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Experimental Assessment of The Performance and Exhaust Emissions Characteristic of a Diesel with Jatropa Curcas-Ceiba Pentandra Mixture Biodiesel/Bioethanol Blends

Joko Sutrisno[†], S. Dharma[†], A. S. Silitonga[†*], A. H. Shamsuddin[‡], A. H. Sebayang[†], Jassinnee Milano[††], Rahmawaty[†], Supriyanto[†]

[†]Department of Mechanical Engineering, Politeknik Negeri Medan, Jl. Almamater No.1, Kampus USU, Medan 20155
[‡]Institute of Sustainable Energy, Universiti Tenaga Nasional, 43000 Kajang, Selangor Malaysia
[††]Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia
*Corresponding Author Email: ardinsu@yahoo.co.id

ABSTRACT: The depletion of world oil reserves currently positively impacts the development of biofuels such as biodiesel and bioethanol, as this fuel is a renewable and environmentally friendly alternative and is considered to have enormous potential to supply energy needs. The purpose of this research is to investigate the performance and exhaust emissions from single diesel direct injection diesel engine which is fueled by biodiesel-bioethanol-diesel. Biodiesel was obtained from a mixture of *Jatropa curcas-Ceiba pentandra* crude oil with each composition being 50% produced by degumming process, acid catalyzed esterification, and alkaline-catalyzed transesterification. Biodiesel-bioethanol-diesel fuel is mixed in several conditions ie B10BE5, B20BE8, B30BE10, B40BE13, and B50BE15. In general, engine performance for low blend of biodiesel and bioethanol is close to diesel, for some engine parameters such as engine torque, brake power, and brake thermal efficiency. The addition of biodiesel and bioethanol into diesel fuel also has implications for reduced carbon emissions and smoke opacity. Overall, based on test results it can be concluded that the biodiesel-bioethanol mixture in low concentration in diesel fuel qualifies as an alternative fuel in diesel engines.

KEYWORDS: Biodiesel; Bioethanol; Engine performance; Exhaust gas emissions; Alternative fuels

INTRODUCTION

The limited of oil resources, increasing energy demand, oil prices soared and global warming became a major issue in the world today. This is because the world's dependence on fossil fuels is dwindling in number as well as the use of which causes environmental damage As of 2018, the world's primary energy sources consisted of petroleum (34%), coal (27%), natural gas (24%), amounting to an 85% share for fossil fuels in primary energy-consumption in the world [1]. Transportation is a major energy user sectors and is known as the biggest emitter by contributing around 22% of global GHG (greenhouse gas) emissions [2]. Furthermore, energy consumption in the transportation sector has seen an average annual rate of 1.4% increase in the past decades [3, 4]. The light-duty vehicles such as cars and motorcycles consume the most energy compared to freight modes of transportation, such as heavy trucks, marine, and rail; with light-duty vehicles commonly utilising gasoline or diesel as an energy source to power their vehicle [4-7]. This makes the transportation sector the biggest consumer of fossil fuel, as a whole and oil, in particular [5, 8]. These concerns are encouraging researchers to develop biofuels such as biodiesel and bioethanol as a renewable alternative fuel and environmentally friendly, are considered to have great potential to supply the energy needs [9-12]. There are two types of alternative fuels widely used and accepted by the market, biodiesel, and bioethanol to replace fossil diesel and gasoline respectively [13-16]. Biofuels production from favorite biomass resources such as oil palm waste, rice husk, coconut husk, banana, and sugarcane bagasse have been extensively discussed in the literature [22-33]. The use of ethanol blend fuel has long been carried out in Brazil, which uses sugarcane as feedstock, whereas United States program is based on corn [17, 18]. Selection of the two types of oxygenated fuel because it is renewable, environmentally friendly and functional properties similar to petroleum fuel [19]. In addition, the development of biodiesels and bioethanol is also to reduce our dependency on fossil fuels, which in turn, helps in reducing their negative impact of their use [20]. Substitution even a small fraction of total consumption by alternative fuels will have a significant impact on the economy and the environment [21].

Biodiesel is one of the promising alternative fuels to replace diesel and bioethanol is regarded as a potential fuel to substitute gasoline [13, 22, 23]. Biodiesel can be obtained from various sources which include edible and non-edible vegetable oil, waste oil and animal fat, which is generated through the process of transesterification of triglycerides present in vegetable oil with alcohol in the presence of alkaline or acidic catalysts [24-26]. Meanwhile, ethanol can be obtained from the conversion microbial lignocellulosic biomass through fermentation of some types of biomass such as lignocellulosic biomass (such as straw, grass and wood, etc.), starchy (such as corn, barley, corn, etc.) and sucrose-containing raw materials (eg sugarcane, sugar beet, sweet sorghum, etc). [15, 16, 27-29]. On the other hand, in its application, bioethanol it is possible to be mixed with diesel fuel in diesel engines without requiring major modifications [30]. However, the blending of bioethanol with diesel has its own challenges, because bioethanol has a lower density, viscosity, cetane number and a smaller lower heating value than diesel fuel [31]. In compression ignition engines, the addition of ethanol into the fuel is used as an additive or fuel mixture [32].

