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Combustion, performance and emission characteristics of a DI diesel engine fueled with *Brassica juncea* methyl ester and its blends

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Abstract

In this study, mustard biodiesel (B100) was produced from low quality crude mustard oil and tested in a 4-cylinder, direct-injection, diesel engine to investigate the combustion, performance and emission characteristics of the engine at different engine speed and full load condition. Biodiesel and its blends showed increased peak cylinder pressure and reduced ignition delay when compared to diesel fuel (B0). Pre-mixed combustion phase and the start of injection timing for B100 and its blends took place earlier than B0. During engine performance tests, 10% and 20% biodiesel blends showed 4-8% higher brake specific fuel consumption and 9-13% lower brake power compared to diesel fuel. Engine emissions tests showed 9-12% higher NO, 19-42% lower HC, and CO for B100 blends compared to B0. In conclusion, 10% and 20% B100 blends can be used in diesel engines without modifications.

Keywords: Mustard biodiesel; Characterization; Combustion characteristics; Engine performance; Emission analysis;

Nomenclature	
% vol	Percentages of volume
ASTM	American society for testing and materials
ATDC	After Top Dead Centre
BSFC	Brake specific fuel consumption
BSEC	Brake specific energy consumption
BTE	Brake Thermal Efficiency
BP	Brake Power
CN	Cetane Number
CO	Carbon-monoxide
CA	Crank Angle
B0	Diesel fuel
FAC	Fatty Acid Composition
FFA	Free Fatty Acid
GC	Gas Chromatography
HC	Hydrocarbon
H_2SO_4	Sulphuric Acid
IV	Iodine Value
KOH	Potassium Hydroxide
B100	Mustard Biodiesel
MSO	Mustard Seed Oil
NO	Nitric oxide
NO_x	Oxides of nitrogen
PB	Palm Biodiesel
ppm	Parts per million
rpm	Revolution per minute
SN	Saponification Number
TDC	Top Dead Centre
B10	10% biodiesel blended with 90% diesel
B20	20% biodiesel blended with 80% diesel

1. Introduction

To preserve economic growth and maintain standard of living, energy has become an indispensable factor for mankind. The industrial economy of a country and global primary energy production is very much dependent on non-renewable fossil energy. This ever-increasing energy consumption is not sustainable due to the unequal geographical distribution of fossil fuels as well as environmental, geopolitical and economic concerns. Most importantly, fossil resources like coal, petroleum and natural gas are non-renewable, and the price of petroleum is escalating day by day [1, 2]. Additionally, the use of fossil fuels incurs a high level of greenhouse gas emissions, which pollute the environment [3]. This twin crisis of energy and environmental degradation have motivated researchers to not only look into new strategies and engine optimization to reduce the harmful emission, but also find alternative energy resources [4]. To ensure global energy security, biodiesels are considered a renewable and ecofriendly source of energy [5]. As an alternative fuel, biodiesel is one of the best options among other renewable fuel sources due to its potential to reduce exhaust pollutants and to be used in the diesel engine without any modification.

Biodiesels are mono alkyl esters and are generally derived from the fatty esters of vegetable oil or animal fat through chemical treatment [6, 7]. Biodiesel differs from diesel fuel in its physicochemical properties. Many chemical treatments are available to convert vegetable oil into biodiesel to improve the physicochemical properties. Transesterification is one of the most popular chemical treatments to reduce the density and viscosity of crude vegetable oil. Biodiesel extraction sources vary from country to country depending on environmental conditions and the availability of feedstock. Biodiesel can be extracted from both edible (palm, coconut, rapeseed, canola) and non-edible (jatropha, calophyllum, rubber, cotton seed, mahua) oil sources [8].

The mustard plant belongs to the Brassicaceae plant family, which is a very rich source of many important biodiesel feedstocks such as *Brassica alba* L., *Brassica napus* L., *Camelina sativa* L. and *Brassica carinata* L. Among these, rapeseed has gained widespread acceptance as a common biodiesel feedstock [9].The production cost of mustard oil is lower than that of rapeseed or canola, although it is relatively a new feedstock for biodiesel production. Mustard plants can be grown in drier areas and require lower amounts of pesticides and other agricultural inputs than rapeseed. Excessive amount of erucic acid (more than 50%) generally makes mustard non-edible, although it is used as a condiment and in pickles [10]. In some studies, it was found that low quality mustard seed oil which is unsuitable for food use can be adopted for biodiesel production [11]. After oil extraction, mustard seeds cannot be fed to livestock due to the hot mustard flavor. Hence, mustard oil is suitable for biodiesel production and, unlike canola, using mustard as a biodiesel feedstock does not interfere with the food chain.

Mustard seeds are hard and round, and usually around 1 to 1.5 millimeters in diameter with a color ranging from yellow to light brown. Mustard oil is extracted by pressing these seeds. In a realistic harvest of winter mustard in Finland, about 1200 kg of mustard seed are grown per hectare of land; around 300 liters of mustard oil can be extracted from 1200 kg of seeds [11]. Zheljazkov et al. [10] found that around 590-875 kg of mustard biodiesel can be produced from one hectare of land. As the cost of the pressing device is low, so B100 can be produced at a cost compared with untaxed diesel fuel and appears to be an economically acceptable biodiesel feedstock for use in the near future. Indian mustard (*Brassica juncea* L.) is a species of Brassicaceae family and is an annual herbaceous plant [12]. *Brassica juncea* has high yield potential when grown in humid and hot areas, and intensive research is being carried out to improve its productivity. Recently, in Australia, Indian mustard has been introduced as a short season oil seed crop in regions where rainfall is low[13].

Fig.1. Mustard (*Brassica juncea*) plant and seed

Limited data have been published on testing B100 and MSO [14]. A farmer in southwestern Finland fueled his tractor with low quality seed pressed mustard oil and found promising performance and emission characteristics. Niemi et al. [15] were inspired to carry out research based on this interesting finding. A turbocharged four-cylinder DI diesel engine was fueled with MSO without any modification. Similar brake torque, break thermal efficiency and in-cylinder pressure rise were found for MSO compared to diesel fuel. In another set of experiments, Niemi and Illikainen [16] found more promising performance and emission for MSO by adjusting the injection timing. Replacing diesel fuel with MSO initially reduced NO_x emission, which was further reduced by advancing injection timing. Under idling conditions, wet NO_x emission was 160 ppm for MSO and around 360 ppm for diesel fuel. The break specific CO emission was found to be almost equal for both fuels. Different components of HC emissions were measured separately, but overall HC emissions for MSO were lower than with diesel fuel. Azad et al. [17] investigated different blends of B100 in a four-stroke single cylinder diesel engine and found good results for the 20% blend regarding overall BTE; however, the maximum BTE was found for the 30% B100 blend. Anubumani and Singh [18] experimented with a four-stroke single cylinder CI engine fueled with mustard and neem biodiesels and found better engine performance for the 20% B100 blend compared to neem biodiesel and diesel fuel. Less significant variations in smoke intensity were found between neem and B100; 20% B100 showed a marginal decrease in smoke intensity. However, a comparison of the combustion, engine performance and emission characteristics of the mustard biodiesel with diesel fuel are not available in the scientific literature.

