Energy Conversion and Management 76 (2013) 362–367

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Production of palm and Calophyllum inophyllum based biodiesel and investigation of blend performance and exhaust emission in an unmodified diesel engine at high idling conditions

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ARTICLE INFO

Article history:
Received 27 May 2013
Accepted 27 July 2013

Keywords:
Biodiesel
Palm
Calophyllum
Idling
Emission
Fuel consumption
Production

ABSTRACT

Rapid depletion of fossil fuels, increasing fossil-fuel price, carbon price, and the quest of low carbon fuel for cleaner environment – these are the reason researchers are looking for alternatives of fossil fuels. Renewable, non-flammable, biodegradable, and non-toxic are some reasons that are making biodiesel as a suitable candidate to replace fossil-fuel in near future. In recent years, in many countries of the world production and use of biodiesel has gained popularity. In this research, biodiesel from palm and Calophyllum inophyllum oil has been produced using the trans-esterification process. Properties of the produced biodiesels were compared with the ASTM D6751 standard: biodiesel standard and testing methods. Density, kinematic viscosity, flash point, cloud point, pour point and calorific value, these are the six main physicochemical properties that were investigated. Both palm biodiesel and Calophyllum biodiesel were within the standard limits, so they both can be used as the alternative of diesel fuel. Furthermore, engine performance and emission parameters of a diesel engine run by both palm biodiesel–diesel and Calophyllum biodiesel–diesel blends were evaluated at high idling conditions. Brake specific fuel consumption increased for both the biodiesel–diesel blends compared to pure diesel fuel; however, at highest idling condition, this increase was almost negligible. Exhaust gas temperatures decreased as blend percentages increased for both the biodiesel–diesel blends. For low blend percentages increase in NO_X emission was negligible but as blend percentages increase, emission increased significantly. CO and HC emission for both biodiesel–diesel blends were lower compared to pure diesel fuel. 20% Calophyllum biodiesel–diesel blends emitted lowest HC and CO emission.

1. Introduction

Diesel fuel is one of the major sources of energy in transportation, agricultural and industrial sector. Adaptability, reliability, higher combustion efficiency and handling facilities – for these key qualities diesel fuel is widely used all over the world [1]. However, emissions from fossil fuels are one of the leading cause environment pollution [2]. Researchers suggests that if no strict policy is undertaken, these emissions will rise up to 39% in 2030 [3]. Again, fossil fuel depletion is another major problem currently the world is facing today. To resolve these problems, researchers are concentrating on developing renewable fuels which will be able to satisfy worldwide energy demand and also they must be technically viable, environmentally suitable, and domestically obtainable. It is predicted that, within 2015, renewable fuels will be the second largest energy source in the power production sector. Increasing fossil fuel price and carbon pricing as well as decreasing technology costs – these factors are hugely liable for the fast growth in the popularity of renewable energy. Biodiesel is considered as a vital source of renewable energy since it has the potential to reduce greenhouse gases, fulfill energy demand and reduce global warming [4]. In a short period of time, from 2001 to 2010, biodiesel production increased to 294,690 barrels per day, whereas, consumption increased to 313,770 barrels per day from 16,490 barrels per day. Biodiesel, denoted also as the fatty acid methyl ester, are produced from animal fats or vegetable oils by using dilution, pyrolysis, microemulsion and trans-esterification process [5,6]. Advantage of biodiesel is that it is environment friendly, renewable, non-flammable, biodegradable, and non-toxic [7,8]. One of the biggest plus point of biodiesel is that its properties are comparable with diesel fuel [9,10]. Another advantage of using biodiesel is that, pure or blended with diesel, it can be used in an unmodified diesel engine [11].

When engine is run with biodiesel and their blends with diesel fuel it affects the engine performance and emissions of diesel engine.

