Tailoring fuel properties using jatropha, palm and coconut biodiesel to improve CI engine performance and emission characteristics

Md. Arbab Iqbal*, Mahendra Varman*, Masjuki Hj. Hassan, Md. Abul Kalam, Sajjad Hossain, Imtenan Sayeed

Center for Energy Science, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 22 June 2014
Received in revised form
4 April 2015
Accepted 4 April 2015
Available online 11 April 2015

Keywords:
Biodiesel
Fuel properties
Optimum blend
Engine performance
Engine emission

ABSTRACT

Biodiesel can be used effectively as engine fuel despite several limitations in its fuel properties. A set of experiment was conducted to improve fuel properties by blending palm biodiesel (PB) with coconut biodiesel (CB) and jatropha biodiesel (JB). MATLAB optimization tool was used to identify the optimum blend ratio for good fuel properties. A linear relationship among fuel properties was considered for MATLAB coding. The resulting optimum blend ratio and the equations of the MATLAB code were used to predict the fuel property values and were compared with the experimental values of the optimum blend fuel properties. Two new biodiesel blends were developed, namely, the optimum blends of palm–coconut (PC) biodiesels and jatropha–palm–coconut (JPC) biodiesels. Both biodiesels demonstrated overall improved fuel properties compared with those of the individual biodiesels presented in the blends. Engine performance and emission were tested using 20% blend of each biodiesel (JB, PB, CB, PC, and JPC) with petroleum diesel (OD). The engine performance and emission characteristics for the PC and JPC blends were then compared with those of OD. The average engine power for the blend of 20% JPC biodiesel and 80% OD (JPC20) was maximum at lower fuel consumption than the blend of 20% PC biodiesel and 80% OD (PC20) at full load condition. The emission characteristics of JPC20 were also comparable to or lower than those of OD, except for HC. However, when both engine performance and emission were considered, JPC20 was found to be the best fuel compared with OD and other fuel blends.

1. Introduction

The world energy crisis caused by fossil fuel depletion and the increasing concern for the environment motivated scientists to find an alternative, eco-friendly source of energy. Many countries have conducted extensive research (Huang et al., 2010; Leung et al., 2010) to solve this problem. One of the proposed solution is biodiesel, which is nontoxic and biodegradable (Bozbas, 2008; Patil and Deng, 2009). The use of biodiesel minimizes greenhouse gas emission because of closed carbon cycle of biodiesel (Dias et al., 2008; Gerpen, 2005).

Using biodiesel sometimes extends the life of engine components (Gerpen, 2005). Biodiesel can be applied in existing diesel engines without any modification (Helwani et al., 2009). However, the fuel properties of biodiesels are different from those of ordinary diesel. Hence, a slight modification is sometimes recommended. Several key fuel properties should be characterized before a biodiesel can be used in a diesel engine, such as density, kinematic viscosity, flash point, and calorific value.

Fuel flow, spray, and atomization characteristics are directly governed by the kinematic viscosity of the fuel and influence combustion (Lichty, 1967; Tate et al., 2006). Vegetable oils usually have high viscosity, which causes poor atomization and engine deposits and increases the energy consumption of fuel pumps (Alptekin and Canakci, 2009). High viscosity of fuel also causes freezing in cold countries and problem in fuel pumping. Therefore, transesterification of triglycerides improves this fuel property (Ghanei et al., 2011).

Flash point is one of the most important fuel properties. Flash point indicates the minimum temperature at which the vapor of the fuel ignites when an ignition source is applied. High flash point results in safe fuel handling and storage, preventing unexpected fuel ignition during combustion (Sajjad et al., 2014).