The aims of this experimental endeavor were to produce, characterize and analyze the combustion, engine performance and emission of mustard biodiesel pressed from low quality inedible mustard seed. Combustion, engine performance and emission were carried out for B10, B20 and B100 blends and compared with B0.

2. Materials and methodology

2.1. Feedstock and chemicals

Mustard oil extracted from low quality inedible seeds was purchased from local farms in Bangladesh. All necessary chemicals for the transesterification process were purchased from LGC Scientific, Kuala Lumpur, Malaysia.

2.2. Equipment list

The transesterification, blending and analysis of test fuels were carried out at the Energy Laboratory and the Engine Tribology Laboratory, Department of Mechanical Engineering, University of Malaya. Table 1 shows the summary of the equipment and methods used to determine the fuel properties.

Table 1

List of equipment used for testing fuel properties

2.3. Biodiesel production process

Generally, transesterification is performed in two steps: (1) acid esterification and (2) base transesterification. Acid esterification is needed if the acid value of the vegetable oil is greater than 4 mg KOH/g. The acid value is calculated by performing a titration. For mustard oil, only base transesterification was needed as acid values were found to be lower than 4 mg KOH/g .

For the base transesterification process, a jacket reactor with a 1 liter capacity was used with a IKA Eurostar digital model stirrer and a Wiscircu water bath arrangement. Meanwhile, 1% w/w of KOH (base catalyst) dissolved in 25% v/v methanol and poured into the flux. Then, the mixture was stirred at 700 rpm and the temperature was maintained at 70°C. The mixture was heated and stirred for 3 h and poured into a separating funnel where it formed two layers. The lower layer contained glycerol and impurities and the upper layer consisted of the methyl esters of vegetable oil. The lower layer was discarded and the yellow upper layer was washed with hot distilled water (100% v/v) and stirred gently to remove remaining impurities and glycerol. The biodiesel was then processed in an IKA RV10 rotary evaporator to reduce the moisture content. Finally, the moisture was absorbed using sodium sulfate and the final product was collected after filtration.

2.4. Fatty acid composition

Different vegetable oils have different fatty acid compositions (FAC). The FAC is unique for a particular species. Table 2 shows the FAC of B100. Gas chromatography (GC) analysis (Agilent 6890 model) was used to determine the FAC. Table 3 shows the GC operating conditions. Single bonded fatty acids are known as saturated fatty acids, while fatty acids containing double bonds are known as unsaturated fatty acids. B100 contains only 5% saturated fatty acids, with the remainder as unsaturated fatty acids. More than 53% erucic acid was found by GC analysis, which is a unique characteristic for this feedstock. This high amount of erucic acid makes the oil inedible.

Table 2

Fatty acid composition of mustard biodiesel

Table 3

GC operating conditions

2.5. Characterization of fuel properties

The major physicochemical properties of crude mustard oil, B10, B20, B100 and B0 were measured and are presented in Table 4. Characterization of the produced biodiesels was done according to U.S. biodiesel standard ASTM D6751. The saponification number (SN), iodine value (IV) and cetane number (CN) were calculated using the fatty acid composition results and empirical equations (1), (2) and (3), respectively [19].

$$\mathrm{SN} = \sum \frac{(560 \times \mathrm{Ai})}{\mathrm{MWi}} \dots\dots\dots\dots\dots (1)$$

$$\mathrm{IV} = \sum \frac{(254 \times \mathrm{D} \times \mathrm{Ai})}{\mathrm{MWi}} \dots\dots\dots\dots\dots (2)$$

$$\mathrm{CN} = 46.3 + \frac{5458}{\mathrm{SN}} - \frac{0.225}{\mathrm{IV}} \dots\dots\dots.. (3)$$

where A_i is the weight percentage of each fatty acid component, D is the number of double bonds present in each fatty acid and MW_i is the molecular weight of each fatty acid component.

Table 4

Physicochemical properties of mustard biodiesel and its blends compared to diesel

2.6. Blending of biodiesel

Biodiesel blends were prepared using an electric homogenizer. The homogenizer was fixed on a vertical stand by a clamp which allows its height to be changed. The homogenizer was rotated at 2000 rpm to mix biodiesel with B0. All blending percentages were volume based proportions.

2.7. Engine set-up and exhaust gas analyzer

The experiment was carried out using an inline four-cylinder diesel engine. The engine specifications are listed in Table 5. The schematic diagrams of the engine test set-up and of engine test bed are shown in Fig. 2 and Fig. 3, respectively. BSFC and engine power were measured by sensors and processed by the data logger which was interfaced with a computer. To analyze the combustion characteristics, pressure sensors were installed in the engine and a charge amplifier were used to amplify the collected data which was then sent to a data analyzer. Crank angle was measured using Crank angle encoder (RIE-360). In-cylinder pressure was measured by using a Kistler 6058A type pressure sensor. It was installed in the swirl chamber through the glow plug port. Kistler 2614B4 type charge amplifier was used to amplify the charge signal outputs from the pressure sensor. A high precision Leine & Linde incremental encoder was used to acquire the top dead center (TDC) position and crank angle signal for every engine rotation. Simultaneous samplings of the cylinder pressure and encoder signals were performed by a computer with Dewe-30-8-CA data acquisition card. One hundred consecutive combustion cycles of pressure data were collected and averaged to eliminate cycle-to-cycle variation in each test.

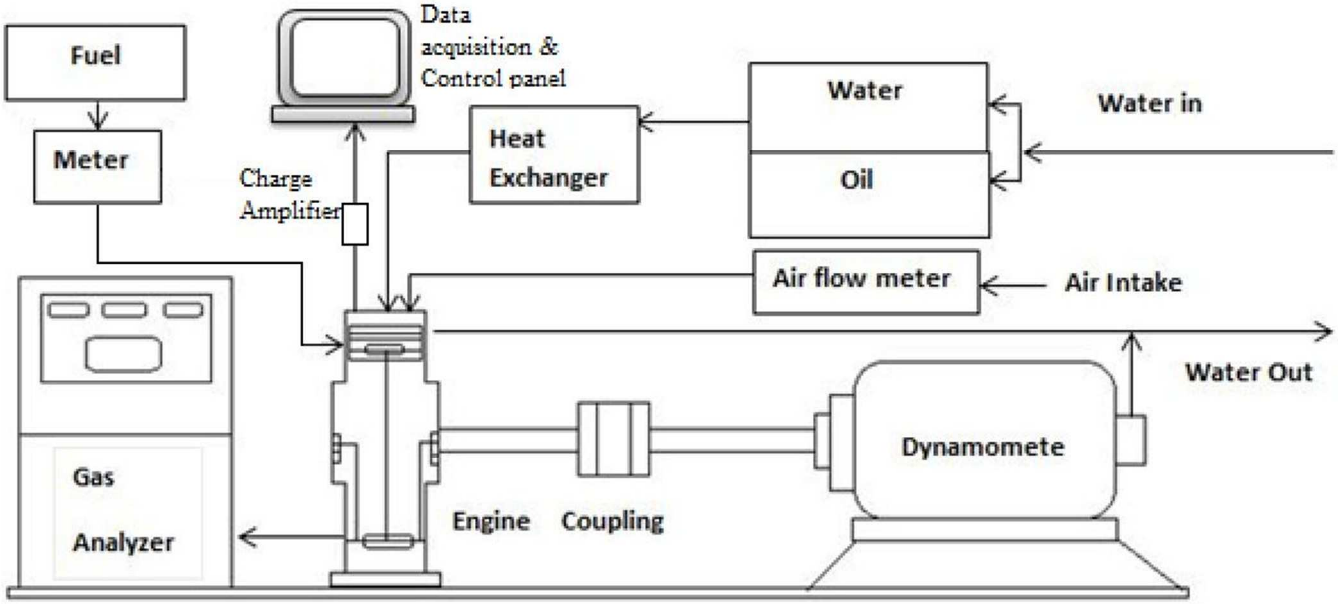

Fig.2. Schematic diagram of engine test set-up

Fig.3. Engine test bed

Table 5

Test engine specification.