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0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.07.061

Many researches have been done to evaluate engine performance and emissions using biodiesel and their blends [12–22]. Also, many researches has been done to evaluate the engine performance and emissions using only diesel fuel at idling condition [23–31]. However, there has been only one study that was done to investigate the impact of biodiesel on engine performance and emission during high idling condition [32]. When the engine runs at low load and at rated speed it is called high idling condition. Currently this is the major problem truck industry is currently facing. After driving for a certain period, it is mandatory for drivers to take a rest. During this time, the drivers keep the engine idling in order to maintain cab comfort and to provide power to the loads in the cab, such as heating, air conditioning, refrigerators, and microwaves [33–36]. Studies indicate that long-haul trucks are idling for between 6 and 16 h daily [37]. When the engine is running in idle conditions, it takes a rich mixture of air and fuel, such that the fuel consumption rate is high. Furthermore, during idling, the engine is not able to work at peak operating temperature and the combustion of fuel is incomplete, which leaves fuel residues in the exhaust and thus, emission levels increases. As biodiesels application in diesel engine will increase day by day, more studies needs be conducted to find out the impact of using biodiesel on fuel consumption and exhaust emissions of diesel vehicles at high idling condition.

In this experiment production process of palm biodiesel and Calophyllum inophyllum biodiesel has been discussed. Also, engine performance and exhaust emission test while running blends of these biodiesels during idling condition has been reported too. Also, comparison with the results obtained while running the engine with diesel fuel has been reported too.

2. Feedstocks

2.1. Palm oil

Amongst the plant families, palms are the most popular and extensively cultivated. *Elaeis guineensis* Jacq is the most highly productive species. It can be cultivated in all tropical areas where weather is humid and hot like Malaysia and Indonesia [38]. This particular variety can annually produce 10–35 tonnes/ha of palm fruits. Oil is extracted from both the pulp and the seed. Oil palm trees are commercially cultivated to serve edible oil to the market [39].

2.2. Calophyllum inophyllum

Calophyllum inophyllum, also known as Penaga Laut, is a non-edible oilseed ornamental tree which belongs to *Clusiaceae* family [40,41]. It grows in coastal areas and areas where there are adjacent lowland forests. It grows in warm temperatures in wet or moderate conditions and a minimum of 1000–4000 mm rainfall is also needed per year. Its kernels have high oil content, the average oil yield is 11.7 kg-oil/tree or 4680 kg-oil/ha.

3. Biodiesel production process

All the feedstock oils were purchased from local farm of Malaysia and Indonesia respectively. All necessary chemicals for trans-esterification were purchased from LGC Scientific, Kuala Lumpur, Malaysia.

Biodiesel was produced using the following two steps:

(1) Acid esterification.
(2) Base trans-esterification process.

Methanol was used as solvent with sulfuric acid (H_2SO_4) and potassium hydroxide (KOH) for acid and base trans-esterification respectively. First step is needed if the acid value of crude oil is higher than 4 mg KOH/gm. Acid value was calculated directly by doing titration. For Calophyllum inophyllum oil, both steps were needed and for palm oil, only base trans-esterification was needed.

Using acid catalyst, the first step reduced free fatty acids (FFA) level of crude vegetable oil up to 1–2%. A favorite jacket reactor of 1 l capacity was used with IKA Eurostar digital model stirrer and Wiscircu water bath arrangement. 1 Liter of crude vegetable oil with 200 ml methanol and 0.5% v/v sulfuric acid were taken in the flask for acid catalyzed esterification. The mixture was constantly stirred at 700 rpm and a temperature range of 50–60 °C maintained at atmospheric pressure by circulating hot water through the jacket. To determine the FFA level, 5 ml sample was taken from the flask at every 10 min interval and trans-esterification process was carried out until FFA level was reduced up to 1–2%. After completing the acid esterification process the product was poured into a separating funnel where sulfuric acid and excess alcohol with impurities were moved to the top. Top layer was separated and lower layer was collected for base trans-esterification.