* Corresponding authors. Tel.: +603 79674448; fax: +603 79675317.
E-mail addresses: arbab128@yahoo.com (Md.A. Iqbal), mahendra@um.edu.my (M. Varman).

http://dx.doi.org/10.1016/j.jclepro.2015.04.011
0959-6526/

Nomenclature

OD	Ordinary Diesel or petroleum diesel
JB	Jatropha Biodiesel
PB	Palm Biodiesel
CB	Coconut Biodiesel
PC	Optimum blend of palm and coconut biodiesel
JPC	Optimum blend of jatropha, palm and coconut biodiesel
P20	Blend of 20% PB and 80% OD
J20	Blend of 20% JB and 80% OD
C20	Blend of 20% CB and 80% OD
PC20	Blend of 20% PC and 80% OD
JPC20	Blend of 20% JPC and 80% OD
CI	Compression ignition
BSFC	Brake specific fuel consumption
CO	Carbon mono-oxide
CO_2	Carbon di-oxide
HC	Hydro carbon
NO_x/NO	Oxides of nitrogen

When a unit quantity of fuel is burnt during combustion, the amount of heat released is called the calorific value of the fuel. Increased calorific value is desired because this fuel property facilitates the release of heat during combustion and improves engine performance at low fuel consumption (Sajjad et al., 2014).

Cetane number is a prime indicator of the quality of fuel used in compression ignition engines. Cetane number is a dimensionless descriptor that is related to ignition delay time, which is the time that passes between the start of fuel injection and the onset of ignition. A short ignition delay corresponds to a high cetane number, and vice versa. High cetane number is desired for fuels in CI engines (Sajjad et al., 2014).

Several researchers have attempted to improve biodiesel fuel properties by blending biodiesels with OD (Ahmed et al., 2014; Palash et al., 2013; Rahman et al., 2014). Use of additives to improve biodiesel fuel properties is also very common (Hussan et al., 2013; Jie et al., 2010; Rizwanul Fattah et al., 2014). Although the use of additive-added blends improves some performance or emission aspects, these blends affect other parameters adversely. In addition, they are associated with high production costs. The current study introduces a new concept to improve biodiesel fuel properties by blending two or three pure biodiesels at an optimized ratio. The effects on engine performance and emission are tested using multiple biodiesel blends with improved fuel properties.

Palm oil is the most common and largely produced oil in Malaysia and Malaysia is the largest exporter of palm oil in the world. In addition, the commercial use of 5% blend of PB has started in Malaysia. For this reason, PB is considered the primary biodiesel, and JB and CB have been blended with the PB to improve fuel properties. However, food grade oil use is highly disputed as a threat to food security. JB comes from a non-edible source, which means that its increased use will not affect our food chain. Moreover, jatropha is a good prospect in South-East Asia region, especially in Malaysia and Indonesia (Silitonga et al., 2011), because this genus grows even in harsh environments (Silitonga et al., 2013). CB is chosen because of its good fuel properties. CB has good emission characteristics, such as NOx emission (Kinoshita et al., 2006, 2007). Given that the properties of JB and PB are close to each other, a blend of these two biodiesels is disregarded.

Several researchers have conducted experiments on single biodiesel blends (Canakci et al., 2009; Manieniyan and Sivaprakasam, 2008; Sharon et al., 2012). In most cases, 15%–25% blend of biodiesel with OD showed relatively better engine performance than any other blend ratios (Manieniyan and Sivaprakasam, 2008; Mofijur et al., 2013; Shahabuddin et al., 2012). In this experiment, fuel properties have been improved by biodiesel–biodiesel blending and the effect of 20% blend of new biodiesels as well as individual biodiesels on engine performance and emission characteristics have been studied and compared with those of pure OD.

2. Blending technique

Experiments were conducted using two to three component blends of JB, PB, and CB with petroleum diesel. Most of the important fuel properties, such as density, kinematic viscosity (Alptekin and Canakci, 2008, 2009), oxidation stability (Jain and Sharma, 2011), flash point (Kim and Lee, 2010; Alptekin and Canakci, 2009), calorific value, and cetane number (Benjumea et al., 2008) vary linearly in multiple biodiesel blends. Hence, the linear relationship among the fuel properties was considered to determine the optimum blending ratio.

MATLAB optimization tool was utilized to determine the optimum blend ratio. The optimization tool is a built-in tool of MATLAB 2012, which is a software that includes functions for linear programming, quadratic programming, binary integer programming, nonlinear optimization, nonlinear least squares, systems of nonlinear equations, and multi-objective optimization. The tool can be used to find optimal solutions, perform trade-off analyses, balance multiple design alternatives, and incorporate optimization methods into algorithms and models.