The engine was run under full load conditions and different engine speeds ranging from 1000 rpm to 4000 rpm in 500 rpm intervals. Before running the engine with biodiesel blends, the engine was first run with diesel fuel to warm up. Same procedure was followed before the engine shut down. The in cylinder pressure and engine performance data for B10, B20, B100 and B0 were recorded. To determine the exhaust emission, a BOSCH (model ETT 0.08.36) exhaust gas analyzer was used. The gas analyzer details and pollutant measuring method are presented in Table 6. NO and HC were measured in ppm and CO was measured in %vol using the BOSCH exhaust gas analyzer. To determine the baseline parameters, the engine was first fuelled with diesel fuel. Later on, it was fuelled with blended biodiesels and each test was repeated at least three times to calculate the mean value. Fuel flow was measured using a KOBOLD ZOD positive-displacement type flow meter having accuracy of ±0.89 l/h.

Table 6

Details of BOSCH exhaust gas analyser

2.8. Calculation of heat release rate

The heat release rate was calculated based on the cylinder gas pressure data collected during the test. By applying the first law of thermodynamics as shown in equation 4, heat release rate per crank angle was calculated not taking the cylinder wall heat loss into consideration.

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} . P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} . V \frac{dP}{d\theta} \qquad (4)$$

Where θ is crank angle, dQ/dθ is the heat release rate per crank angle, P is the pressure, V is the cylinder volume and γ is the specific heat ratio. Value of γ is taken to be 1.37 and 1.30 during compression and expansion respectively.

3. Results and discussion

3.1. Characterization of mustard biodiesel-diesel blends

The major physicochemical properties of all the tested fuels are presented in Table 4. The density of B100 was found to be 5% higher than B0. However, the densities of B10 and B20 were found to be very close to B0 and the density values of all blends were within the ASTM standard density range for biodiesel.

The transesterification of crude mustard oil reduced its kinematic viscosity from 45.53 mm^2/s to 5.76 mm^2/s. Although the viscosity of B100 was found to be higher than that of B0, it was still within ASTM specifications. The kinematic viscosities of all blends remained within ASTM limits and the viscosity values of B10 and B20 were close to that of B0. Therefore, these two blends can be used in diesel engines without major engine modifications.

The calorific value of B100 was found to be 40.40 MJ/kg. In fact, this value is higher than most of the conventional biodiesels found on the market. The calorific values of B10 and B20 were only 1% and 2% less than that of B0, which is acceptable.

Biodiesel is prone to oxidation due to the presence of unsaturated fatty acids in the vegetable oil, which remains unchanged after transesterification [20]. Thus, they degenerate more quickly than B0. According to European biodiesel standards (EN14214), the minimum value of the biodiesel induction period is 6 h at 110°C. Most conventional biodiesels do not conform to this limit. Considering oxidation stability, mustard oil is a high potential feedstock. The oxidation stability of crude mustard oil was 11 h, which was improved up to 16 h after transesterification (Table 4). This high oxidation stability ensures the long-term storage capacity of B100 which is better than any other conventional biodiesel. It was observed that B10 and B20 meet the specifications of the European standard EN590 (20 h).

3.2. Combustion characteristics

Engine combustion characteristics for biodiesel blends were investigated by means of cylinder gas pressure and heat release. The heat release was calculated from the cylinder gas pressure data collected during the test.

Engine cylinder pressures for biodiesel blends and B0 were compared under full load at a medium engine speed of 3000 rpm. Biodiesel and its blends followed the similar cylinder pressure pattern to that of B0. Fig. 4 shows the changes in cylinder gas pressure with respect to crank angle at 3000 rpm engine speed. No significant trace of knock was found as cylinder pressure smoothly varied over the engine speed range. Maximum cylinder gas pressure occurred within the range of 1º- 4º CA ATDC for all tested fuels. Peak cylinder pressure of B10, B20, B100 and B0 were found 75.92 bar, 76 bar, 76.2 bar and 74.95 bar occurring at 2.8º, 1º, 0.8º and 4º CA ATDC. This shows that B100 attains peak pressure around 3.2º earlier than B0. Peak cylinder pressure of B10, B20 and B100 were 1.2%, 1.4% and 1.6% higher than B0 respectively. Peak cylinder pressure depends on the burned fuel fraction during the premixed burning phase, i.e. the initial stage of combustion [21]. Combustion starts earlier for biodiesel and its blends than for B0 because of the shorter ignition delay period and higher cetane number of biodiesel. Though ignition delay period was not measured in this study, the start of combustion may reflect the variation in ignition delay among all tested fuels. At high temperature, the chemical reactions during the injection of biodiesel resulted in the break-down of the high molecular weight esters. These complex reactions led to the formation of low molecular weight gases. Rapid gasification of this lighter weight compounds in the fringe of the spray spreads out the jet, ignited earlier and reduced ignition delay period [22, 23].