Diesel engines dominates the largest contributors from transportation and agriculture machinery to environmental pollution caused by exhaust emissions, and they are responsible for several health problems as well. To facilitate lowering these emissions, fuel derived from a renewable source is highly promising [33]. Biodiesel and bioethanol are the potential fuels which could be used in current engines without much alteration [34]. These alternative fuels should be preferably available from renewable sources. Therefore, attention is mainly focused towards biomass- based fuels. Many studies explored the usage of higher C–H alcohols to diesel/biodiesel blends has reviewed on the effect of ethanol blends with diesel on regulated and unregulated emissions of compression ignition engines. They said that ethanol based fuels may be used with diesel fuel, utilizing different dual fuel operation techniques [5, 35, 36]. These methods are most often encountered within blending and fumigation. Thus, The blending method, the ethanol fuels are blended with the diesel fuel before the in-cylinder injection. This method implies some limitations regarding the stability of the mixture; therefore, additives are required. Khoobbakht et al. (2019) observed the emission biodiesel-ethanol-diesel blends. The results showed that increasing biodiesel and/or ethanol percentages in the fuel blends caused to reduce the engine brake power. A low level of biodiesel and/or ethanol in the fuel blends could enhance the engine brake thermal efficiency in comparison with the pure diesel fuel or high level of biodiesel and/or ethanol in the diesel fuel blends. Silitonga et al. (2018) have found that the addition of bioethanol to diesel reduces CO and HC emissions. Park et al. (2012) confirmed that bioethanol addition lowered biodiesel HC and CO emissions. Barabás et al. (2010) also agreed with the result stating that the addition of bioethanol to biodiesel fuel lowers its CO emissions. Subbaiah et al. (2010) explored the use of rice bran oil biodiesel as an additive in diesel–ethanol blends for compression ignition engines, and the performance and emissions of the compression ignition engine fueled with B10, B10E5, B10E10, and B10E15, compared to B100 and fossil diesel was shown maximum brake thermal efficiency of 28.2% observed with blend B10E15. Furthermore, the presence of ethanol in diesel fuel resulted in increased thermal efficiency and specific fuel consumption, reduce engine power and significantly led to a reduction in exhaust emissions such as smoke opacity, particulate matter (PM) and NO_x [37]. On the other hand, the addition of ethanol has implications in decreased lubrication, low of cetane number and solubility, high heat of vaporization, and high auto-ignition temperature The presence of ethanol in diesel fuel cause immiscibility in the fuel mixture [32].

Jatropha curcas and *Ceiba pentandra* seeds obtained from Cilacap, Centre Java, Indonesia and Bioethanol from Bogor, West Java, Indonesia. The oil obtained from these seeds is nontoxic, free from sulphur and aromatics and biodegradable. It also has a high boiling point, cetane number and flash point, low vapour pressure and high density which enhance the running of engines. It has been found that 1 kg of *Jatropha Curcas* and *Ceiba Pentandra* seeds yields 500 ml and 450 ml of oil.

The objective this study includes:

- To analyze the properties of biodiesel from *Jatropha curcas* and *Ceiba pentandra* mixture biodiesel blend with bioethanol.
- To investigate the effects biodiesel-bioethanol-diesel fuel blends on engine performance and exhaust emissions in diesel engine.

However, no specific work has been conducted on using nonedible *Jatropha Curcas Ceiba Pentandra* mixture biodiesel blending with bioethanol and diesel fuel in compression ignition engine applications. Further, the detailed investigation of the effect of bioethanol in *Jatropha Curcas Ceiba Pentandra* mixture biodiesel biodiesel has not been attempted before. Hence, this study details the outcome of using bioethanol as an oxygen-donating additive on performance and emissions and patterns of *Jatropha Curcas* and *Ceiba Pentandra* biodiesel in a diesel engine. Authors believe that the outcomes of this study could make a significant contribution to the alternative fuel research area.

MATERIAL AND METHODS

Materials

In this study, a commercial diesel fuel obtained from local fuel station in Kuala Lumpur, Malaysia. Biodiesel was produced through alkaline-catalyzed transesterification process from a mixture of *Jatropha curcas-Ceiba pentandra* with the percentage of each crude oil is 50%, here in after abbreviated as J50C50. Parameters production such as the methanol-to-oil ratio, agitation speed, and the concentration of catalyst was determined by the response surface methodology based on Box-Behnken, in accordance with previous studies [25]. Meanwhile, bioethanol used in this study were purchased from Bogor, West Java, Indonesia.

