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LOCAL RESOURCE EXPLOITATION

Diesel engine operated with hybrid oil ethyl ester and its blends: Performance, combustion and emission characteristics evaluation

Moteur diesel fonctionnant avec de l'ester éthylique d'huile hybride et ses mélanges : évaluation des caractéristiques de performance, de combustion et d'émission

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ABSTRACT:

As energy demands increase and fossil fuels are limited, research is directed towards alternative renewable fuels that are eco-friendly and efficient energy carriers. Biodiesel and bioethanol count among the most viable alternatives and infinite green fuels that can be used in internal combustion engine as this engine remains indispensable in modern industry. Hence, emission, combustion and performance that are relevant problems need to be addressed. In this study, engine test has been carried out to evaluate the performance, combustion and emission characteristics of a computerized Kirloskar diesel engine, fueled with hybrid oil ethyl ester and its diesel blends at different loads. Diesel had lowest Brake specific fuel consumption (BSFC) (0.35 kg/kWh) and biodiesel (B100) has highest value of BSFC (0.54 kg/kWh) at 100 % load. Cylinder pressure for biodiesel-diesel fuel was almost same as diesel before and after the 60° crank angle. Maximum heat release rate profiles of B10, B20 and B30 seemed to be synchronous to diesel fuel. Carbon Monoxide (CO) and smoke emissions were found significantly lower when operating on biodiesel-diesel blends; with a decrease of 26.79 % CO emission for B100 than diesel, but Nitrogen Oxide (NOx) emissions are found to be higher at full load.

Keywords: Biodiesel, Efficiency, Greenhouse gas, Hybrid, Ignition, Emission.

RÉSUMÉ :

Alors que la demande d'énergie augmente et que les combustibles fossiles sont limités, la recherche est orientée vers des carburants renouvelables alternatifs ; efficaces vecteurs d'énergie et respectueux de l'environnement. Le biodiesel et le bioéthanol comptent parmi les alternatives les plus viables et les carburants verts infinis qui peuvent être utilisés dans un moteur à combustion interne, car ce moteur reste indispensable dans l'industrie moderne. Par conséquent, des problèmes pertinents y afférant parmi lesquels : les émissions, la combustion et la performance ; doivent être abordées. Dans cette étude, des tests moteur ont été effectués à différentes charges, pour évaluer les performances, la combustion et les caractéristiques d'émission d'un moteur diesel Kirloskar informatisé, alimenté avec de l'ester éthylique d'huile hybride et de ses mélanges au diesel conventionnel. De ces analyses, le diesel a la plus faible consommation spécifique (BSFC) de carburant (0,35 kg/kWh) et le biodiesel (B100) a la valeur la plus élevée de BSFC (0,54 kg/kWh) à 100 % de charge. La pression cylindrique pour le biodiesel-diesel était presque la même que celle du diesel avant et après l'angle de manivelle de 60 °. Les profils de taux de dégagement de chaleur maximum de B10, B20 et B30 semblaient être synchrones avec celui du diesel conventionnel. Les émissions de monoxyde de carbone (CO) et de fumée se sont avérées significativement plus faibles lors de l'utilisation de mélanges biodiesel-diesel ; avec une diminution de 26,79 % des émissions de CO pour le B100 par rapport au diesel, mais les émissions d'oxyde d'azote (NO_x) sont plus élevées à pleine charge.

Mots clés : Biodiesel, Efficacité, gaz à effet de serre, hybride, allumage, émission.

1. INTRODUCTION

In the last years, the awareness of energy and environmental problems, which encouraged biodiesel production from different vegetable oils (soybean, rapeseed and sunflower), seems very interesting for several reasons: it can replace diesel oil in internal combustion engines efficiently, it is environmentally safe and without major adjustments (Farouk et al., 2016; Peterson et al., 1999); only a small decrease in performances is reported. The wider role of diesel engines is associated with emissions like nitrogen oxides (NOx) and smoke, which are objectionable as per the existing emission norms (Pauleta et al., 2013). Due to air pollution, human body experiences respiratory and cardiovascular ailments. It was estimated that there were almost 620,000 deaths in 2010 due to air pollution. With the continuous use of diesel engines in vehicle operation and, power generation; emissions have increased at an alarming rate since incomplete combustion of the air–fuel mixture leads to a wide range of harmful components: Carbon monoxide (CO), Hydrocarbons (HC), NOx, SOx, particulate matter (PM), ammonia, cyanides, toluene, benzene and aldehydes. Renewable fuel sources such as biodiesel and ethanol can play a modest role in reducing greenhouse gases and other potentially emission related to fossil fuels. Having the potential to significantly reduce the greenhouse gas emissions by as much as 30 % from their combustion in internal combustion engine, the main advantages of using these biofuels are their renewability, biodegradability and technical competitiveness to conventional petro-diesel. Biodiesel is derived from the fats of animals and plants.