Same experimental setup was used for alkaline catalyzed trans-esterification process. Meanwhile, 1% w/w of KOH dissolved in 25% v/v if methanol was poured into the flus. Then the mixture was stirred at same speed and temperature was maintained at 70 °C. The mixture was heated and stirred for 3 h and again poured into a separating funnel where it formed two layers. Lowered layer contained glycerol and impurities and upper layer was methyl ester of vegetable oil. Lower layer was discarded and yellow upper layer was washed with hot distilled water (100% v/v) wand stirred gently to remove remaining impurities and glycerol. Biodiesel was then taken in an IKA RV10 rotary evaporator to reduce the moisture content. Finally, moisture was absorbed by using sodium sulfate and final product was collected after filtration.

4. Biodiesel property test

The properties of palm biodiesel (PB100), diesel and Calophyllum inophyllum biodiesel (CIB100) were measured at the Energy Laboratory and the Engine Tribology Laboratory, Department of Mechanical Engineering, University of Malaya. Density, kinematic viscosity, flash point, cloud point, pour point and calorific value, these six main physicochemical properties were measured using following methods. Table 1 shows the summary of equipments and methods used to determine fuel properties. Table 2 shows the individual fuel properties along with standard biodiesel properties.

5. Engine test

An inline four cylinder, water cooled Mitsubishi Pajero engine was used to perform the engine test. The engine was coupled with an eddy current dynamometer which can be operated at a maximum power of 20 kW with operating speed ranged from 1000 to 4000 rpm. The engine test was conducted at three idling conditions, which are: 1000 rpm at 10% load (1.25 kW), 1200 rpm at 12% load (1.8 kW) and 1500 rpm at 15% load (2.82 kW). Fuels tested were: Diesel, PB5 (5% palm biodiesel–diesel blend), PB10 (10% palm biodiesel–diesel blend), PB20 (20% palm biodiesel–diesel blend), CIB5 (5% Calophyllum biodiesel–diesel blend), CIB10 (10% Calophyllum biodiesel–diesel blend), and CIB20 (20% Calophyllum biodiesel–diesel blend). Fig. 1 shows the schematic diagram of the experimental setup. The engine specification is listed in Table 3. To measure fuel consumption, exhaust gas temperature, power, and speed of engine sensors were installed and data were collected through data logger via software named "REO-dCA". Also, exhaust emissions

Table 1
List of equipment used for fuel properties testing.

Property	Equipment	Model	Manufacturer	Standard method	Accuracy
Flash point	Pensky-martens flash point tester	NPM 440	Normalab, France	ASTM D93	±0.1 °C
Cloud and pour point tester	Cloud and pour point tester	NTE 450	Normalab, France	ASTM D2500	±0.1 °C
Kinematic viscosity and density	Stabinger Viscometer	SVM 3000	Anton Paar	ASTM D7042	±0.1 mm^2/s
Calorific value	Semi auto bomb calorimeter	6100EF	Perr, USA	ASTM D240	±0.001 MJ/kg

Table 2
Fuel properties of diesel, palm biodiesel and Calophyllum inophyllum biodiesel.

Properties	Unit	Diesel	Palm biodiesel	Calophyllum inophyllum biodiesel	ASTM D6751-06 standard
Density	kg/m^3	833.1	858	869	860–900
Cetane number	–	47	52	57	47 min
Viscosity	mm^2/s	3.556	4.63	4.0	1.9–6.0
Flash point	°C	77.5	189	140	130 min
Cloud point	°C	8	6	13.2	−3 to 12
Pour point	°C	6	2	4.3	−15 to 10
Calorific value (lower)	kJ/g	44.664	39.907	41.397	–