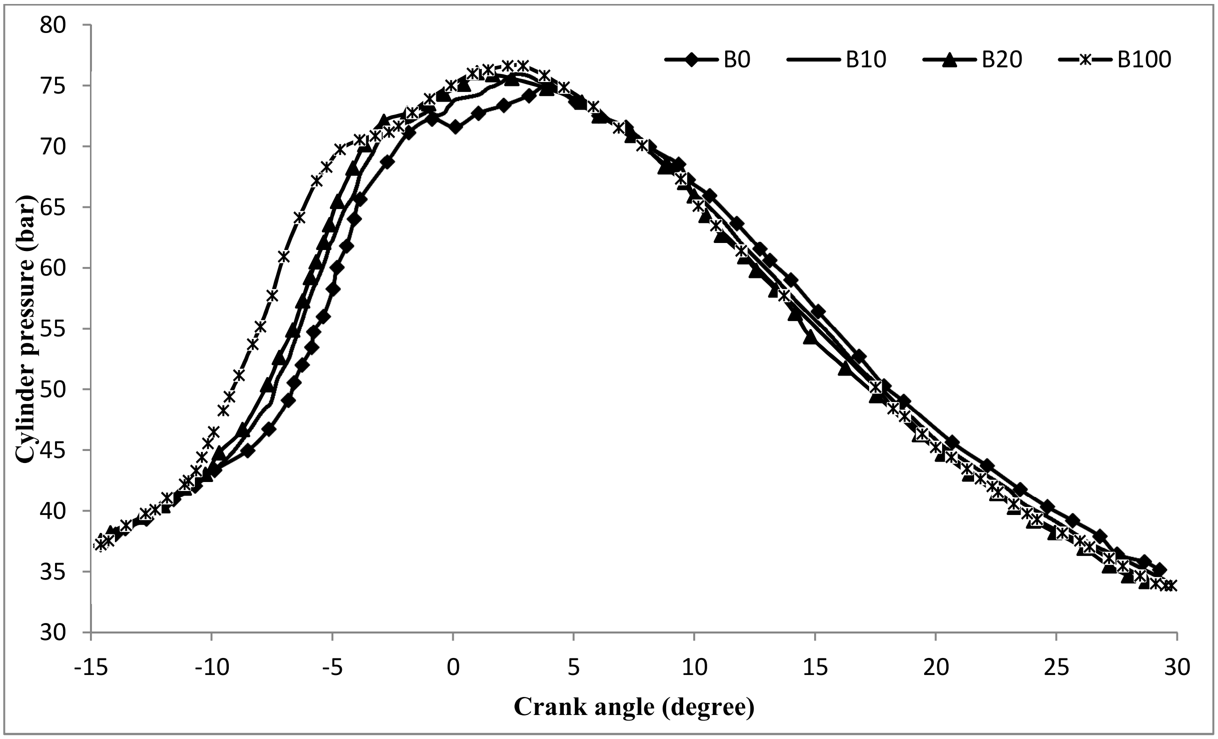

Fig.4. Cylinder pressure versus crank angle at 3000 rpm speed and full load condition

The heat release rate indicates the ignition delay and combustion duration. Fig.5 shows the calculated heat release rates of all tested fuels as functions of crank position at 3000 rpm and full load condition. All tested fuels indicated rapid premixed burning followed by a diffusion combustion period. It can be seen that the start of combustion happens earlier for B100. Due to their early start of combustion and shorter ignition delay, biodiesel and its blends completed the premixed combustion phase earlier than B0. The total combustion duration seems to be shorter with the increase in biodiesel blend ratio. Peak heat release rate for B100 and B0 were found 68 J and 51J respectively. Higher peak heat release rate and in cylinder pressure of B100 also showed impact on the amount of NO emission. However, the heat release during the late combustion phase for B100 was found lower than that of B0. This is because of the higher oxygen content of biodiesel ensures complete combustion of the fuel that was left over during the main combustion phase and continue to burn in the late combustion phase.

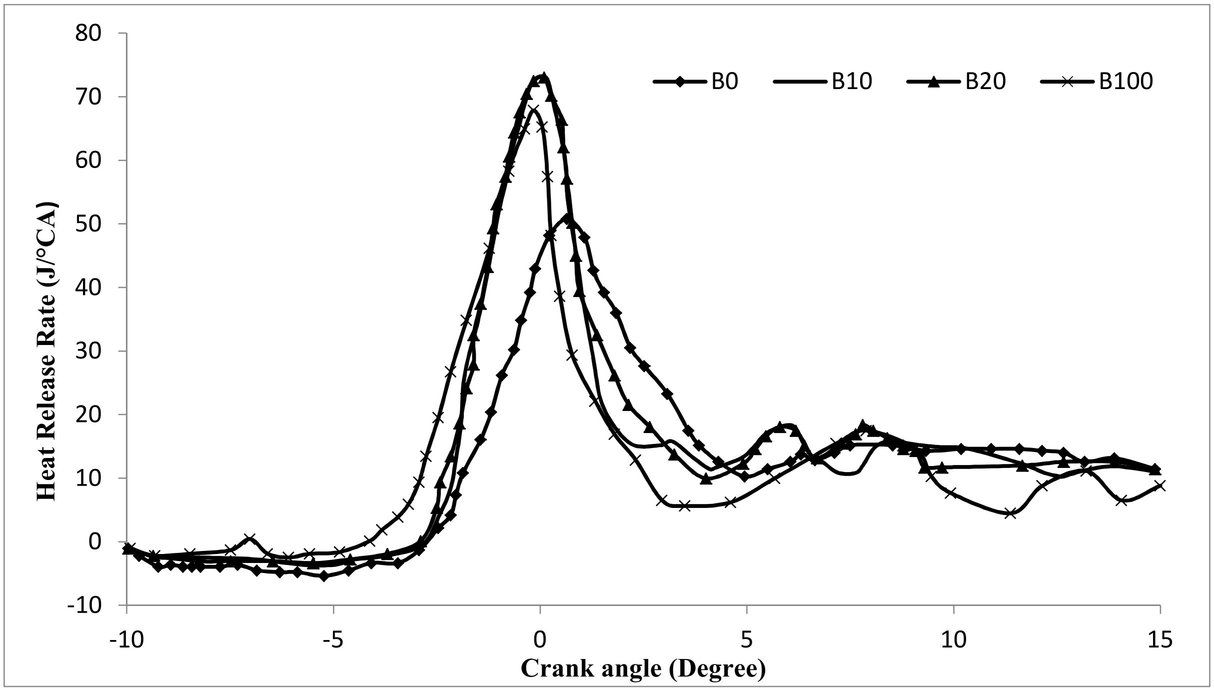

Fig.5. Heat release rate versus crank angle at 3000 rpm speed and full load condition

3.3. Performance Analysis

Performance parameters such as change in BSFC and BP were measured with respect to engine speed for all tested fuels under full load condition.

BSFC refers to the ratio between the fuel mass flow rate and engine power. Fig. 6 shows the variation in BSFC with respect to engine speed. It was observed that the BSFC of biodiesel was generally higher compared to B0. Due to the higher density and lower calorific value of B100, the increase in BSFC vs. B0 is obvious [24, 25]. The average BSFC values for B10, B20 and B100 were found to be 4%, 8% and 18% higher than the BSFC of B0. The lowest BSFC values for B10, B20 and B100 were 260 g/kWh, 265 g/kWh and 290 g/kWh at 1500 rpm.