To determine the optimum blending ratio, several constraints were initially considered. The upper and lower limits for a specific fuel property were considered according to the highest and lowest values of the property of the individual fuel present in the blend and the limit of the ASTM standard. For those properties for which low values are desired (i.e., viscosity and density), the median value was regarded as the upper limit. For example, in case of the jatropha–palm–coconut (JPC) blend, JB had the lowest induction time, and CB had the highest induction time. According to the ASTM standard, induction time should be at least 3 h; thus, the constraint was set higher than 3 h. In addition, JB had the highest viscosity, whereas CB had the lowest. Given that PB had the median value among the three, PB viscosity value was regarded as the upper limit for the optimization tool. For example, if A, B, and C are the values of a specific fuel property of three different fuels, X, Y, and Z are the final blend ratios, respectively, and the upper limit for that fuel property value is Q, then the inequality used for MATLAB will be $AX + BY + CZ < Q$.

3. Experimental procedure

This experiment consists of two parts, namely, fuel property improvement and engine test. Fuel properties are improved by blending two or three pure biodiesels. The engine test was performed at full load with variable speed and constant speed with variable load conditions.

3.1. Fuel properties improvement

Engine performance and emission are directly affected by the physicochemical properties of the fuel, such as density, viscosity, flash point, oxidation stability, calorific value, cetane number, iodine value, and acid value (Atabani et al., 2013). These properties indicate the quality of a fuel. Among these properties, most researchers focus on density, kinematic viscosity, oxidation stability, flash point, calorific value, and cetane number to determine the quality of fuel (Kalam et al., 2003; Yusaf et al., 2011). Different standards, such as ASTM, BS, and ISO, define the range of each fuel property. Among these standards, ASTM is the most widely followed. To meet the standard for engine performance and emission, the value of the fuel properties must be within the range indicated by the standard.

In this experiment, new biodiesels with improved fuel properties were developed by blending JB, PB, and CB; two or three of these biodiesels were considered at a time. Table 1 presents the list of apparatus used to establish the fuel properties. Tables 2 and 3 show the individual fuel properties of JB, PB, and CB. After developing the MATLAB code, a linear relationship was used to find the optimum blend ratio for two or three fuel blends. The constraint considered for the MATLAB optimization and the optimum blend ratios are listed in Table 4. For density and viscosity, the median values of the three biodiesels are considered as the upper limit, and the minimum ASTM limit (3 h) is considered as the lower limit for induction time. To maintain high calorific value, the limit considered for the calorific value is close to the maximum value among the three biodiesels. In case of flash point, although the minimum ASTM limit is 130 °C, 160 °C is considered to maintain high possible flash point. A high flash point is desired. The theoretical fuel property values for the blends were then determined by using the optimum blend ratio and the linear equations. Finally, the blends were prepared according to the optimum blend ratio (Table 4), and the fuel properties of the blends were tested in the laboratory (Table 5).

3.2. Sample calculation

The inequality used to obtain the optimum blend ratio for JPC are following:

Assuming X, Y and Z are the blend ratio of JB, PB and CB respectively.

For density: $0.8833X + 0.8793Y + 0.8771Z < 0.8793$
For viscosity: $4.805X + 4.663Y + 3.180Z < 4.663$
For induction time: $2.08X + 3.24Y + 5.12Z > 3$
For flash point: $202.5X + 188.5Y + 136.5Z > 160$
For calorific value: $39.839X + 39.907Y + 36.985Z > 38.5$
Relation among the ratios: $X + Y + Z = 1$

Solving above inequalities using MATLAB, the obtained values of X, Y and Z are 0.23, 0.559 and 0.211 respectively. Therefore, the blending ratios of jatropha, palm and coconut biodiesels for the JPC blend are 23%, 55.9% and 21.1% respectively.

3.3. Engine test

The experiment was conducted using an inline four-cylinder, water-cooled Mitsubishi Pajero engine. The engine specification is listed in Table 6. BOSCH BEA-350 (specification is listed in Table 7) exhaust gas analyzer was used for engine emission analysis. Fig. 1 illustrates the schematic experimental setup.