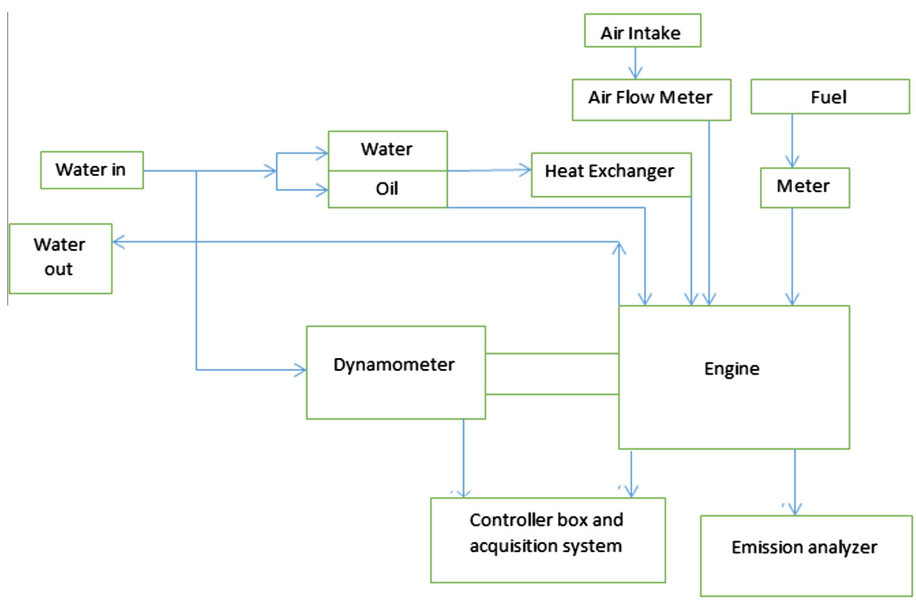

Fig. 1. Schematic diagram of the engine test bed.

Table 3
Engine specification.

Engine type	4 Cylinder inline
Displacement	2.5 L (2476 cc)
Bore	91.1 mm
Stroke	95.0 mm
Injection system	Direct, naturally aspirated
Torque	Max. 132 N-m, at 2000 rpm
Power	Max 50 kW at 4000 rpm
Compression ratio	21:1
Injection pump	Common rail mechanically controlled

were measured using BOSCH BEA-350 exhaust gas analyzer and AVL 4000. AVL 4000 was used to measure NO_X (Table 4).

The engine was connected with test bed and a computer data acquisition system. Data acquisition system collects signal, rectify, filter and convert the signal to the data to be read. The data acquisition board is connected to the laptop, where user can monitor, control and analysis the data using REO-dCA software. Using this software the engine was operated at the three idling conditions. When the engine is operated at idling conditions engine performance and fuel consumption data's are stored in the computer through the software. For performance test, each fuel sample has been tested for three times and their results are averaged.

Table 4
Equipment used in engine test.

Equipment name	BOSCH BEA-350 exhaust gas analyzer
Measured	HC (parts per million or ppm)
	Carbon monoxide (percentage volume or %vol)
	Carbon dioxide (percentage volume or %vol)
Equipment name	AVL 4000 (Manufacturer: Graz/Austria)
Measured	NO_X (parts per million or ppm)
Equipment name	DYNOMAX 2000 data control system
Measured	Exhaust gas temperature (EGT)
	Brake specific fuel consumption (BSFC)

6. Results and discussion

Fig. 2 shows the brake specific energy consumption at different idling conditions for diesel, palm biodiesel and Calophyllum biodiesel blends. At all idling conditions, energy consumption rate for diesel fuel was lowest. As blend percentages increased bsec increased due to having lower heating value compared to diesel fuel. However, at 1500 RPM, slightly higher combustion temperature and additional oxygen content of the biodiesel facilitate better combustion and shows less increase in bsec compared to diesel than that was seen in other speeds. The brake specific energy consumption of PB20 at all idling conditions were higher than any other fuel sample. As Calophyllum biodiesel has higher heating value than palm biodiesel, it showed improved energy consumption rate compared to palm biodiesel, still however, energy consumption rate was higher than diesel in all condition.