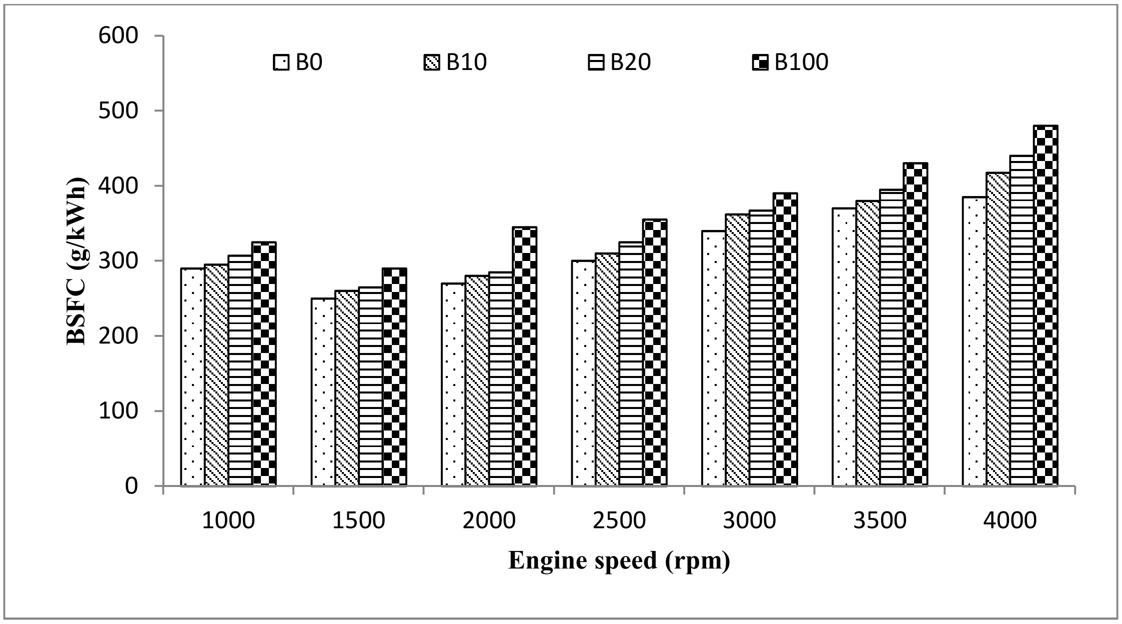

Fig.6. Variation of BSFC with engine speed

The variation in engine BP output with engine speed for all tested biodiesels and B0 is presented in Fig. 7. The maximum BP output for B10, B20 and B100 were 41 kW, 39 kW and 36 kW respectively at 3500 rpm. The maximum power output of B10, B20 and B100 was 9%, 13% and 20% less than B0, respectively. The reduction in BP with the B100 may be explained due to the higher density and viscosity, which resulted in poor atomization and low combustion efficiency [26].

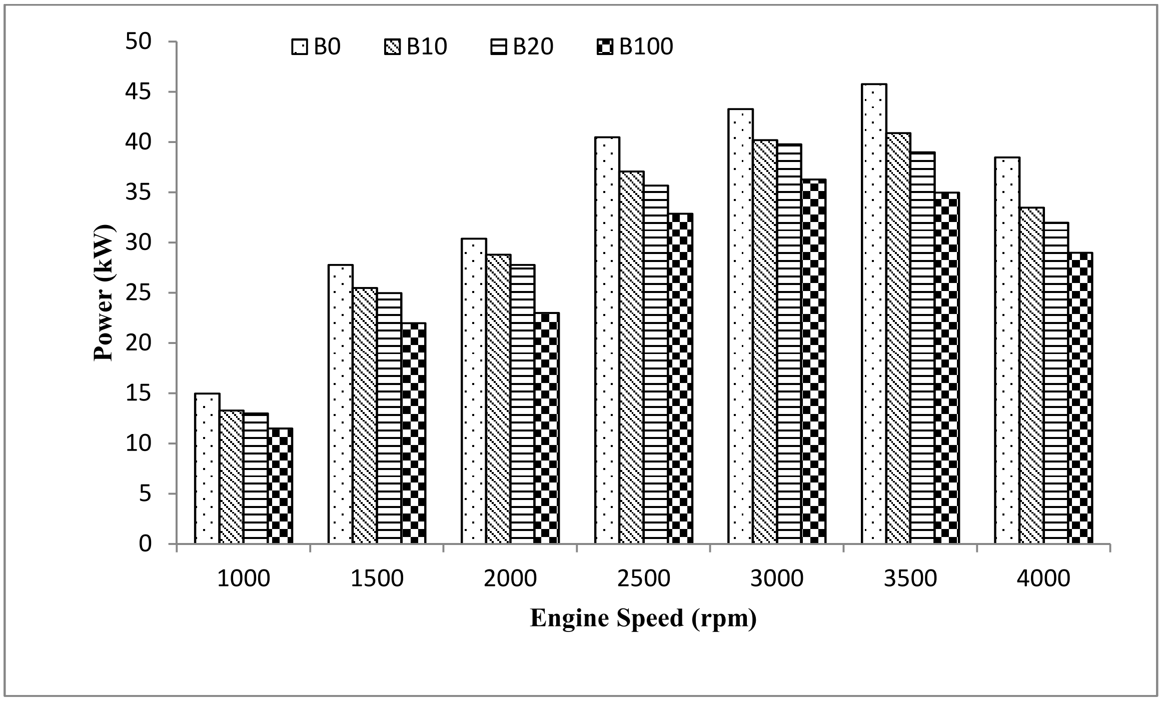

Fig.7. Variation of BP with engine speed

The variation in engine BTE output with engine speed for all tested biodiesels and B0 is presented in Fig. 8. From the figure, BTE of pure diesel was highest at all speeds while that of pure biodiesel (B100) was lowest. The primary reason for the decrease in the BTE of biodiesels is the higher BSFC due to biodiesel having lower calorific value, which is also supported by other literatures[1,27]. At 1500 RPM maximum efficiency was achieved for all tested fuel samples.

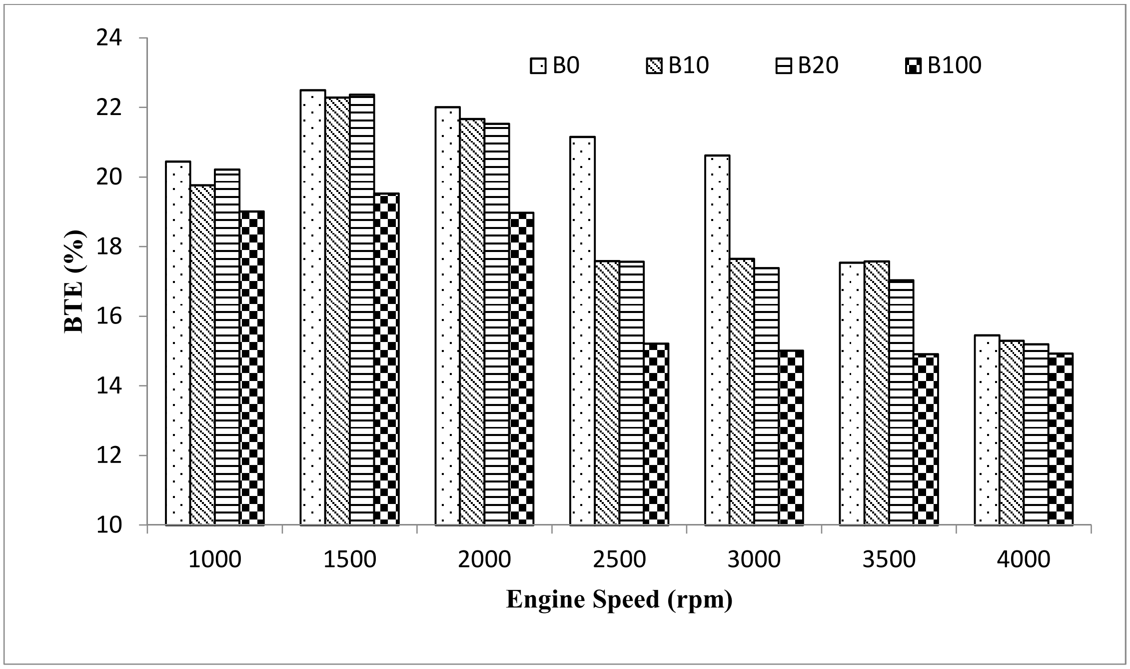

Fig.8. Variation of BTE with engine speed

Fig. 9. shows the BSEC for biodiesel and diesel. Under almost all engine speed range, the BSEC for biodiesel is closer to that of diesel. The small variation may be due to the combined effect of lower heating value and high density of biodiesel [28].