In this study, the engine was run at full load condition at different engine speeds that range from 1000 rpm to 4000 rpm with a 500 rpm interval and a constant speed of 2000 rpm at different engine loadings of 0%–100%. The engine performance and emission data for OD, J20, P20, C20, JPC20, and PC20 were recorded. Each test was performed thrice to avoid random errors. REO-dCA data acquisition unit was used to collect engine performance data.

3.4. Statistical analysis

Instrument selection, condition, calibration, environment, observation, reading and test procedure are the sources of errors

Table 1
Apparatus used for testing fuel properties.

Properties	Apparatus
Density	Stabinger Viscometer SVM 3000
Kinematic viscosity	Manufacturer: Anton Paar
Induction time	873 Biodiesel Rancimat Manufacturer: Metrohm
Flash point	Pensky-Martens flash point-automatic NPM 440 Manufacturer: Normalab, France
Calorific value	Semi auto bomb calorimeter Model: 6100EF Manufacturer: Perr, USA
Cloud and pour point	Cloud and Pour point tester – automatic NTE 450 Manufacturer: Normalab, France

Table 3
Percentage (wt.%) of fatty acid composition of the biodiesels.

Fatty acid	Jatropha (wt.%)	Palm (wt.%)	Coconut (wt.%)
C6:0	<0.1	<0.1	0.3
C8:0	<0.1	<0.1	6.5
C10:0	<0.1	<0.1	6
C12:0	0.1	0.3	42.1
C14:0	0.1	1	17.4
C16:0	14.7	38.1	11.3
C16:1	0.6	0.2	0.2
C18:0	7.6	4.1	3.8
C18:1	44.1	44.2	9.2
C18:2	31.5	11	3
C18:3	0.3	0.3	<0.1
C20:0	0.2	0.4	0.2
C20:1	0.1	0.2	<0.1
C22:0	0.1	0.1	<0.1
C22:1	0.1	<0.1	<0.1
C24:0	0.5	0.1	<0.1
Total saturation	23.3	44.1	87.6
Monounsaturation	44.9	44.6	9.4
Polyunsaturation	31.8	11.3	3
Total fatty acid	100	100	100

Table 2
Experimentally investigated individual fuel properties.

Properties	Standard and limit	Jatropha biodiesel	Coconut biodiesel	Palm biodiesel	Diesel
Density at 40 °C (g/cm^3)	–	0.8833	0.8771	0.8793	0.8331
Kinematic viscosity at 40 °C (cSt)	ASTM-D445 (1.9–6)	4.805	3.180	4.663	3.556
Induction time (h)	ASTM-D7462 (3 h min)	2.08	5.12	3.24	–
Flash point (°C)	ASTM-D93 (130 °C min)	202.5	136.5	188.5	77.5
Higher calorific value (kJ/g)	–	39.839	36.985	39.907	44.664
Cloud point (°C)	–	10	1	13	7
Pour point (°C)	–	10	–4	15	8
Cetane number[a]	ASTM-D613 (47 min)	51	60	55	47

[a] Supplier given values.

Table 4
Boundary constraint and optimum blending ratio derived using MATLAB.

Blend content	Constraint					Optimum blend ratio (%)		
	Upper limit of density at 40 °C (g/cm^3)	Upper limit of kinematic viscosity at 40 °C (cSt)	Lower limit of Induction time (h)	Lower limit of Flash point (°C)	Lower limit of higher calorific Value (kJ/g)	JB	PB	CB
PC	0.8793	4.663	3.00	160.0	39.000	0	87.6	12.4
JPC	0.8793	4.663	3.00	160.0	39.000	23	55.9	21.1

Table 5
Experimental blended fuel properties.

Fuel	Density at 40 °C (g/cm^3)	Kinematic viscosity at 40 °C (cSt)	Induction time (h)	Flash point (°C)	Higher calorific value (kJ/g)
PC	0.8774	4.436	3.66	180.5	38.555
JPC	0.8779	4.322	3.41	186.5	38.760

and uncertainties of an experiments. Table 7 contains the measurement range and accuracy of the instruments used for this experiment. Statistical analysis is required to prove the accuracy of the data of experiments. Statistical analysis was carried out by applying two-tailed Student's t-test for independent variables to test for significant differences between samples set means using Microsoft Excel 2013. Differences between mean values at a level of $p = 0.05$ (95% confidence level) were considered statistically significant.

