weighed and placed in a combustion crucible at a temperature of approximately 22°C. The crucible was then closed up inside a decomposition vessel, which in turn was filled with oxygen at a pressure of 30 bars for 30 seconds to ensure adequate oxygen for the combustion process. The cooling water in the tank fillers was kept at an initial temperature of within 18°C to 24°C range. The oxygen-filled decomposition vessel was inserted into the measuring cell that is equipped with a magnetic stirrer. The cell cover was then closed for the test to commence. Total run time for each experiment was about 8.2 minutes.

2.7. Engine performance analysis

Engine performance tests while fuelled by jatropha methyl ester and its blends with petroleum diesel were conducted on a TD43F engine test rig. The test rig is water cooled four-stroke diesel engine that is directly coupled to an electrical dynamometer. The dynamometer was used for engine loading. In addition to the conventional engine design, the engine incorporates variable compression design feature which allows the compression ratio to be varied from 5:1 to 18:1. The layout of the experimental setup is shown in Figure-1 while engine specifications are presented in Table-1.

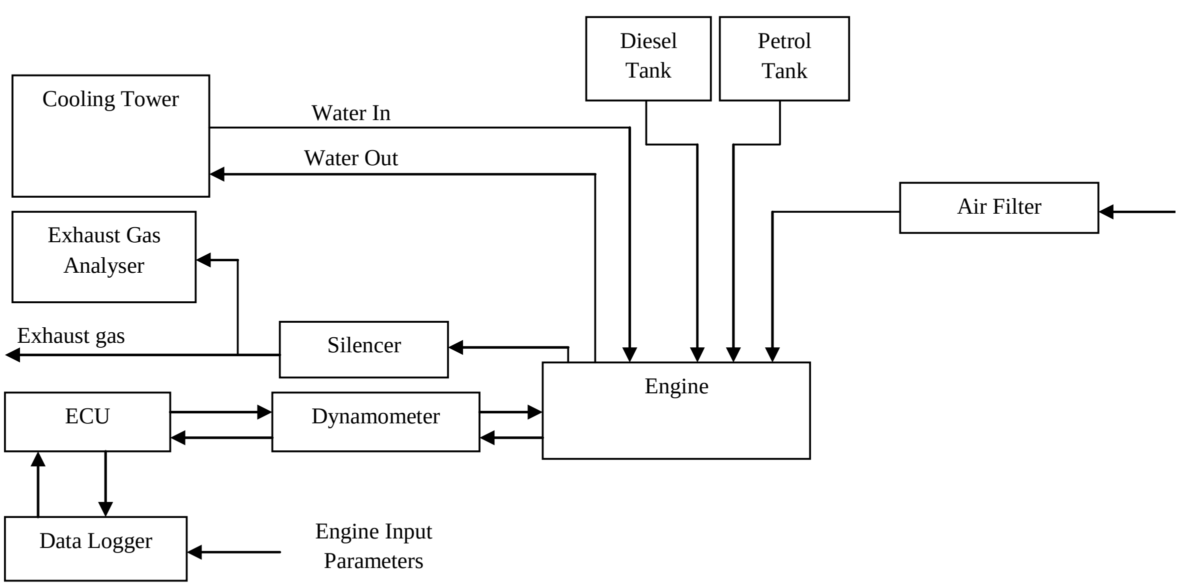

Figure-1. Schematic arrangement of the experimental setup.

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Table-1. Engine specifications.

Parameter	Specification
Make	Farymann
Type	A30
Compression ratio	Variable 5:1 to 11:1 (Petrol), 12:1 to 18:1 (Diesel)
Number of cylinders	1
Cylinder bore	95 mm
Stroke	82 mm
Swept volume	582 cc
Speed range	1000 to 2500 rpm (2750rpm over-speed cut-out)
Max Power	9.5kW
Max torque	45Nm
Ignition timing	30^o BTDC to 10^o ATDC
Choke sizes	19, 21, 23, 25mm
Dynamometer d.c motor	5-7kW 2500 rpm with thermostat

Source: (Tec Quipment, 2012).