Brake thermal efficiency is defined as break power of a heat engine as a function of the thermal input from the fuel. It is used to evaluate how well an engine converts the heat from a fuel to mechanical energy. Fig. 3 demonstrates brake thermal efficiency at different idling conditions for diesel calophyllum and palm biodiesel–diesel blends. The equation to calculate BTE is,

$BTE = 3600 \times 10^6/(CV \times BSFC)\%$. From Fig. 3 it can be seen that for conditions 1000 RPM 10% load and 1200 RPM 12% load BTE for both the biodiesel–diesel blends decreases significantly. This is due to the reason that, with increase in blend percentages, calorific value decreases, so the fuel consumption of the engine should increase to maintain same power output. But, these increases were much higher than it was supposed to be. As a result there is rapid decline of BTE for these two conditions. However, at 1500 RPM and 15% load engines increase in bsfc is almost inversely proportional to the decrease of calorific value of the blends. As a result at this condition, BTE of the engine is almost constant for all the fuels tested. Compare to palm biodiesel, Calophyllum achieved better efficiency, however, diesel fuel achieved highest efficiency at all conditions.

Heating value, cetane number, density and kinematic viscosity these four physicochemical properties have potential impact on exhaust gas temperature (EGT). Diesel fuel was found to have the highest EGT value at all conditions tested. All biodiesel blends tested showed lower EGT than diesel fuel due to higher cetane number, higher viscosity and density and lower heating value of biodiesels. Lower EGT is an indication of good burning of fuel inside cylinder. As blend percentages increased EGT decreased. As, compared to palm biodiesel, Calophyllum biodiesel have higher cetane number, higher viscosity and density and lower heating value, so as a result, it was seen that Calophyllum biodiesel–diesel blends achieved lower EGT than the palm biodiesel-blends (Fig. 4).

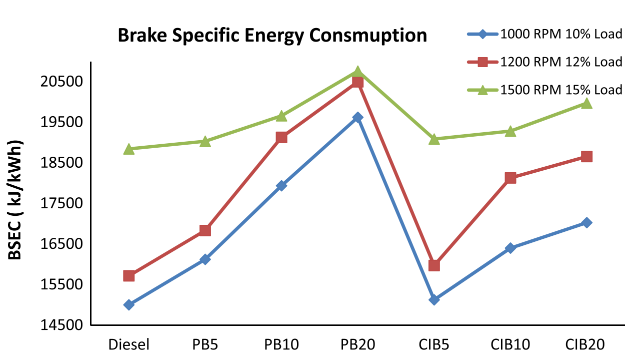

Fig. 2. Brake specific energy consumption at different idling conditions for diesel, palm biodiesel and Calophyllum biodiesel blend.

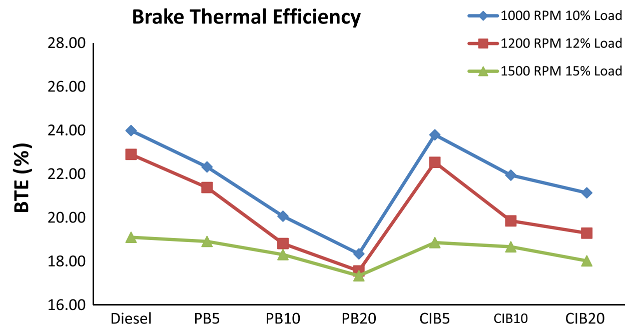

Fig. 3. Brake thermal efficiency at different idling conditions for diesel, palm biodiesel and Calophyllum biodiesel blend.

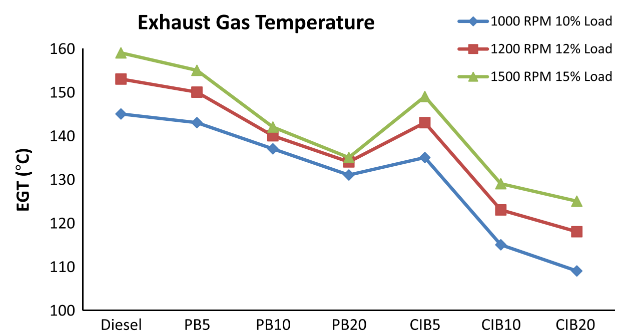

Fig. 4. Exhaust gas temperature at different idling conditions for diesel, palm biodiesel and Calophyllum biodiesel blend.