Biodiesel-bioethanol-diesel fuel blends and properties

The biodiesel, bioethanol, and diesel were blended at different volume ratios at the Biofuel Laboratory, Faculty of Engineering, University of Malaya. A double-jacketed glassware was used for this purpose, and each blend was mixed thoroughly using IKA RW20 digital overhead stirrer at an agitation speed of 2000 rpm for two days in order to attain a homogeneous blend. The biodiesel-bioethanol-diesel blends were stored in vacuum chamber at 15 C and 0 bar, following the specifications given in the ISO 8217 standard, in order to ensure that the fuels remain stable over a certain period. It is also necessary to store the biodiesel-bioethanol-diesel blends at the right temperature in order to ensure that the viscosity of the fuels is optimum during engine operations. The blends prepared in this study are as follows: *Jatropa curcas-Ceiba pentandra* biodiesel (ie 10, 20, 30, 40, and 50 vol%) with the addition of bioethanol by 5, 8, 10, 13 and 15 vol%. These are designated samples as B10BE5, B20BE8, B30BE10, B40BE13, and B50BE15, respectively. The physicochemical properties of the biodiesel-bioethanol-diesel fuel blends (i.e. B10BE5, B20BE8, B30BE10, B40BE13, and B50BE15) were determined in accordance with the ASTM D6751 and EN 14214 test methods. Several tests were conducted to determine the physicochemical properties of the fuel blends such as density, kinematic viscosity, higher heating value, flash point, and oxidation stability.

Experimental design

In this study, TF 120 M Yanmar diesel engine with 7.7 kW power was used as the test engine. The schematic layout of the diesel engine with instrumentation installed is shown in Figure. 1 and the engine technical specifications are summarized in Table 1. A dynamometer with maximum power of 20 kW, 80 Nm torque and 10,000 rpm was connected to the engine. In addition, the engine was also connected to an automatic measurement system which measures and records the performance of the engine parameters such as engine torque, brake power, BSFC and EGT at full throttle position and various engine speeds.

Moreover, the exhaust gas emission parameter measured using a BOSCH portable emission analyser (Model: BEA-150), including carbon monoxide, carbon dioxide, nitrogen oxides and smoke opacity. Smoke opacity measurements done by collecting the exhaust fumes from the engine using a gas analyser filter through the sensor sample. Calibration and maintenance of gas analyser is done separately and scheduled using gas samples provided by Robert Bosch Sdn. Bhd., Malaysia. The specifications of BOSCH portable emission analyser are shown in Table 2.

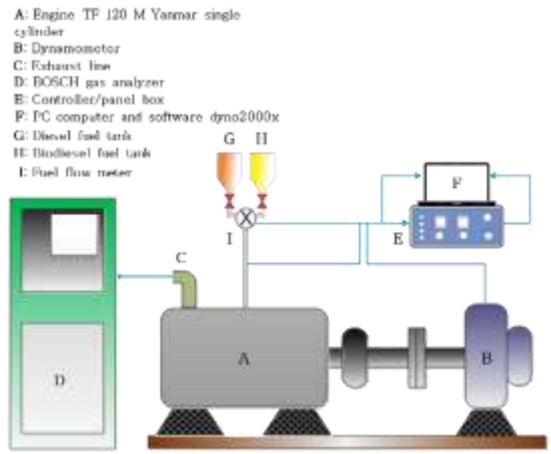

Figure 1. Schematic layout of the single-cylinder direct injection diesel engine set-up

Tabel 1. Technical specifications of the engine

Type	Specifications
Injection system	Direct injection
Number of cylinders	One
Type of cooling system	Water cooling
Cylinder bore (mm)	92
Stroke (mm)	96
Displacement (L)	0.638
Compression ratio	17.7:1
Max. power (kW)	7.7
Max. engine speed (rpm)	2400
Injection timing (deg.)	bTDC 17.0
Injection pressure (kg/cm^2)	200

Tabel 2. Technical specifications of the gas analyser

	Exhaust component	Measurement range	Resolution
Measurement ranges, resolution	CO (%vol.)	0.000–10.00	0.001
	CO_2 (%vol.)	0.00–18.00	0.01
	HC (ppm vol.)	0–9999	1
	NO_x (ppm vol.)	0–5000	≤ 1
Smoke opacity meter	Degree of opacity (%)	0–100%	0.1

The experiments were initiated with the engine fuelled with diesel. This was done to determine the baseline characteristics of the engine and exhaust emissions. The engine was run at full throttle position within a speed range of 1600–2400 rpm. The engine speed was incremented at 200 rpm. The Dynomax-2000 system data controller software was used to monitor the conditions of the engine. The same procedure was repeated for each biodiesel-bioethanol-diesel fuel blend (i.e. . B10BE5, B20BE8, B30BE10, B40BE13, and B50BE15) and the same operating conditions were used for each experiment. The experiment was carried out in triplicate for each biodiesel-diesel blend in order to examine the repeatability and reproducibility of the data and the average value for each investigated parameter was determined. During the experiment, the fuel volumetric flow rate was measured using a fuel gauge fitted to the equipment. The engine emissions and smoke opacity were detected by a smoke sensor placed at the engine exhaust pipe. The sensor was connected directly to the Bosch BEA 150 diesel emissions analyzer in order to record the data.