To establish that engine operating conditions were reproduced consistently as any deviation could exert an overriding influence on performance and emissions results, the reproducibility of the dynamometer speed control set points were maintained within ± 0.067 Hz of the desired engine speed. Prior to the data recording, the compression ratio was set to the desired level and the engine speed was set to a maximum of 2500 rpm at full throttle. The engine was allowed to run on petroleum diesel fuel under steady state operating conditions, as opposed to transient conditions characterized by the stop-go type of pattern, for approximately 30 minutes to reach fully warm conditions. This ensures best engine efficiency and effective burning of effects of the warm up cycle and to clear out any moisture from the system and exhaust. This also established the engine's operating parameters which constitute the baseline that was compared with the subsequent case when the engine was fuelled by jatropha biodiesel and its blends with petroleum diesel. After the engine operating temperature had stabilized, the first sets of readings for brake power, engine torque and specific fuel consumption at the maximum speed of 2500 rpm were recorded. The dynamometer load was then increased by adjusting the load current control mechanism until the engine speed reduced by steps of 250 rpm to a minimum value of 1000 rpm. For each step, the data for brake power, engine torque and specific fuel consumption were automatically captured onto a personal computer (PC) using the data acquisition software provided by the engine manufacturer. All measurements were repeated three times for each test setting, while the test sequences were repeated three times.

2.8. Emissions measurement

Emissions measurement was carried out using an Exhaust Gas Analyzer that works on exhaust gas analyzer system software and the Driveability and Emissions Calculation Software (DECS). At the commencement of engine performance analysis described in Section 2.7, the Exhaust Gas Analyzer was powered, allowed to warm-up for 10 minutes, and to zero (setting all the gases to zero). The sample hose was then connected, with the probe placed in the tail (exhaust) pipe. Readings were taken at intervals of 250 rpm of engine speed after conditions had stabilized at each speed. The technology of this analyzer allows for auto calibration before every analysis and a high degree of accuracy in the analysis of low concentrations of gases found in the engine. The DECS software was used for calculating and analyzing other emissions related engine performance characteristics. For purposes of repeatability, the emission analyzer accuracy and measuring range are shown in Table-2.

Table-2. Emissions analyzer accuracy and measuring range.

Parameter	Accuracy	Range
Hydrocarbons (HC)	4.00 ppm	0-24 000 ppm
Carbon monoxide (CO)	0.06%	0-10%
Carbon dioxide (CO_2)	0.30%	0 - 20%
Oxygen (O_2)	0.10%	0 - 25%
Nitrogen oxides (NO_X)	1.00 ppm	0 - 5 000ppm

Source: (Ems, 2012)

3. RESULTS AND DISCUSSIONS

3.1. Physico-chemical properties

The fuel properties of jatropha biodiesel and its blends with petroleum diesel are presented in Table-3 while Table-4 presents regression models for the fuel properties.

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Table-3. Fuel properties of jatropha biodiesel and its blends with petroleum diesel.

Property	Blends										
	B0	B10	B20	B30	B40	B50	B60	B70	B80	B90	B100
Viscosity (40^{o}C, mm^2/s)	2.73	3.00	3.02	3.27	3.34	3.37	3.41	3.37	3.25	3.44	3.47
Cloud point (^{o}C)	2	2	2	2	0	0	-1	-1	-1	-1	-2
Pour point (^{o}C)	-12	-5	-5	-5	-4	-4	-4	-1	-1	-1	- 2
Flash point (^{o}C)	79	89	89	87	87	103	91	87	89	91	105
Heating value (MJ/kg)	46.5	46.4	45.4	45.3	44.7	43.9	43.6	42.9	42.5	42.4	42.1
Free fatty acids (%)	0.14	0.28	0.22	0.36	0.22	0.31	0.28	0.28	0.31	0.20	0.13

Table-4. Regression models for fuel properties.

Property	Regression model	R^2
Viscosity (40^{o}C, mm^2/s)	$y = -9 \exp(-05x^6) + 0.003x^5 - 0.045x^4 + 0.301x^3 - 1.023x^2 + 1.7865x + 1.711$	0.9683
Cloud point (^{o}C)	$y = 0.0002x^6 - 0.010x^5 + 0.148x^4 - 1.049x^3 + 3.439x^2 - 4.882x + 4.346$	0.9703
Pour point (^{o}C)	$y = -0.0005x^6 + 0.019x^5 - 0.334x^4 + 2.962x^3 - 13.802x^2 + 31.627x - 32.382$	0.9699
Flash point (^{o}C)	$y = -0.0058x^6 + 0.222x^5 - 3.275x^4 + 23.476x^3 - 84.646x^2 + 143.65x - 0.636$	0.7992
Heating value (MJ/kg)	$y = -0.0002x^6 + 0.007x^5 - 0.100x^4 + 0.680x^3 - 2.362x^2 + 3.373x + 44.924$	0.9931
Free fatty acids (%)	$y = 8 \exp(-06x^6) - 0.0003x^5 + 0.003x^4 - 0.005x^3 - 0.045x^2 + 0.250x - 0.056$	0.6807