With the use of biodiesel, HC, CO, and particulate matter emissions decrease in comparison to diesel fuel (Canakci et Van Gerpen, 2013; Canakci, 2005). Studies investigating the slight increase in NOx emission suggested that the NOx increase is the result of a few connected factors but not determined by a change in a single fuel property (Mueller et al., 2009). As the different physical properties of biodiesel can lead to different ignition delays and combustion performance (Solaimathu et al., 2013); this work focuses on, the assessment of performance, combustion and emission characteristics of ternary hybrid biodiesel on a CI engine operation. The various analyses of performance, combustion and emissions, are conducted making use of a combination of biodiesel (B100) produced by transesterification of a hybrid vegetable oil and it blends (BXX) with conventional fossil fuel.

2. MATERIALS AND METHODS

2.1. Materials

The material used in this part of the work is the hybrid biodiesel achieved from shear butter (SHB), neem oil (NMO) and waste kitchen oils (WKO) as depicted by Nouadjep et al. (2019). Test samples which include: diesel (B0), biodiesel blends “BXX” (B10, B20, B30, B40 prepared on a v/v % basis) and B100, were used in a diesel engine to assess engine properties. A four stroke single cylinder DI stationary diesel engine was used to study the performance, combustion and emission characteristics of hybrid biodiesel. Specifications of the test engine are shown in Table 1. Since fuels having flash point above 65 °C are considered to be safe for handling and storage (Senthur et al., 2017), the biodiesel prepared is safe because it has a flash point of 190 °C.

Table 1. Technical specifications of the engine used

Make	Kirloskar
Model	TAF 1
Type	Direct injection, air cooled
Bore x Stroke (mm)	87.5 x 110 mm
Compression ratio	17.5:1
Swept volume	661 cm^3
Rated power	4.7 kW
Rated speed	1500 rpm
Start of injection	24° bTDC
Connecting rod length	220 mm
Injector operating pressure	21 Mpa

2.2. Methods

2.2.1. Engine test procedure.

The test procedure was conducted under steady state conditions, i.e. without any changes in the engine to assess performance, combustion and emission characteristics. The engine is coupled with an eddy current dynamometer for varying the engine load from 0 to 100 % by incremental steps of 25 %. Conducting tests at a constant speed of 1500 rpm and recording readings for each load. The fuel consumption for each case was measured by using a stopwatch. The engine was operated on diesel (B0) first, and then on synthesized biodiesel (B100) and its blends (B10, B20, B30, B40). Engine emission characteristics with respect to gases like NOx, Carbon monoxide (CO), Hydrocarbons (HC) and Carbon dioxide (CO_2) when running on diesel, the biodiesel and its various blends were found by AVL digas 444 (Five gas analyzer). The exhaust smoke opacity of fuels was measured using AVL437C smoke meter and the exhaust gas temperature was measured using a K-type thermocouple**.** The experimental setup is shown in Figure 1.

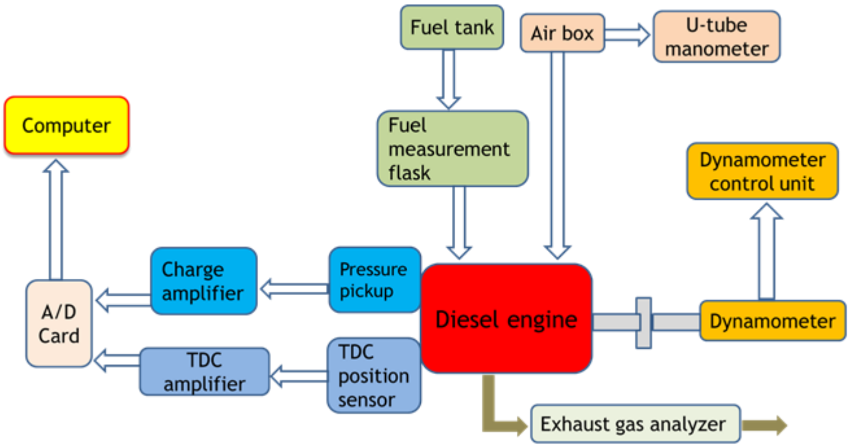

Figure 1: Experimental setup (Arun et al., 2018 ; Senthur et al., 2017)

The computerized diesel engine was directly coupled with the dynamometer and loaded by electrical resistance. The required quantity of biodiesel and emulsifying agent were added in the fuel tank and the separate fuel measurement unit was connected with the engine.