Uncertainty analysis

The uncertainties of the measured parameters can be estimated and reduced to a certain extent by careful selection and calibration of the measuring instruments, planning the experiments in a systematic manner, implementing reliable data acquisition procedures, and controlling the experimental conditions. It is important to estimate the uncertainties of the engine performance parameters (i.e. BSFC, engine torque, brake power, EGT, and BTE) and exhaust emission parameters (i.e. CO, CO_2, and NO_x emissions, and smoke opacity) since the uncertainties reflect the accuracy of these parameters. The uncertainty represents the range where it is believed that the true value of the parameter lies within this range Overall

The final result of each sample was the quadratic sum of each of the expanded uncertainties indicated in Equation. (1):

The experimental uncertainty = square root of [(uncertainty of fuel flow measurement)^2 + (uncertainty of BSFC)^2 + (uncertainty of load)^2 + (uncertainty of brake power)^2 + (uncertainty of EGT)^2 + (uncertainty of BTE)^2 + (uncertainty of NO_x)^2 + (uncertainty of CO)^2 + (uncertainty of CO_2)^2

+ (uncertainty of smoke opacity)^2] = square root of [$(2.428)^2 + (2.051)^2 + (0.405)^2 + (1.873)^2 + (0.088)^2 + (0.772)^2 + (1.24)^2 + (1.55)^2 + (0.14)^2$] = 4.458 % [1]

The total percentage uncertainty of an experimentally found trial (the measurements were repeated 3 times for each test) can be calculated as 4.46 % which is less than 5 % (95 % confidence level), within an acceptable range of errors and uncertainties analysis [38].

RESULT AND DISCUSSION

Properties of crude oil, biodiesel and its blends

The physicochemical properties of the crude oil, biodiesel and biodiesel-bioethanol-diesel fuel blends are presented in Table 3. It is known that the kinematic viscosity measured at 40 °C and the density measured at 15 °C of the crude J50C50 oil are 27.22 mm^2/s and 908.30 kg/m^3, respectively. The crude J50C50 oil has a high acid value and lower calorific value, where it shows that the importance of two-step biodiesel production (acid-catalysed esterification, followed by alkaline-catalysed transesterification). This process results in a striking change in the properties of the crude J50C50 oil when it is converted into J50C50 biodiesel. The kinematic viscosity decreased up to 85%, whereas the acid value and density decreases reached 98.4% and 8.4%, respectively. In contrast, the calorific value increases of more than 5%. The J50C50 biodiesel was produced in accordance with the ASTM D6751 and EN 14214 standard test methods. The properties of bioethanol to the biodiesel-diesel fuel mixture are shown in Table 3. The addition of bioethanol to the mixture causes the decreasing of some fuel properties such as density, viscosity and calorific value. These results are consistent with previous research by [7] who observed changes in the fuel properties of a safflower mixture of biodiesel-bioethanol-diesel fuel. The results show that there is a decrease in viscosity value and heating value after the addition of bioethanol up to 5% into the mixture. The declining properties of the biodiesel-bioethanol-diesel viscosity can lead to inferior fuel injection. Meanwhile, the calorific value of the fuel affects the output power generated during the combustion process.

Table 3. The properties of J50C50 biodiesel, biodiesel-diesel fuel blends and biodiesel-bioethanol-diesel fuel blends

Properties	Unit	ASTM D6751	EN 14214	Diesel[a]	J. *curcas*[a]	C. *pentandra*[a]	Crude J50C50[a]	J50C50 biodiesel[a]	Bioethanol[a]	J50C50 biodiesel-bioethanol-diesel fuel				
										B10BE5	B20BE8	B30BE10	B40BE13	B50BE15
Kinematic viscosity at 40 °C	mm^2/s	1.9–6.0	3.5–5.0	2.96	4.57	4.74	27.22	3.95	1.35 at 20 °C	3.27	3.25	3.36	3.42	3.4614
Density at 15 °C	kg/m^3	880	860–900	846.1	876.2	885.7	908.3	831.2	804.6	852.4	852.5	856.8	860.2	863
Calorific value	MJ/kg	–	35	45.36	39.46	39.46	38.22	40.92	27.6	41.581	40.543	39.59	38.261	38.117
Flash point	°C	100–170 min.	> 120	75.5	125.5	120.5	–	196	–	–	–	–	–	–
Acid value	mg KOH/g	0.5 max.	0.5 max.	0.17	0.46	0.51	15.82	0.25	–	0.37	0.37	0.47	0.47	0.46
Pour point	°C	–	–	3	3	4	–	0.5	–	7	7	11	13	15
Cloud point	°C	–	–	2	2	4	–	0.5	–	–	–	–	–	–
Oxidation stability at 110 °C	h	3 min.	6 min.	15.2	14.01	1.76	–	10.01	–	–	–	–	–	–
Cetane index	–	47 min.	51 min.	49.6	59	56	–	58	–	–	–	–	–	–

[a]Result (J50C50) = J. *curcas*-C. *pentandra* (50:50 %wt.)