3.1.1. Viscosity

The results presented in Table-3 largely indicate that viscosity increased with increase in the blend of jatropha biodiesel from B10 to B100. It was observed that the viscosities were within the limits specified by ASTM D445 which ranges from 1.9 - 6.0 mm^2/s. This implies that biodiesel blending enhanced fluidity of the fuel for the diesel engine and that good spray pattern would generate across the combustion chamber, allowing for proper mixing with air. A similar trend was observed by Rao *et al*. (2008) and Prasad *et al*. (2009) for blends of jatropha methyl ester with diesel and blends of castor oil with diesel respectively, whose viscosity increased as the percentage of biofuel increased in the blends. The optimal correlation developed for viscosity of jatropha methyl ester blends with petroleum diesel was a polynomial relationship of order 6. The regression model yielded an R^2 of 0.97. This can be used to predict the viscosities of biofuels at any blend percentage with petroleum diesel.

3.1.2. Cloud, pour and flash points

Cloud point decreases with increase in percentage of jatropha methyl ester in the blend, while pour point increases with increase in jatropha methyl ester in the blend. The cloud and pour points of the methyl ester blends may not be low enough to be usable in diesel engines in extremely cold weather. The flash points of jatropha methyl ester and its blends are lower than the ASTM D93 specification of a minimum of 130^{o}C, and may not ensure storage and transportation that is completely safe from fire hazards. Blending with other methyl esters is one way to improve the flash point. The regression models of both cloud and pour points of jatropha methyl ester and blends that yielded optimal correlations were polynomial relationships of order 6 with R^2 values of approximately 0.97 for both properties. These correlations can be used to predict the cloud and pour points of the biofuels at any blend percentage with petroleum diesel. The R^2 value obtained for the regression model of flash point of jatropha methyl ester at various blends with petroleum diesel is 0.80, which is relatively low and can be used to some extent to predict flash point at any blend percentage.

3.1.3. Heating value

The heating values of jatropha methyl ester blends decreased from 46.4 to 42.1MJ/kg from B10 to B100. These values were however lower than the value of 46.5 MJ/kg obtained from the reference petroleum diesel (B0). The heating values of jatropha methyl ester blends decreased as the percentage of jatropha methyl ester increased in the blends. This was because the carbon content of the biodiesel blends decreased with increase in percentage of the methyl ester in the blends. The optimal correlation developed for heating values of jatropha methyl ester and its blends was again a polynomial relationship of order 6 as shown in Table-4. The regression model for the heating value yielded the strongest correlation with R^2 value of 0.99.

3.1.4 Free fatty acid

The free fatty acid of jatropha methyl ester (B100) was lower than that of the reference petroleum diesel (0.14 %). A polynomial relationship of order 6 was obtained as optimal for the regression model of free fatty acid of jatropha methyl ester at various blends with petroleum diesel. The regression model gave a correlation coefficient, R^2 value, of 0.68. This implies that the correlation can be used to some extent to predict the free fatty acid of the biofuels at any blend percentage with petroleum diesel.

3.2. Performance characteristics

The engine performance indicators considered were brake power, specific fuel consumption (SFC) and brake thermal efficiency (BTE). Figure-2(a) shows the engine brake power plots for various biodiesel fuel blends at engine load points varying from 30% to 90%. Brake power is the useful power available at the crank shaft of the engine and its magnitude is dependent on the nature of the fuel. Despite petroleum diesel having a marginally higher heating value than jatropha methyl ester and its blends, with a maximum difference of 9.5%, jatropha methyl ester and its blends produced relatively high brake power than petroleum diesel across all load points. This can be attributed to more efficient combustion due to in-bound oxygen in the biodiesel. However for all the fuels, brake power decreased with increase in engine load.