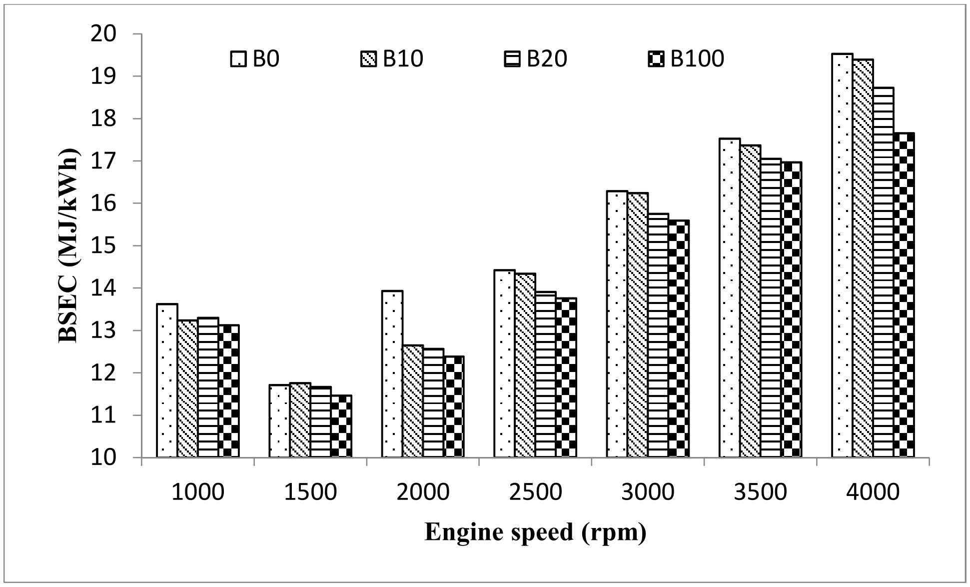

Fig 9. Variation of BSEC with engine speed

3.4. Emission analysis

Emission analysis was carried out at different engine speeds ranging from 1000 to 4000 rpm at 100% load. NO, HC and CO emissions were measured for all tested fuels and the average values are presented.

The average NO emissions for all tested fuels with respect to engine speed are shown in Fig. 10. On an average, it was observed that B10, B20 and B100 produced 9%, 12% and 20% more NO than B0, respectively. The higher cetane number and shorter ignition delay of B100 increased NO emissions [29]. Combustion analysis clearly indicated the shorter ignition delay and higher heat release rate of B100 than B0. Moreover, many researchers have found that the higher oxygen content of biodiesel is responsible for increases in NO emissions [30]. Generally, higher oxygen content results in a higher combustion temperature, which leads to greater NO emissions.

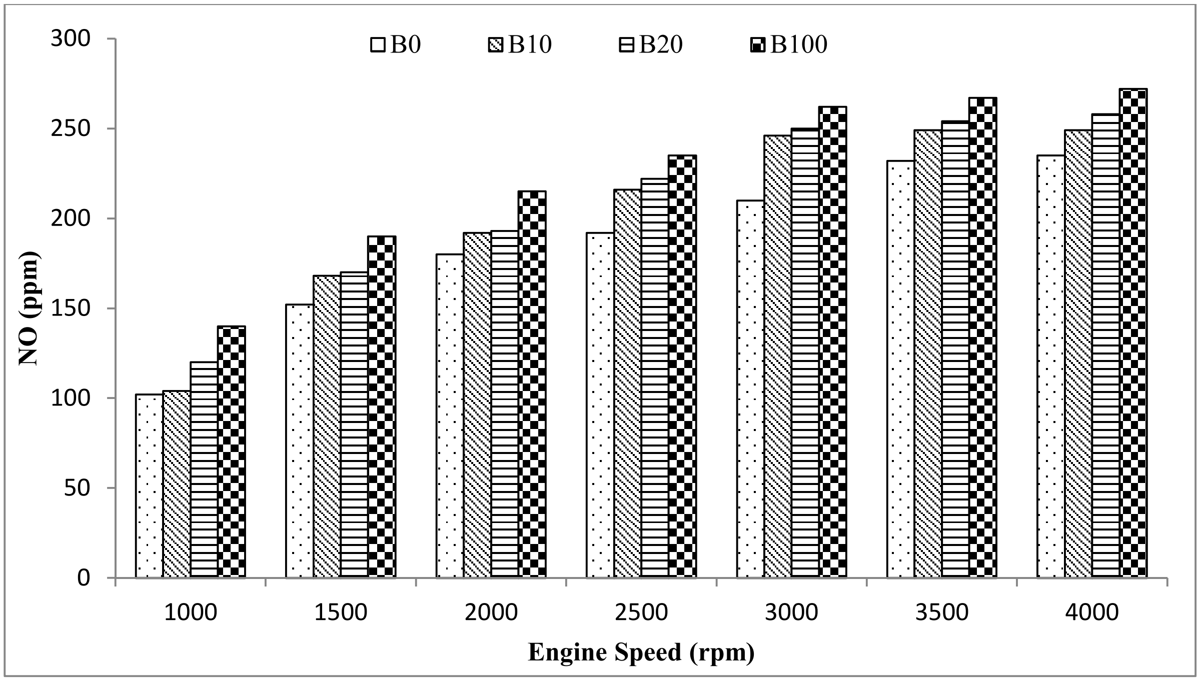

Fig.10. NO emission for all tested fuels at different engine speed

Hydrocarbons present in the emission are either partially burned or completely unburned. HC emissions result from incomplete combustion of fuel due to flame quenching at the cylinder lining and crevice region [26]. The average HC emissions for all tested fuels at different engine speeds are shown in Fig.11. It was observed that HC emissions decreased with an increase in the blending percentage in the blends. The average HC emissions of B10, B20 and B100 were 24%, 38% and 50% lower than B0, respectively. The higher oxygen content of biodiesel ensures more complete combustion, which helps to reduce HC emissions.