Engine performance

Brake specific fuel consumption

Brake specific fuel consumption (BSFC) is an important parameter used to evaluate the effect of different fuel blends on the engine performance. The BSFC of the diesel engine is dependent on the relationship between a numbers of variables: volumetric fuel injection system, fuel density, viscosity and lower heating value (LHV) [39]. The variation of the BSFC for biodiesel-bioethanol-diesel fuel blends is shown in Figure 2. It is known that there is a decrease of BSFC due to the increased in engine speed. Indeed, all of the fuels tested in this study result in a decrease in the BSFC when the engine speed varies from 1600 to 1800 rpm, followed by a slight increase thereafter up to a speed of engine at 2400 rpm. Figure 2 shown that the BSFC tends to increase along with the increase of biodiesel content in the mixtures. It is known that, there is an increase in BSFC with increased bioethanol content in the mixture. The B50BE15 or bioethanol 15% mixture has the highest BSFC reaching 736.3 g/kWh at 2400 rpm. The increase in BSFC is due to the lower of heating value of biodiesel and bioethanol compared to diesel fuel [40]. In addition, the presence of higher latent heat from bioethanol vaporization, causing lower temperatures in-cylinder and away from the top dead center (TDC), resulting in incomplete combustion [41].

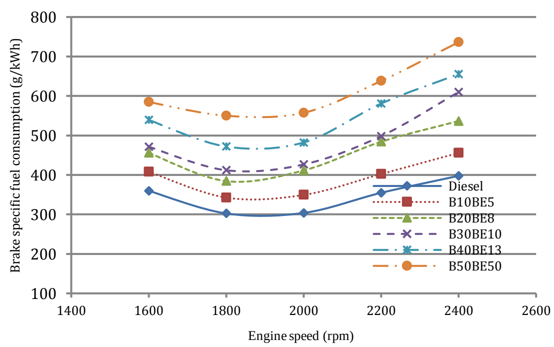

Figure 2. Variation of the brake specific fuel consumption for biodiesel-bioethanol-diesel blends at full load and various engine speeds

Engine torque

The variation of the engine torque (ET) for the J50C50 biodiesel-bioethanol-diesel fuel blend within an engine speed range of 1600–2400 rpm is shown in Figure 3. It is known that the ET increases with speed until it reaches a maximum value, followed by a decrease when the engine speed is further increased and this is evident from Figure 3. The diesel fuel has a maximum torque of 25.06 Nm at 1800 rpm. It appears that the addition of bioethanol resulted in a decrease in ET in almost every mixed composition, in which the B10BE5 mixture had the highest ET of 24.07 Nm at 1900 rpm and B50BE15 had the lowest ET of 14.31 Nm at 2400 rpm. The lower torque results in the biodiesel-bioethanol-diesel fuel blends are caused by the amount of oxygenated calories (biodiesel and bioethanol) in the fuel mixture. In addition, higher density and lower heating value in diesel biodiesel-bioethanol blended fuels, cause the lower atomization ratio [4].

In general, Figure 3 shows that the ET values for J50C50 biodiesel-bioethanol-diesel fuel blends are lower compared to that for diesel fuel. This is due to the fact that biodiesel has high viscosity, low volatility and heavier molecules and consequently, biodiesel-bioethanol-diesel fuel blends evaporate at a slower rate and they are more difficult to burn compared to diesel fuel [42]. The higher fuel viscosity reduces the amount of fuel being fed into the oil pump and the engine's volumetric efficiency remains lower, which decreases engine torque [43]. In addition, the calorific value of the fuel is a crucial constraint in determining the ET. Increasing the percentage of biodiesel in biodiesel-bioethanol-diesel fuel blends decreases the calorific value of the resultant fuel, which in turn, lowers the ET [44].