Generally CO formation is resulted from incomplete combustion. Incomplete combustion occurs when flame front approaches to crevice volume and relatively cool cylinder liner. Therefore, flame temperature is cooled down and results in incomplete progression to CO_2.

Fig. 5 shows CO emissions at different idling conditions for diesel, palm biodiesel and Calophyllum biodiesel blend. The lowest CO emission is achieved for CIB20 at all the operating conditions. Also, in every condition diesel fuel produced maximum emission. As blend percentage of biodiesel in diesel increased emission decreased, this may be due to the higher concentration of O_2 in the air–fuel mixture which ensured improved combustion and hence reduction in CO emission at idling conditions. Compared to Calophyllum biodiesel, palm biodiesel showed less decrease in CO emission as blend percentages increased. This is may be due to the reason that palm biodiesel has higher viscosity than Calophyllum biodiesel, which degraded the spray characteristics and caused improper mixing which led to improper combustion.

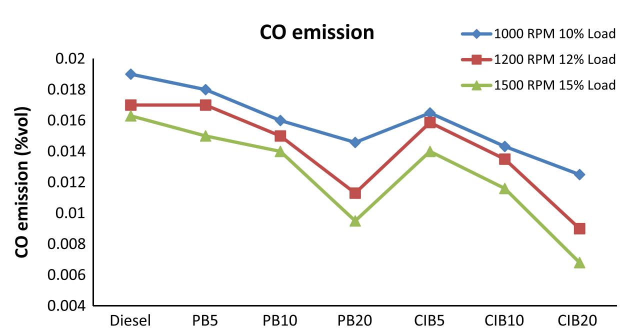

Fig. 5. CO emissions at different idling conditions for diesel, palm biodiesel and Calophyllum biodiesel blend.

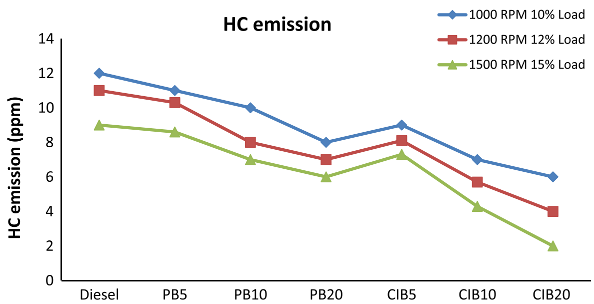

Fig. 6. HC emissions at different idling conditions for diesel, palm biodiesel and Calophyllum biodiesel blend.

Fig. 6 represents HC emission at different idling conditions for diesel, palm biodiesel and Calophyllum biodiesel. It can be seen that, diesel fuel emits highest amount of HC at all conditions and CIB20 blend emits lowest.

Again, as there is higher oxygen concentration in the biodiesel–diesel blends which enhances the oxidation of unburned hydrocarbons, HC emission decreases with increase in percentages of biodiesel blends. Furthermore, increase in speed decreases HC emission for all tested fuel. This is due to the reason that increase in speed ensures better mixing of air and fuel.

Fig. 7 demonstrates NO_X emission at different idling conditions for diesel, palm biodiesel and Calophyllum biodiesel blends. Diesel fuel exhibited lowest emission at all condition. As blend percentages of biodiesel increases emission increases. CIB20 emitted highest amount of NO_X and were closely followed by PB20. Biodiesel blends produce higher emission due to having higher cetane number and lower ignition delay. However, it is observed that as engine speed increases emission decreases due to the fact that increase in speed reduces the ignition delay which results in less amount of time to form NO_X. To describe the reason behind the increase in NO_X emission it is useful to define three separate periods within the overall combustion cycle:

- Ignition delay period.
- Pre-mixed combustion period.
- Diffusion combustion period.