The specific fuel consumption is a measure of volumetric fuel consumption for any particulate fuel. In this work, petroleum diesel fuel had the highest specific fuel consumption throughout the load settings and B20 had the lowest. The maximum variation between these two fuels was 49% at 90% engine load, and the minimum was 40% at 50% engine load. Since energy content and viscosity are marginally different between petroleum diesel and jatropha methyl ester and its blends, the trend shown in Figure-2(b) may be due to efficient combustion of the methyl ester and its blends as a result of the in-bound oxygen. Figure-2(c) shows variation in thermal efficiency for the fuels with increase in engine load. It was observed that for all the loads, petroleum diesel fuel showed the lowest thermal efficiency when compared with blends. B20 showed the highest thermal efficiency, with a maximum value of 60.3% at 30% engine load and a minimum value of 20.6% at 90% engine load. Generally, brake thermal efficiency decreases with increase in engine load for all fuels.

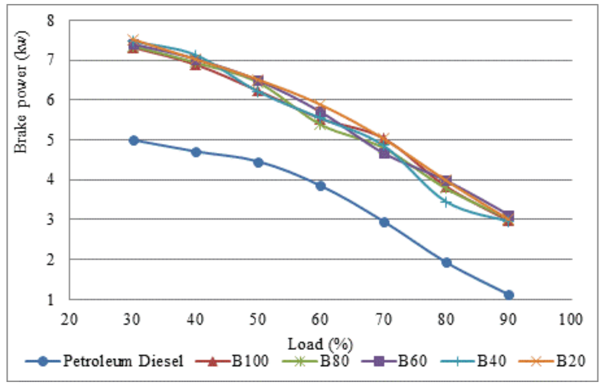

Figure-2(a). Variation of brake power with engine load for fuel blends.

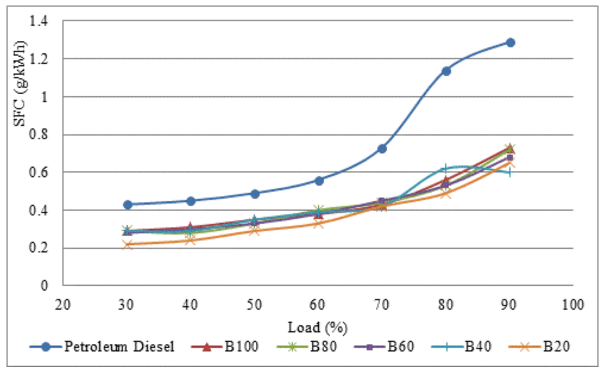

Figure-2(b). Variation of SFC with engine load for fuel blends.

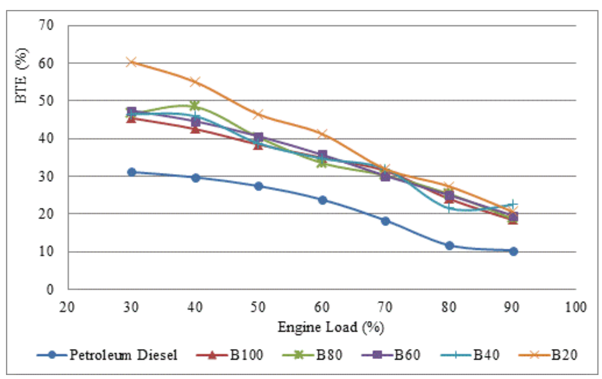

Figure-2(c). Variation of BTE with engine load for fuel blends.

Figure-2. Performance measures.

3.3. Emissions

The emissions presented in this work are unburnt hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2) and soot. Oxides of nitrogen (NO_x) are not presented in this work because they needed verification with a different instrument. Figure-3(a) shows that HC emissions of jatropha methyl ester and its blends are much lower than those of petroleum diesel. The HC emissions of jatropha methyl ester and its blends are closely comparable to each other but distinctly different

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from those of petroleum diesel. This reduction in HC emission could be attributed to the contribution of oxygen from the biodiesel that enables more complete combustion. A maximum HC emission reduction of 95% was observed for B40 blend at 90% engine load when compared with petroleum diesel. The high HC emissions for petroleum diesel which increase with increase in load is attributed to lower fuel to air equivalence ratio, while the presence of extra oxygen atoms in biofuels further lowers HC emissions. This is because at high load conditions, the fuel to air equivalence ratio approaches 1, so the excess oxygen of the biodiesel and its blends is favourable for achieving a more complete combustion through superior evaporation rate and atomization of the methyl ester and blends, and subsequent mixing of fuel with air. The viscosity of jatropha methyl ester and its blends were found to be closely comparable to that of petroleum diesel; hence this could not counteract the effect of oxygen enrichment in the biofuels.