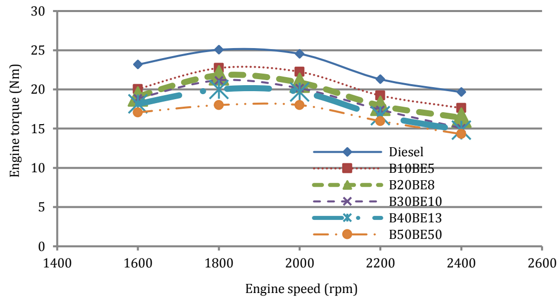

Figure 3. Variation of the engine torque for biodiesel-bioethanol-diesel blends at full load and various engine speeds

Brake power

The variation of the brake power (BP) for biodiesel-bioethanol-diesel fuel blends in the single-cylinder direct injection diesel engine is shown in Figure 4. It is known that the variation of the brake power as a function of engine speed is similar for all fuels tested in this study. When compared to other bioethanol blends, B10BE5 has a better brake power engine, which is slightly lower than diesel fuel, with a maximum BP is 4.65 kW at 1800 rpm. As the figure shows, the addition of bioethanol into the mixture decreases BP for the entire mixture. It appears that the B50BE15 mixture has the lowest BP of 2.6 kW at 1600 rpm. The decline in BP values along with the increase in bioethanol content in the mixture is associated with the decreasing lower heating value of biodiesel-bioethanol fuel because the lower heating value of bioethanol and biodiesel is lower than diesel fuel [45]. The reduction of BP is caused by frictional force, poor mixture formation as well as higher viscosity and density of the biodiesel [44, 46]. The high viscosity and lower calorific value of the biodiesel results in uneven combustion characteristics and decreases the engine brake power [47].

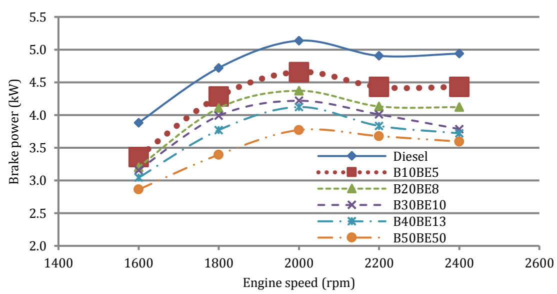

Figure 4. Variation of the brake power for biodiesel-bioethanol-diesel blends at full load and various engine speeds

Exhaust gas temperature

The exhaust gas temperature (EGT) is a parameter of the quality of combustion in the cylindrical combustion chamber. The increase in EGT is associated with more amount of fuel is required by the engine to produce the extra power which is also needed to take up the additional loading [6]. The EGT is also directly related to the air/fuel ratio, which explains why a higher air/diesel fuel ratio results in higher EGT [48]. The variation of the EGT for biodiesel-bioethanol-diesel fuel blends within an engine speed range of 1600–2400 rpm at full load is shown in Figure 5**.** It is shown that the EGT increases with an increase in engine speed up to 2200 rpm, but there is a minor decrease in the EGT at higher speeds. It appears that the addition of bioethanol in the fuel mixture results in a slight increase in EGT along with an increase in bioethanol content and engine speed. The occurrence of an increase in EGT on a small scale due to the presence of bioethanol causes shortened combustion duration in the combustion chamber [49]. B10BE5 has EGT very close to diesel fuel, while B50BE15 has the highest EGT that is 511.2 ºC. This is due to the fact that biodiesel has a higher cetane number, which results in longer ignition delay and slower burning rate [50].

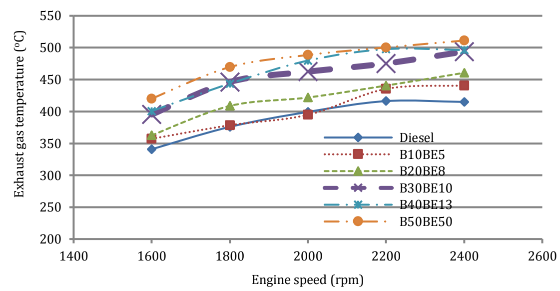

Figure 5. Variation of the exhaust gas temperature for biodiesel-bioethanol-diesel blends at full load and various engine speeds

Brake thermal efficiency

The brake thermal efficiency (BTE) is used to evaluate how well the engine is able to convert heat of from combustion of fuel into mechanical energy. The BTE is defined as the brake power of the heat engine as a function of the thermal input of the fuel. The variation of the BTE for biodiesel- bioethanol-diesel blends with different percentage of J50C50 biodiesel at various engine speeds is shown in Figure 6. It is known that, the increasing of engine speed caused the increase in BTE which reaches a maximum value at 1800 rpm. The BTE then decreases at speeds beyond 1800 rpm. Figure 6 shows the decrease in BTE reached 30.6% after addition of 15% bioethanol in the mixture (B50BE15). Decreasing the BTE value due to the addition of bioethanol may be associated with lower heating values of the mixed fuel affecting fuel injections, resulting in poor atomization during the premixed combustion phase [4]. The presence of bioethanol also has an impact on increasing latent heat of vaporization leads to increase the heat losses, as well as decreasing cetane numbers that cause longer ignition delays and incomplete combustion to occur as more fuel is burned in the expansion stroke [45].