The ignition delay period is the time between start of injection and start of ignition. This period is related to the cetane number of the fuel, with higher cetane leading to shorter ignition delay. Typically, biodiesel fuels have higher cetane numbers than petroleum diesel [42,43]. A shorter ignition delay could allow the fuel mixture and initial combustion products to have a longer residence time at elevated temperature, thereby increasing thermal NO_X formation. Again, during the pre-mixed combustion period, fuel and air that have already mixed ignite, causing a rapid rise in temperature and pressure. The extent to which these temperature and pressure increases occur depends upon the amount of fuel that has already been injected, which is related to the length of the ignition delay. With longer ignition delays, more fuel is injected and mixed with air before ignition occurs, thus leading to more extreme temperature and pressure increases. And thus increases NO_X emission.

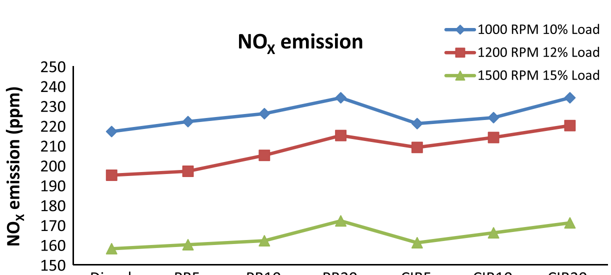

Fig. 7. NO_X emissions at different idling conditions for diesel, palm biodiesel and Calophyllum biodiesel blend.

The results obtained from this study is supported by Roy et al. [32]. Authors found that CO emissions for all fuels are lower at higher engine speeds, and the higher the biodiesel percentage in biodiesel–diesel blends, the lower the CO emissions are. Also, HC emission showed similar trends. Upto 5% biodiesel blends NO_X increase was negligible but as blend percentage moved up to 20% emission increased significantly.

7. Conclusion

Pure palm and Calophyllum inophyllum biodiesel have been produced and their fuel characteristics have been evaluated. An experimental investigation has been carried out to figure out the engine performance and emission parameters at high idling conditions. The most important conclusions derived are summarized as follows:

- Biodiesel produced from palm and Calophyllum both satisfies the ASTM standards and thus can be used as alternative to diesel fuel.
- At high idling conditions, brake specific energy consumption for both palm biodiesel and Calophyllum biodiesel blends increased compare to diesel fuel. However, at the highest idling speed the difference of energy consumption was almost negligible. As blend percentages of biodiesel increased energy consumption increased.
- Due to having higher heating value compared to palm biodiesel, Calophyllum biodiesel blends produced better BSEC.
- CO and HC emission decreased with increase in blend percentages and at all tested conditions they were lower than diesel fuel. CIB20 achieved lowest emission in both the cases.
- Increase in NO_X emission for small blend percentages were negligible compared to diesel, however, PB20 and CIB20 emission increased significantly.
- Exhaust gas temperature was lower for all biodiesel blends compared to diesel fuel at all tested conditions. Lower EGT indicates better burning of fuel. With the increase in blend percentages of palm biodiesel and Calophyllum biodiesel EGT also decreased, CIB20 achieved the lowest EGT amongst all blends.
- Compare to palm biodiesel, Calophyllum achieved better efficiency, however, diesel fuel achieved highest efficiency at all conditions.
- For conditions 1000 RPM 10% load and 1200 RPM 12% load BTE for both the biodiesel–diesel blends decreased significantly.

Acknowledgements

The authors would like to appreciate University of Malaya for financial support through High Impact Research grant titled: Clean Diesel Technology for Military and Civilian Transport Vehicles having Grant number UM.C/HIR/MOHE/ENG/07.

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