Figure-3(b) describes CO emission pattern of jatropha methyl ester, its blends and petroleum diesel under various engine loading conditions. CO emissions are observed to increase with increase in engine load for petroleum diesel, but do not seem to be affected much by increase in load on the part of biofuels. The reduction of CO emission for the methyl ester and its blends is due to more complete combustion governed by abundance of oxygen from the blend fuel which promotes the oxidation of CO to CO_2. Furthermore, the reduction in CO emission could be supported by improved fuel properties (Table-3) such as low viscosity and improved cold flow properties which clearly emphasize the promotion in combustion process and subsequent oxidation of CO to CO_2.

Figure-3(c) shows variation of CO_2 emission of jatropha methyl ester, its blends and petroleum diesel under various engine loading conditions. While CO_2 is non-toxic, its main environmental effect is as a greenhouse gas. By enhancing the greenhouse effect, greenhouse gas emissions are leading to increases of the earth's atmospheric, land and sea temperatures. It is therefore imperative to ensure that engine fuel technologies seek to minimise such emissions to mitigate climate change. Figure-3(c) indicates that CO_2 emissions from the combustion of jatropha methyl ester and its blends are much lower than those produced from combustion of petroleum diesel, which is desirable. The level of oxygen emission is simply an indication of whether or not the engine was starved of oxygen for combustion during the power stroke. A higher proportion of O_2 emissions indicate that the engine had surplus oxygen for combustion, and a low proportion indicates a near oxygen starvation which impacts combustion efficiency. Figure-3 (d) indicates a higher oxygen depletion rate with petroleum diesel than with jatropha methyl ester and its blends.

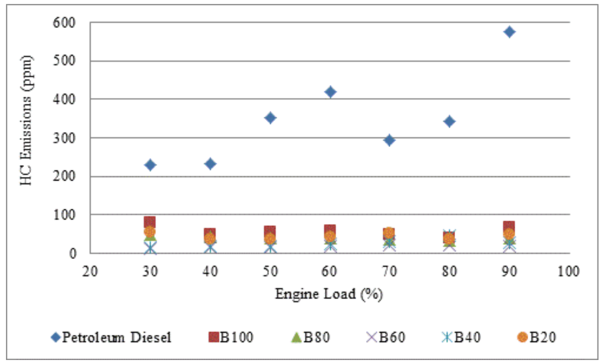

Figure-3(a). Variation of HC emissions with engine load.

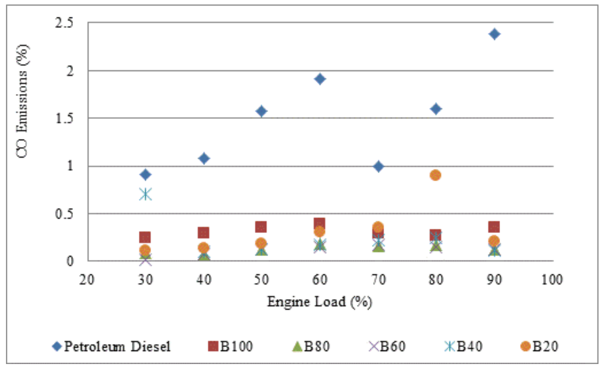

Figure-3(b). Variation of CO emissions with engine load.

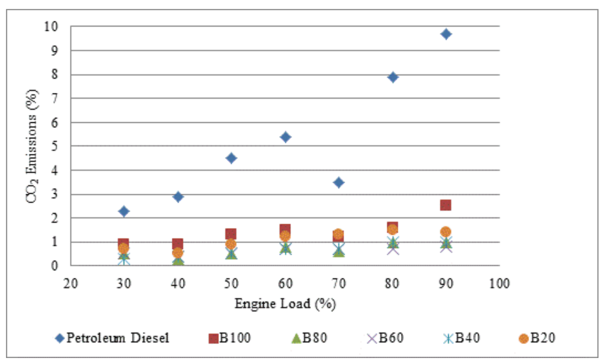

Figure-3(c). Variation of CO_2 emissions with engine load.

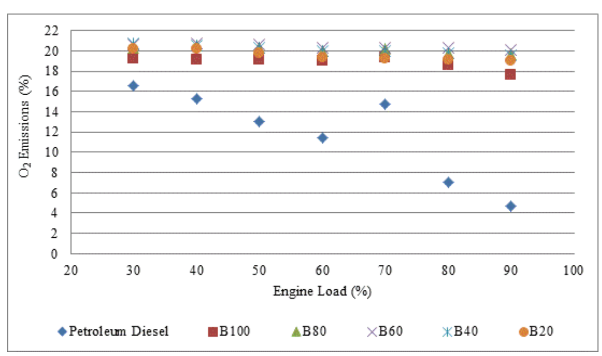

Figure-3(d). Variation of O_2 emissions with engine load
Figure-3. Emissions characteristics.