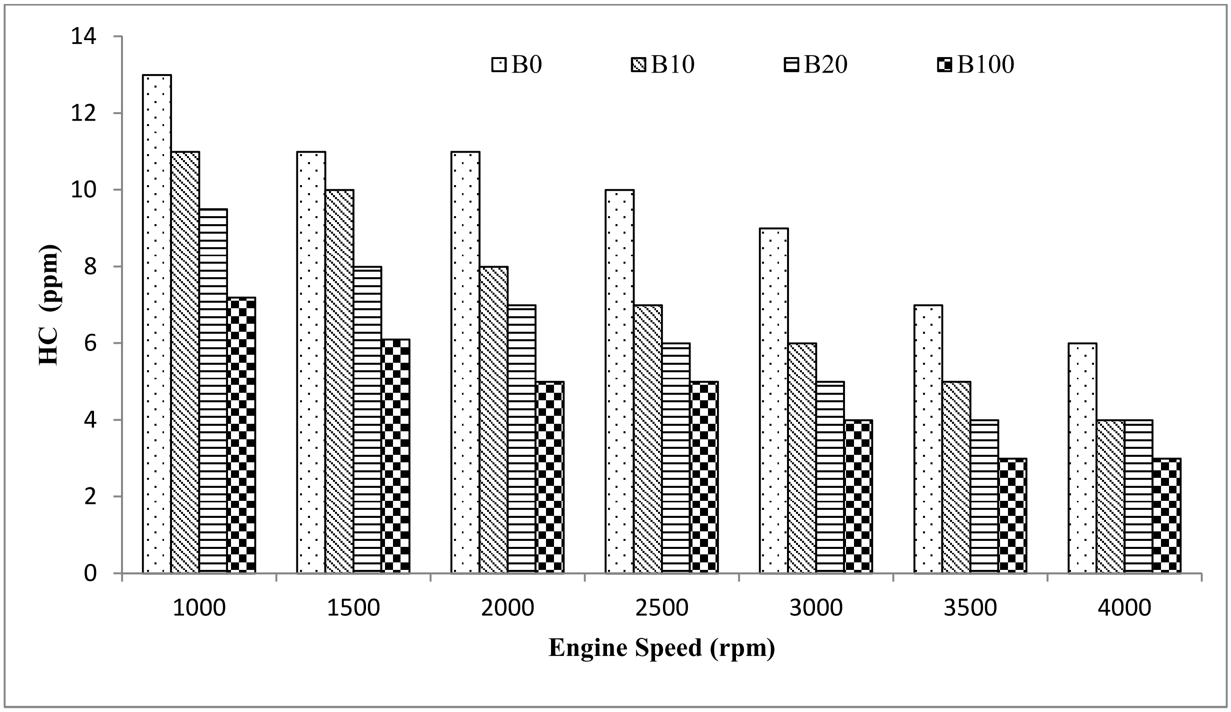

Fig.11. HC emission for all tested fuels at different engine speed

The comparison of the average CO emissions for all tested fuels at different engine speeds is presented in Fig. 12. The average CO emissions of B10, B20 and B100 were found to be 19%, 40% and 62% lower than B0, respectively. CO is produced when the progression to CO_2 is incomplete due to incomplete combustion. The higher oxygen content in biodiesel promotes complete combustion and results in lower CO emissions.

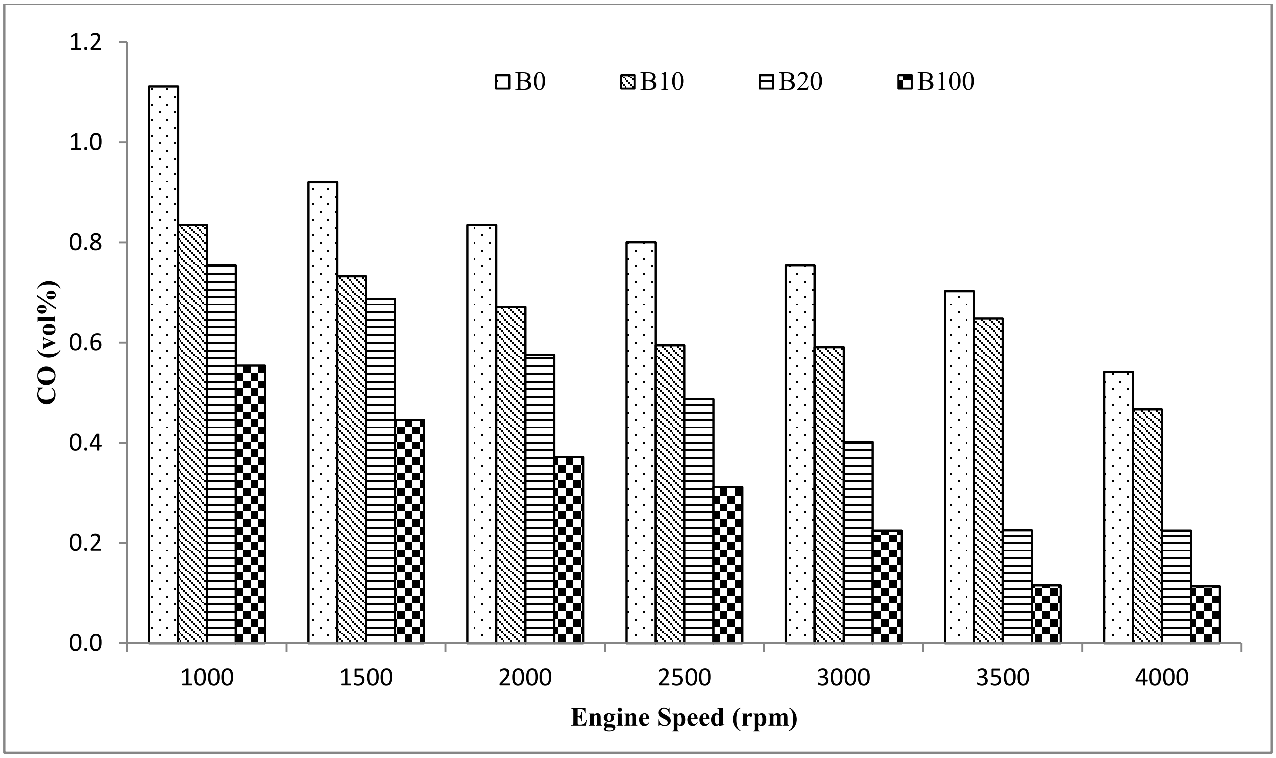

Fig.12. CO emission for all tested fuels at different engine speed

4. Uncertainty analysis

Errors and uncertainties in experiments can arise from instrument selection, conditions, calibration, environment, observation, reading and test planning. Uncertainty analysis is needed to demonstrate the accuracy of the experiments. The accuracy of the speed, fuel measurement, brake power, and time tests was ±10 rpm, ±1% of the reading, ± 0.07 kW and ±0.1 s, respectively. The relative uncertainty of BSFC was determined using a linearized approximation method of uncertainty. Table 7 shows a summary of the values of measurement accuracy and the relative uncertainty of BSFC determination. Table 8 shows a summary of the values of measurement accuracy and the relative uncertainty of various parameters such as BP, CO, HC and NO emissions for B0 at an engine speed of 3500 rpm.

Table 7

Summary of the values of measurement accuracy and the relative uncertainty of BSFC determination

Table 8

Uncertainty analysis

5. Conclusion

Mustard oil is a promising and relatively new feedstock for biodiesel production. Therefore, this experimental investigation aimed to study the feasibility of biodiesel production from low quality mustard oil, and to characterize the biodiesel blends, as well as their combustion, engine performance and emission characteristics. The following conclusions can be drawn based on the experimental investigation:

- A methyl ester biodiesel was produced from low quality crude mustard oil by a method of alkaline transesterification. Characterization of B100, B10 and B20 demonstrated that all the important fuel properties of biodiesel are compatible with diesel engine and the engine can satisfactorily perform on B10 and B20 without modification.
- B100 and its blends completed the premixed combustion phase earlier than B0 due to their shorter ignition delay period and higher cetane number.
- The maximum in cylinder pressure occurred within the range of 1-4º CA ATDC for all tested fuels. The peak cylinder pressure and heat release of B100 and its blends were found more closed to TDC compared to B0.
- The average BSFC of B10 and B20 were 4% and 8% higher than B0. In contrast, the average BP of the B100 blends were also 9-13% lower than for B0. The lower calorific

value and higher viscosity and density of B100 compared to B0 resulted in this decrease in performance.