4. Results and discussion

This section presents the improvement of fuel properties using the optimized blend and the effect of the new optimized biodiesel blends on engine performance and emission characteristics.

4.1. Fuel properties

Regarding experimental values of fuel properties of JB, CB, PB, and OD (Table 2), the densities of all biodiesels are clearly close to one another and are about 5%–6% higher than the density of OD. The kinematic viscosities of JB and PB are also close to each other, but CB has the lowest kinematic viscosity, which is about 30% lower than that of other biodiesels. A large variation is observed in the case of induction time. JB has a poor induction time, which is lower than the ASTM standard of 3 h. PB has an induction time that is close to the ASTM standard, and CB has the highest (5.12 h). The flash points of all the biodiesels are sufficiently high, except for CB, whose flash point is close to the minimum ASTM limit (130 °C). The calorific value of biodiesels is on average 11% lower than that of OD. CB has the lowest calorific value (36.98 kJ/g). The cetane number of the biodiesels is higher than that of OD, and a higher cetane number is desired for better engine performance.

A comparison of Tables 2 and 5 can easily show the improvement of fuel properties. In the case of PC, about 5% and 13% improvement in kinematic viscosity and induction time, respectively, with respect to pure PB are observed. A slight improvement is observed for density, and the flash point is much more acceptable than the minimum ASTM limit. These improvements of fuel properties are achieved only by 3% sacrifice in calorific value. For JPC, about 7% and 5% improvement for kinematic viscosity and induction time are observed. The change in flash point, calorific value, and density are similar to PC. This phenomenon indicates that the blending of two or more biodiesels improves fuel properties.

Fig. 2 shows the variation between the theoretical (obtained using the optimum blend ratio and the linear equations used in MATLAB) and experimental (obtained from the laboratory test) values of fuel properties. The deviations of density, kinematic viscosity, and calorific value are lower than 2%. However, in the cases of induction time and flash point, the variation is relatively high (maximum 8.5%), because these two properties are affected by the chemical composition and molecular structure of the fuel. For other fuel properties, the variation is very low (less than 3%), which validates the linear relationship of the fuel properties for the blends.

4.2. Engine performance

Brake specific fuel consumption (BSFC), power, and torque are regarded as engine performance indicators. Fig. 3 shows the BSFC of the biodiesel blends and of OD at different engine speeds. OD shows the lowest BSFC up to medium speed, whereas P20 shows the lowest BSFC at higher speed (higher than 3500 rpm). Among the biodiesel blends, P20, J20, C20, JPC20, and PC20 present on average 2% higher BSFC compared with that of OD. These changes were significant at $0.01 < p < 0.02$. The poor calorific value of the biodiesels causes a hike in BSFC. However, at a higher speed, the higher combustion temperature and additional oxygen content of the biodiesel facilitate better combustion and reduce BSFC (Neto da Silva et al., 2003; Ono et al., 2009).

Fig. 4 shows the BSFC of the biodiesel blends and the OD at different engine loadings at a constant speed (2000 rpm). Lower BSFC values are observed for P20, JPC20, and PC20 for all loading conditions, but C20 and J20 show higher values at lower loading conditions. Considering both testing conditions, the average BSFC

Table 6
Engine testbed equipment specification.

Description	Specification
No. and arrangement of cylinders	4 in-line, longitudinal
Rated Power	42 kW at 3500 rpm
Torque	135 N m, at 2000 rpm
Combustion chamber	Swirl chamber
Total displacement	2477 cm^3
Cylinder bore × stroke	91.1 × 95 mm
Valve mechanism	SOHC
Compression ratio	21:1
Lubrication system	Pressure feed, full flow filtration
Fuel system	Distributor type injection pump
Air flow	Turbocharged
Fuel Injection Pressure	157 bar
Dynamometer	Froude Hofmann eddy current dynamometer Max. Power:250 kW Max. Torque: 1200 Nm Max. Speed: 6000 rpm
Fuel Flow meter	Kobold positive displacement flow meter
Air flow meter	BOSCH air flow meter

Table 7
List of measurement equipment and their uncertainty.