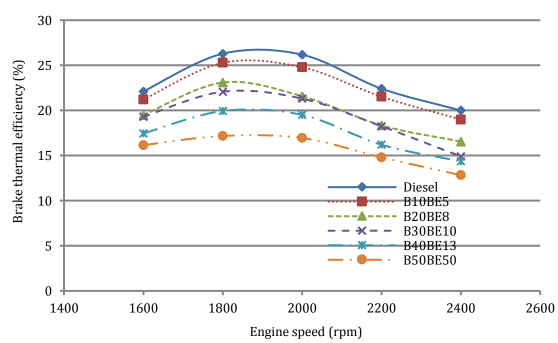

Figure 6. Variation of the brake thermal efficiency for biodiesel-bioethanol-diesel blends at full load and various engine speeds

Exhaust emissions

Nitrogen oxides

Nitrogen oxides (NO_x) are the by-products (pollutants) are positively correlated with the temperature of combustion, which is directly influenced by the engine load [51]. In general, the formation of NO_x is directly linked with the engine parameters such as in-cylinder temperature, oxygen supply, and residence time. This is due to the high activation energy required for the combustion reaction, and this reaction is determined by the equity ratio, oxygen concentration, and combustion temperature [52]. The variation of NO_x emissions for biodiesel-bioethanol-diesel fuel blends within an engine speed range of 1400−2400 rpm is shown in Figure 7. It is noticeable that the NO_x emission is higher at the extremes of the engine speed range investigated in this study for all fuels. The diesel fuel has the lowest NO_x emission (75 ppm) compared with the J50C50 biodiesel-bioethanol-diesel fuel blends. The addition of bioethanol can reduce NO_x emissions but in a small percentage. The lower NO_x emission are 75, 98, 89, 93, and 106 ppm, respectively for

B10BE5, B20BE8, B30BE10, B40BE13, and B50BE50 at 1800 rpm. However, the value of NO_x of biodiesel-bioethanol-diesel is still higher than diesel fuel. This is associated with a decrease in cetane numbers due to the addition of oxygenates. As it is known that cetane numbers have an effect on combustion, low cetane numbers lead to delayed combustion and more accumulated fuel/air mixture, resulting in increased NO_x formation [53].

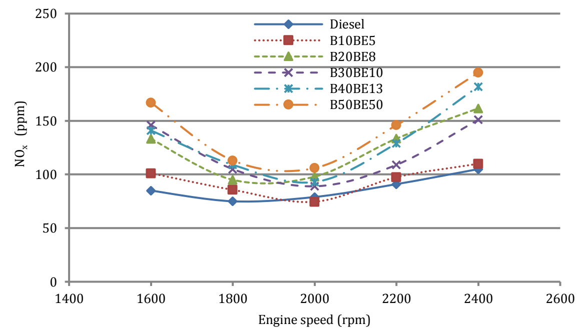

Figure 7. Variation of the NO_x emissions for biodiesel-bioethanol-diesel blends at full load and various engine speeds

Carbon monoxide

Carbon monoxide (CO) emissions are the outcomes of rich combustion with present of reduced oxygen or air in the combustion chamber [54]. The variation of the CO emissions for biodiesel-bioethanol-diesel fuel blends at speed of engine in a range of 1600–2400 rpm can be seen in Figure 8. Figure 8 shows that there is a minor increase of CO emissions when biodiesel is added to the diesel fuel. Overall test results showed a very significant reduction in CO emissions of 17.3, 20.7, 49.2, 48.8, and 46.78%, respectively after the addition of bioethanol of 5, 8, 10, 13 and 15%. The low CO emissions for mixed fuels containing bioethanol are associated with high oxygen amounts of bioethanol, which encourages further CO oxidation during the engine exhaust process [55]. It is clear that CO emissions increase at low and high engine speeds, and decrease at medium speed of 1900 rpm. Increased CO emissions at such high speeds are indirectly caused by the evaporative cooling effect of bioethanol in the emulsion, thereby causing a reduction in flame temperature and decreasing burning velocity [4].

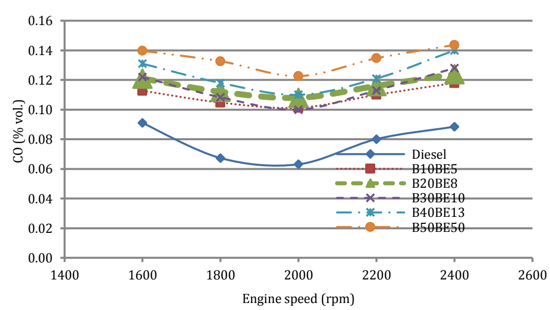

Figure 8. Variation of the CO emissions for biodiesel-bioethanol-diesel blends at full load and various engine speeds