Engine test runs were carried out three times to check the reproducibility and the average value was taken. The variation of in-cylinder pressure with respect to crank angle (CA) was measured using AVL GH12D miniature pressure transducer with AVL 3066A02 piezoelectric charge amplifier and crank angle encoder. Heat release rates at the measured value of pressure and crank angle was calculated and displayed using AVL 617 Indimeter software version V2.00.

2.2.2. Energy Analysis.

Energy analysis is based on the first law of thermodynamics, which is also known as energy conservation law. For doing energy analyses, the following assumptions are made (Sekmen et Yilbasi, 2011): The engine operates at steady state condition. The whole system including dynamometer is selected as control volume. The combustion air and exhaust gas each constitutes an ideal gas mixture. Potential and kinetic energy effects of the incoming and outgoing fluid streams are ignored.

Fuel energy supplied per unit time is given by the following equation:

$$\dot{Q}in = \dot{M}f\ .\ LCV \tag{1}$$

Where $\dot{M}_f$ is mass of fuel consumed per unit time, LCV is lower calorific value of the fuel (kJ/kg).

Heat loss in engine cooling water per unit time is given by the following equation:

$$\dot{Q}cw = \dot{M}cw\ .Cpw\ .\ (T_{c2} - T_{c1}) \tag{2}$$

Where T_{c1}, T_{c2} are engine cooling water inlet and outlet temperatures in K and C_{pw} is the specific heat of cooling water.

Heat Carried away by exhaust gases can be calculated as shown in equation (3) below:

$$\dot{Q_{ex}} = \dot{M_{ex}}\ .\ \dot{Cp_{ex}}\ .(T_{ex1} - T_0) \tag{3}$$

Where T_{ex1}, T_0 are exhaust gas inlet and ambient temperature respectively in kelvin and Cp_{ex} is the specific heat of exhaust gases.

Mass flow rate of exhaust gases can be found by summing up mass in-flow rates of air and fuel.

$$\dot{M_{ex}} = \dot{M}_a + \dot{M}_f \tag{4}$$

Heat gained by water in calorimeter is considered as the heat lost by the exhaust gases in calorimeter.

$$\dot{M_{wcal}}\ .\ C_{pw}\ .(T_{c4} - T_{c3}) = \dot{M_{ex}}\ .\ C_{pex}\ .\ (T_{ex1} - T_{ex2}) \tag{5}$$

The sum of unaccounted for energy losses (which includes heat loss due to radiation, heat loss to oil and friction power loss etc.) can be found as follow:

$$\dot{Q_u} = \dot{Q_{in}} - \left(\dot{Q_{cw}} + \dot{Q_{ex}} + \dot{W_s}\right) \tag{6}$$

2.2.3. Performance and combustion analyses

Brake specific fuel consumption (BSFC). It is a crucial criterion to examine the efficiency with which the fuel is being consumed in an engine. It can be calculated by:

$$BSFC(g/kWh) = W_f/P_b \tag{7}$$

Where: W_f = fuel consumed (g/h),

P_b = brake power (kW) which can be calculated by:

$$P_b = P_g/\eta_g \tag{8}$$

Where: P_g = load (kW),

η_g = efficiency of the engine

Brake thermal efficiency (BTE). BTE depicts the combustion quality of the engine. It can be determined by dividing the useful work by the lower heating value (LHV) of the fuel. This can be simplified and given in equation (9).

$$BTE\ (\%) = \frac{3600}{LHV\ x\ BSFC}\ 100 \tag{9}$$

The exhaust gas temperature (EGT). EGT is proportional to the cylinder temperature. It is literally the temperature of the exhaust gases as they exit the combustion chamber.