Measurement	Measurement range	Accuracy	Measurement techniques
Load	±600 Nm	±0.1 Nm	Strain gauge type load cell
Speed	0–10,000 rpm	±1 rpm	Magnetic pick up type
Time	–	±0.1 s	–
Fuel flow measurement	0.5–36 L/h	±0.04 L/h	Positive displacement gear wheel flow meter
Airflow measurement	0.25–7.83 kg/min	±0.07 kg/min	Hot-wire air-mass meter
CO	0–10% by vol.	±0.02%	Non-dispersive infrared
CO_2	0–18% by vol.	±0.03%	Non-dispersive infrared
HC	0-9999 ppm	±1 ppm	Non-dispersive infrared
NO	0–5000 ppm	±1 ppm	Electrochemical
Brake power	–	±0.03 kW	–
BSFC	–	±0.30 g/kWh	–

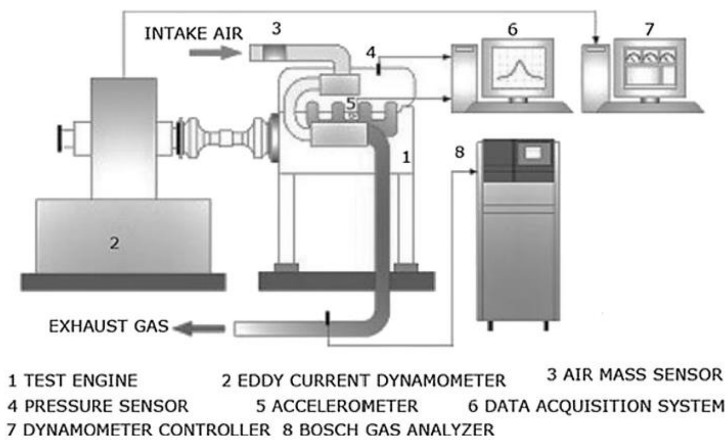

Fig. 1. Schematic diagram of the engine test bed.

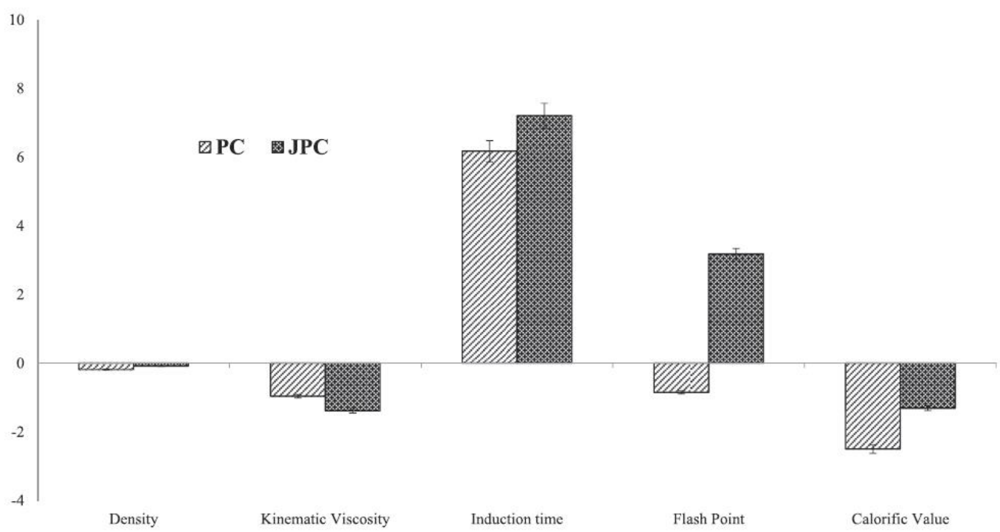

Fig. 2. Percentage (%) of variation between theoretical and experimental blended fuel properties.

Link to full text articles :

http://www.sciencedirect.com/science/article/pii/S0959652615003546

http://ac.els-cdn.com/S0959652615003546/1-s2.0-S0959652615003546-main.pdf?_tid=f84103c2-4010-11e5-a37b-00000aacb361&acdnat=1439287913_a356bbd5b21e719202c01a6b90a6deb9