3.4. Soot production

In addition to emission characteristics discussed in Section 3.3, it was also observed that the combustion of petroleum diesel fuel produced smoke with higher opacity than that from combustion of jatropha methyl ester and most blends. This was validated by measurements of soot produced during combustion of the two fuels in a bomb calorimeter where calorific values of the two fuels were measured. The crucible that was used during the combustion processes was weighed before and after each test run, and the amount of soot produced is presented in Figure-4.

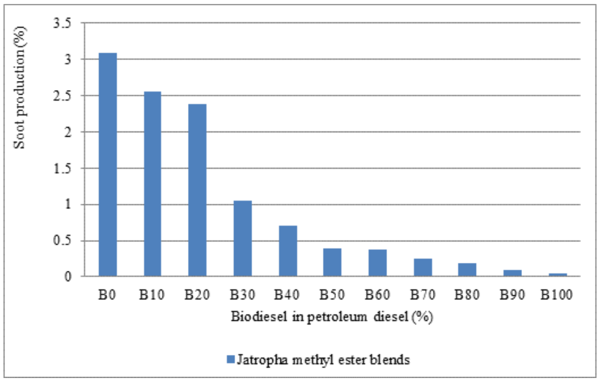

Figure-4. Jatropha methyl ester and blends soot production.

Results presented in Figure-4 show that combustion of 3 ml of petroleum diesel, jatropha methyl ester and its blends produce soot that decreases in magnitude with increase in blending ratio from B0 (100% petroleum diesel) to B100 (100% biodiesel). These results depict a 6th order polynomial relationship with an R^2 value of 0.98 as the optimal correlation. This relationship can be used to predict soot production at any blending ratio of jatropha methyl ester and petroleum diesel. These findings indicate that jatropha methyl ester is a clean fuel that contributes insignificantly to environmental pollution. The results of soot production analysis are consistent with observations made by Graboski *et al.* (1998) that using biodiesel fuel to power internal combustion engines reduces engine emissions of particulates, hydrocarbons and carbon monoxide.

CONCLUSIONS

From the experimental investigations on physicochemical properties, performance and emissions of jatropha methyl ester and its blends with petroleum diesel, the following conclusions can be drawn.

a) Physicochemical properties of jatropha methyl ester and its blends with petroleum diesel depict comparable fuel properties to those of petroleum diesel. Viscosity values for all fuels (petroleum diesel, B100 and blends) fall within specifications of ASTM standards, with a maximum difference of 21% observed between B0 and B100. Cold flow properties of cloud and pour points indicate that biofuels investigated can power the diesel engine without much difficulty in cold weather. The flash points of jatropha methyl ester and its blends were however found to be lower than the ASTM specification of a minimum of 130^{o}C, implying that the fuels are highly flammable and may need extreme handling precaution during transportation.
b) Biofuels depicted better engine performance when compared to petroleum diesel in terms of brake power, SFC and BTE. This is largely attributed to higher combustion efficiency due to extra inbound oxygen.
c) Higher combustion efficiency of biofuels culminated in reduced production of HC, CO and CO_2 emissions when compared with petroleum diesel. Petroleum diesel was also observed to produce the highest amount of soot during combustion in the magnitude of approximately 3% per 3ml of fuel.

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Nomenclature	
ASTM	American Standard Test Methods
ATDC	After Top Dead Centre
B0	100% petroleum diesel
B10	10% biodiesel + 90% petroleum diesel
B100	100% biodiesel
B20	20% biodiesel + 80% petroleum diesel
B30	30% biodiesel + 70% petroleum diesel
B40	40% biodiesel + 60% petroleum diesel
B50	50% biodiesel + 50% petroleum diesel
B60	60% biodiesel + 40% petroleum diesel
B70	70% biodiesel + 30% petroleum diesel
B80	80% biodiesel + 20% petroleum diesel
B90	90% biodiesel + 10% petroleum diesel
BTDC	Before Top Dead Centre
BTE	Brake Thermal Efficiency
ECU	Electrical Control Unit
HC	Hydrocarbons
LCP	Low Centipoise
PM	Particulate Matter
SFC	Specific Fuel Consumption

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