Heat release rate (HRR). It is the rate of heat generation by fire and it is typically measured in Joules or Watts. According to the first law of thermodynamics, the correlation below as derived by Heywood (1988) (Heywood, 1988), was used to determine the HRR.

$$\frac{dQ}{d\theta} = \frac{\delta}{\delta - 1} P \frac{dV}{d\theta} + \frac{1}{\delta - 1} V \frac{dP}{d\theta} \tag{10}$$

Where $\frac{dQ}{d\theta}$ is the HRR per crank angle, θ is the crank angle, P is the pressure, V is the cylinder volume and δ is the specific heat ratio ($\delta = 1.35$).

2.2.4. Error Analysis and uncertainties.

Percentage of uncertainty occurring in the experiments is obtained as is done for error analysis when the results are expressed as standard deviations. Supposing X is a function of several variables, X= f(x_1, x_2, x_3,…,x_n) where x_1, x_2, x_3,…,x_n are independent variables with the same degree of odds. Let *Wx* be the resultant uncertainty and w_{x1}, w_{x2},w_{x3},…w_{xn} be the uncertainties in the independent variables x_1, x_2, x_3,…x_n respectively. The percentage of uncertainty in the result is given by:

$$W_x = \sqrt{\left(\frac{\partial X}{\partial x_1}\right)^2 W_{x_1}^2 + \left(\frac{\partial X}{\partial x_2}\right)^2 W_{x_2}^2 + \cdots + \left(\frac{\partial X}{\partial x_n}\right)^2 W_{x_n}^2} \tag{11}$$

The independent variables include: pressure transducer, angle encoder, NOx, HC, CO, CO_2, O_2, Smoke opacity, K-2 thermocouple, stop watch, manometer and burette.

3. RESULTS AND DISCUSSION

3.1. Performance characteristics

Teoh et al. (2019) and Dwivedi et al. (2013) reveals that biodiesel performs satisfactorily during diesel engine operation. Due to its high lubricity, it causes less wear and tear to engine part. The following parameters are used to evaluate the performance of diesel engine using biodiesel and its blends.

3.1.1. Brake specific fuel consumption (BSFC).

It is the amount of fuel consumed to produce one kW of brake power. It is desirable to obtain a lower value of BSFC meaning that the engine used less fuel to produce the same amount of work. Figure 2 depicts the variation of BSFC of test fuel with varying engine load. It was found for all test blends that BSFC decreases with the increase in load irrespective of the blends and slightly increases under 80 to 100 % loading conditions. Diesel has the lowest BSFC (0.35 kg/kWh) and B100 has the highest value of BSFC (0.54 kg/kWh) at 100 % load. This might come from the fact that biodiesel has lower calorific value (40.88 MJ kg^{-1}) and energy density than diesel fuel (42.39 MJ kg^{-1}), which means that more fuel is consumed to produce the same engine output (Kannahi et Arulmozhi, 2013; Ahmad et al., 2009). For most of the loads, the mixture B30 matched with diesel; which can be owing to more viscosity and high index of hydrogen deficiency of biodiesel (Verma et al., 2015).

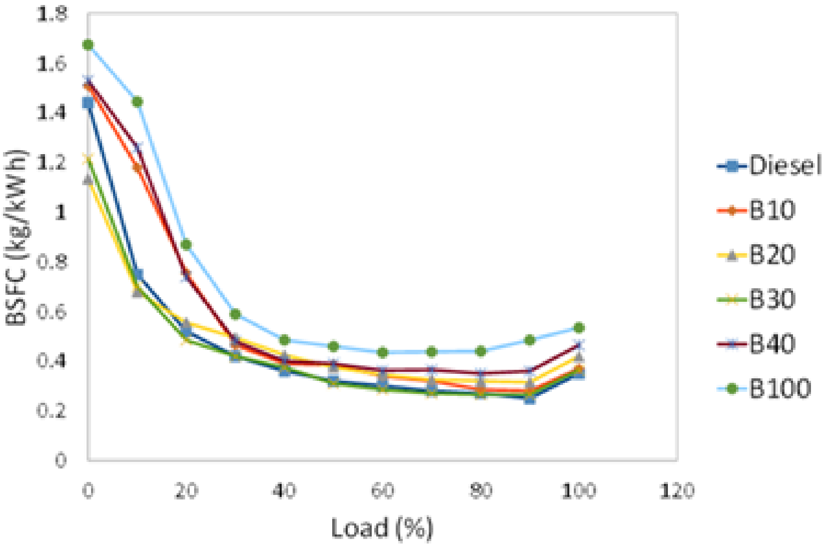

Figure 2: Variation of brake specific fuel consumption with load for various test fuels