Carbon dioxide

The burning of fossil fuels results in increasing concentrations of CO_2 in the atmosphere, which leads to the greenhouse effect. For this reason, it is important to analyze the CO_2 emissions released from diesel engines [52, 56]. CO_2 is produced when the amount of oxygen present in the combustion chamber is sufficient for complete combustion (in other words, ideal combustion). However, complete combustion is rare in practice, resulting in the formation of CO as one of the by-products [57]. The variation of CO_2 emissions for biodiesel-bioethanol-diesel fuel blends at the engine speed ranges from 1600 to 2400 rpm are shown in Figure 9. The results show that the diesel fuel has higher CO_2

emission (4.16%vol.) compared to other biodiesel-bioethanol-diesel blends at 2000 rpm. As seen in the figure that the increase in bioethanol content in line with decreasing CO_2 emissions. When compared to the biodiesel-diesel fuel mixture, the average CO_2 emissions level decreased to 59.5% after the addition of bioethanol. Reduced of CO_2 emissions due to low carbon-to-hydrogen ratios contained in bioethanol molecules can increase the oxidation of CO molecule to CO_2, resulting in more water formation and less CO_2 gas [4].

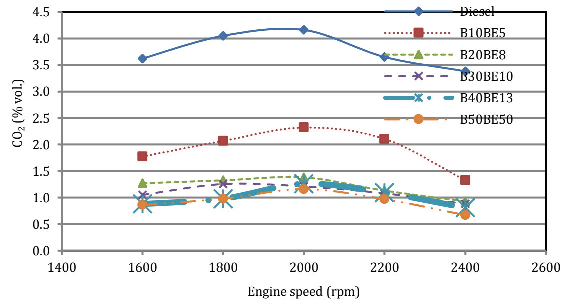

Figure 9. Variation of the CO_2 emissions for biodiesel-bioethanol-diesel blends at full load and various engine speeds

Smoke opacity

The smoke opacity is an indicator of dry soot and particulate matter emissions. In diesel engines, the atomized fuel splits into carbon (formation of soot) during the combustion process and the carbon then oxidizes in the reaction zone (soot oxidation). The carbon particles (known as soot or smoke) form if the amount of oxygen or the local temperature does not support the oxidation process [58]. The variation of the smoke opacity for biodiesel-bioethanol-diesel fuel blends at various engine speeds are shown in Figure 10**.** The addition of bioethanol caused on the reduction of smoke opacity produced. As indicated by Figure 10 that there is a decrease in smoke opacity due to the addition of bioethanol to the biodiesel-diesel fuel blends. The decrease in smoke opacity averaged a small percentage when compared to the use of biodiesel-diesel fuel blends, which were 4.01, 3.35, 1.44, 3.76 and 3.79%, respectively after the addition of bioethanol of 5, 8, 10, 13 and 15%. Reduced smoke opacity in bioethanol-fueled fuels can be attributed to a decrease in maximum flame temperature in the combustion chamber due to backward injection time, these impacts on the ignition delay. The ignition delay makes fuel and air mixed homogeneously and affects the decreased amount of opacity smoke produced [41]. The addition of bio-ethanol which is an oxygenated fuel also causes an increase in the oxygen content in the fuel, which affects the decrease in the formation of soot precursors, so that the opacity smoke produced can be reduced [59].

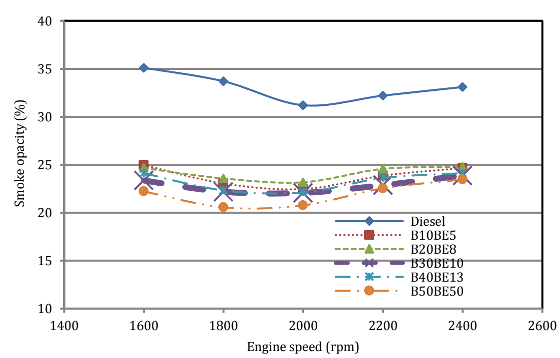

Figure 10. Variation of the smoke opacity for biodiesel-bioethanol-diesel blends at full load and various engine speeds

CONCLUSION

Experimental tests on engine performance and exhaust emissions as a result of the addition of bioethanol into the biodiesel-diesel fuel blends up

to 15% in volume on the emission and performance pattern of *Jatropha curcas-Ceiba pentandra* biodiesel/bioethanol blends was investigated. The following conclusions arise from this study.

- The B10BE5 (containing 10% of J50C50 biodiesel and 5% of bioethanol) showed the potential results of significant physicochemical properties.
- Lower heating value was decreased in diesel biodiesel-bioethanol blended fuels can cause the lower atomization ratio.
- The engine torque, brake power and brake thermal efficiency of B10BE5 has 20.06 Nm, 4.7 kW and 25.3%.
- The CO emissions were lower for B10BE5 than other blends under all conditions. This is because of higher oxygen in the blends.
- NO_x emissions for B10BE5 blends displayed comparable behaviours under all conditions. NO_x emissions lowered with an increase in oxygen percentage in the blend
- Smoke opacity decreased for all blends with the reduction compare to diesel fuel due to the dominance of oxygenated of blends

The presented experimental results demonstrate the viability of biodiesel–bioethanol blends in diesel fuel use for compression ignition engines.

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