- Due to having lower calorific value, BTE of biodiesel blends were lower than diesel fuel at all speed ranges.
- Under almost all engine speed range, the BSEC for biodiesel is closer to that of diesel fuel.
- On average, B10 and B20 produced 9% and 12% more NO than B0, respectively. However, HC and CO emissions were considerably reduced (19-42%) for B10 and B20 compared to B0.
- Preheating the B100 blends up to a specific temperature can reduce the density and viscosity. By using the waste heat from exhaust gas, fuel can be easily preheated in the intake manifold before injection.
- Further research can be carried out to analyze the effect of injection pressure and timing on combustion characteristics of B100 and its blends.

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Table 1

List of equipment used for testing fuel properties

Property	Equipment	Model	Manufacturer	Standard method
Kinematic viscosity and density	StabingerViscometer	SVM 3000	Anton Paar	ASTM D7042
Flash point	Pensky–martens flash point tester	NPM 440	Normalab, France	ASTM D93
Cloud and pour point	Cloud and pour point tester	NTE 450	Normalab, France	ASTM D2500
Calorific value	Semi auto bomb calorimeter	6100EF	Perr, USA	ASTM D240
Oxidation stability	Rancimat testing machine	873 Rancimat	Metrohm, Switzerland	EN 14112
ConradsonsCarbon residue	Carbon conradsons residue tester	NMC440 micro-carbon conradson residue tester	Normalab, France	ASTM D4530

Table 2

Fatty acid composition of mustard biodiesel

No	Fatty acid name (common)	Fatty acid name (systematic)	Structure	Formula	Molecular mass	B100 (Wt%)
1	Lauric	Dodecanoic	12:0	$C_{12}H_{24}O_2$	200	-
2	Myristic	Tetradecanoic	14:0	$C_{14}H_{28}O_2$	228	-
3	Palmitic	Hexadecanoic	16:0	$C_{16}H_{32}O_2$	256	1.9
4	Palmitoleic	Hexadec-9-enoic	16:1	$C_{16}H_{30}O_2$	254	0.2
5	Stearic	Octadecanoic	18:0	$C_{18}H_{36}O_2$	284	1.2
6	Oleic	Cis-9-Octadecanoic	18:1	$C_{18}H_{34}O_2$	282	12.7
7	Linoleic	Cis-9-cis-12 Octadecanoic	18:2	$C_{18}H_{32}O_2$	280	12.3
8	Linolenic	Cis-9-cis-12	18:3	$C_{18}H_{30}O_2$	278	7.2
9	Arachidic	Eicosanoic	20:0	$C_{20}H_{40}O_2$	312	1.0
10	Eicosenoic	Cis-11-eicosenoic acid	20:1	$C_{20}H_{38}O_2$	310	6.4
11	Eicosadienoic	all-cis-11,14-eicosadienoic acid	20:2	$C_{20}H_{36}O_2$	309	0.4
12	Eicosatrienoic	11,14,17-Eicosatrienoic Acid	20:3	$C_{20}H_{34}O_2$	306	0.1
13	Behenic	Docosanoic	22:0	$C_{22}H_{44}O_2$	341	0.9
14	Erucic	13-Docosenoic Acid	22:1	$C_{22}H_{42}O_2$	338	53.7
15	Docosadienoic	13,16-Docosadienoic Acid	22:2	$C_{22}H_{40}O_2$	336	0.8
16	Nervonic	15-Tetracosaenoic Acid	24:1	$C_{24}H_{46}O_2$	366	1.3
Saturated				5.0		
Monounsaturated				74.3		
Polyunsaturated				20.7		
Total				100.0		

Table 3

GC operating conditions

Property	Specifications
Carrier gas	Helium
Linear velocity	24.4 cm/sec
Flow rate	1.10 mL/min (column flow)
Detector temperature	260.0 °C
Column head pressure	56.9 kPa
Column dimension	BPX 70, 30.0 m x 0.25 µm x 0.32 mm ID
Injector	240.0 °C
Temperature	140.0 °C (hold for 2 minutes)
Temperature ramp	8°C/min 165.0 °C
	8°C/min 192.0 °C
	8°C/min 220.0 °C (hold for 5 minutes)

Table 4

Physicochemical properties of mustard biodiesel and its blends compared to diesel

Properties	Units	Standards	ASTM D6751	Crude Mustard oil	B100	B10	B20	B0
Kinematic Viscosity at 40°C	mm^2/s	ASTM D445	1.9-6	45.53	5.76	3.92	4.13	3.69
Density at 15°C	kg/m^3	ASTM D1298	860-900	897	865	826	831	821
Flash point	°C	ASTM D93	>130	212.5	149.5	77.5	80.5	72.5
Cloud point	°C	ASTM D2500	-	-13	5	5	8	-8
Pour point	°C	ASTM D97	-	-14	-18	-3	-3	-6
Calorific value	MJ/kg	ASTM D240	-	40.10	40.40	44.88	44.38	45.27
Oxidation stability	H	EN ISO 14112	3	11	16	70	50	-
Cetane number	-	ASTM D613	47 min	-	76.737	50	58	48
Iodine value	gI/100g	-	-	-	102	-	-	-
Saponification value	-	-	-	-	179	-	-	-
Acid value	mg KOH/g	-		3.65	0.17	-	-	-
Carbon Conradson	%	ASTM D4530	0	-	0			-

Table 5

Test engine specification.

Engine type	4 cylinder inline
Manufacturer	Mitsubishi
Displacement	2.5 L (2,476 cc)
Bore	91.1 mm
Stroke	95.0 mm
Maximum engine speed	4500 rpm
Compression ratio	21:1
Cooling system	Water cooled
Injector opening pressure	130 bar
Injector pump	Mechanically controlled distributor type

Table 6

Details of BOSCH exhaust gas analyser

Equipment name	Model	Measuring element	Measuring method	Upper limit	Accuracy
BOSCH gas analyser	BEA-350	CO	Non-dispersive infrared	10.00 vol.%	±0.001 vol. %
		CO_2	Non-dispersive infrared	18.00 vol.%	±0.001 vol. %
		HC	Flame ionization detector	9999 ppm	±1 ppm
		NO	Heated vacuum typechemiluminescence detector	5000 ppm	±1 ppm

Table 7

Summary of the values of measurement accuracy and the relative uncertainty of BSFC determination

Fuel samples	Values of measurement accuracy (g/kWh)	Relative uncertainty of BSFC determination (%)
B0	±5	1.58
B10	±5	1.51
B20	±5	1.47
B100	±5	1.34

Table 8

Uncertainty analysis

Measurement	**Accuracy**	**Reading at 3500 rpm for diesel fuel**	**Relative Uncertainty**
BP	± 0.07 kW	46 kW	±0.001
CO	±0.001 vol.%	0.703	±0.001
HC	± 1 ppm	7	±0.143
NO	± 1 ppm	232	±0.004

Novelty of the work is that mustard oil is a promising and relatively new feedstock for biodiesel production.