3.1.2. Brake thermal efficiency (BTE).

It depicts the combustion quality of the engine (Mahla et al., 2018) Figure 3 indicates that the BTE increases with increase in load irrespective of the blends. This is due to increase in fuel consumption that increases the BTE. It was noticed that BTE was almost directly proportional to engine load (R= 0.85 - 0.97) for all fuel blends. Similar trends were also observed by Bora and Saha (Bora et Saha, 2015). This may be due to the fact that at higher engine loads the cylinder temperature enhances and hence complete combustion is attained, which consequently results in higher BTE. Impartial combustion of fuel aids in burning of more fuel and increasing the output of the engine and improving the BTE. Among test fuels, BTE values of all biodiesel–diesel blends were lower than the diesel values at all load conditions due to the high calorific value of diesel that results in high energy release due to combustion. At lower loads (30-55 %), B20 gives lower break thermal efficiency (20.24 %) than that of diesel fuel (24.06 %), probably due to higher viscosity, low calorific value and low air–fuel mixing of the blend (Asokan et al., 2016; Jindal et al., 2015; Rakopoulos et al., 2010).

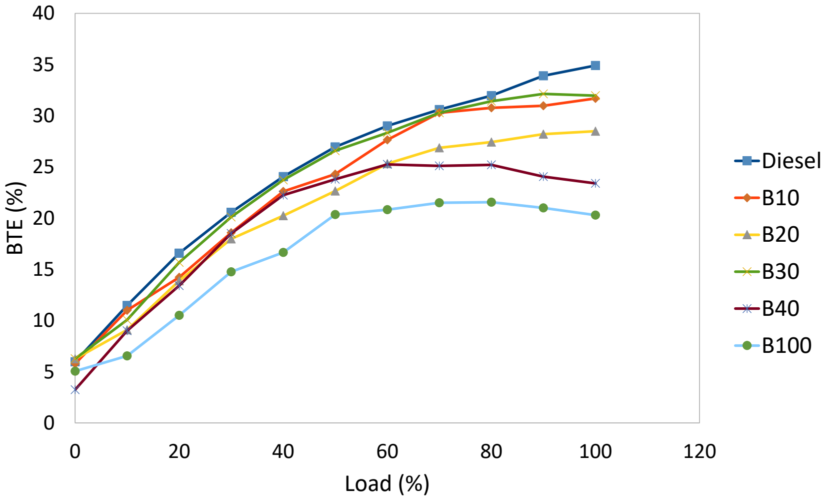

Figure 3: Variation of brake thermal efficiency with load for various test fuels

3.1.3. Exhaust gas temperature (EGT).

This is an indicator of the heat release rate of the fuels tested during combustion period. This helps in studying the increase of NOx emission. Generally, the combustion in the case of biodiesel is improved due to the presence of excess oxygen in the fuel itself. The variation of exhaust gas temperature with applied

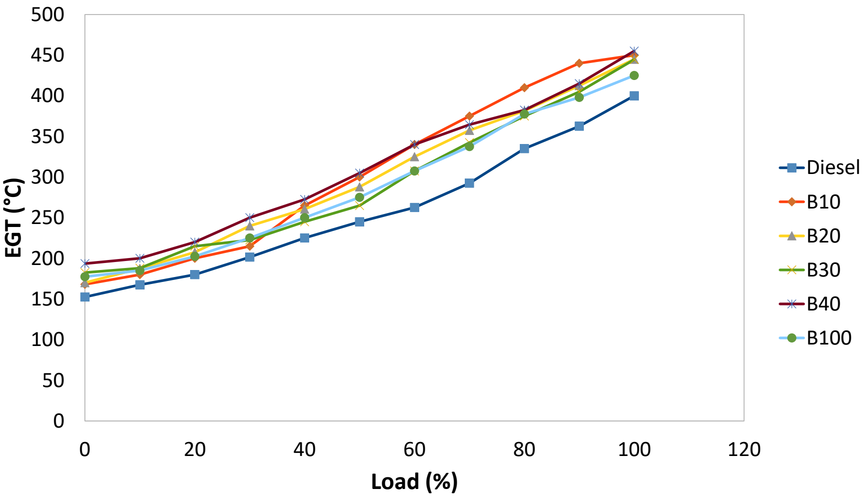

Figure 4: Exhaust gas temperature versus load for all test fuels

It is observed that as load increases, the amount of fuel consumed will increase, which increases the energy liberated due to combustion. Hence, for all test samples EGT increases with increase in load. These findings are in accordance with findings obtained by several researchers. Godiganur et al. (2009) on a six-cylinder turbocharged diesel engine fueled with mahua biodiesel blends observed an increase in EGT with the increase in engine load (about 12 % higher than diesel in the case of B100); Datta et al. (2014) on a double cylinder, four stroke, diesel engine fueled with jatropha biodiesel blends observed an increase in

EGT due to the higher flame temperature of biodiesel. In all cases, biodiesel-diesel blends have shown high EGT when compared to diesel. The heavier molecules of biodiesel (B100) lead to continuous burning even during exhaust, which causes higher EGT (Balusamy et Marappan, 2007). The EGTs of diesel and B100 at 100 % load are 400 °C and 425 °C, respectively.

3.2. Combustion characteristics

The combustion process occurring inside the engine cylinder can be analyzed by variation of cylinder pressure and heat release rate with CA.

3.2.1. Cylinder pressure.

Figure 5 shows the cylinder pressure with crank angle for different fuels and blends at 100 % load of the engine. The cylinder pressure for biodiesel-diesel fuel was almost same as diesel before and after the 60° crank angle. The peak pressure appeared for test fuels between 9° and 11° after top dead center (TDC). The highest peak cylinder pressure of 72.62 bar appeared for diesel at 10° after TDC and the next highest peaks correspond to B10 (69.55 bar) and B30 (68.71 bar), 10° after TDC. Cylinder pressure increases as the load increases because more fuel is burnt in the combustion chamber at higher pressure. The highest peak cylinder pressure of 72.62 bar appeared for diesel at 10° after TDC and the next highest peaks correspond to B10 (69.55 bar) and B30 (68.71 bar), 10° after TDC. The biodiesel-diesel fuels have less peak cylinder pressure when compared to diesel peak pressure as observed by Senthur et al. (2017) and by Arun et al. (2018). This is due to a shorter delay period for biodiesel-diesel fuels.

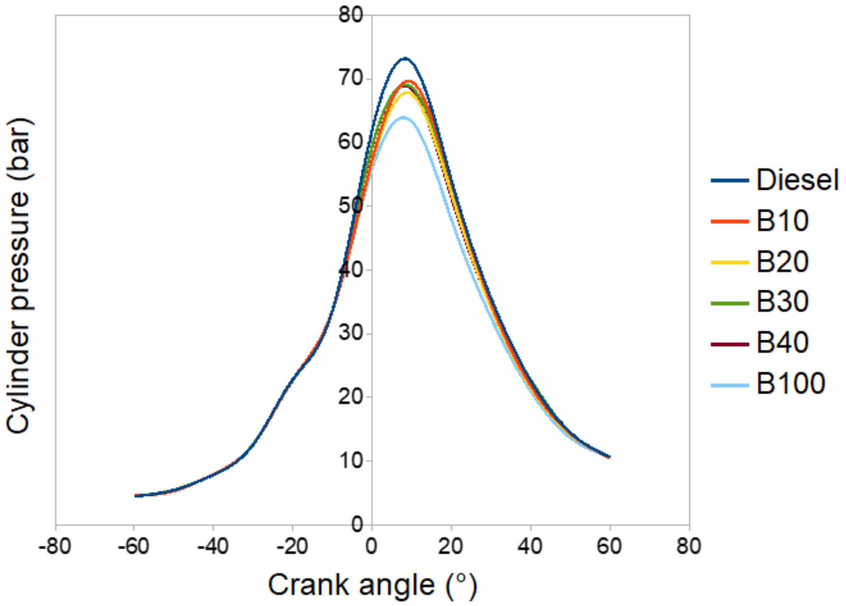

Figure 5: Variation of cylinder pressure at 100 % load for different fuels

3.2.2. Heat release rate.

Heat release rate (HRR) helps to estimate the combustion duration and it also tells about the character of the biodiesel and its blends under combustion. The variations in HRR against crank angle at full load condition for different combinations are shown in Figure 6. All tested fuels almost follow the same trend of heat release for all type of loads. The peak HRR for each fuel sample, B0, B10, B20, B30, B40 and

B100, are 66.13kJ/m^3, 54.81kJ/m^3, 45.32kJ/m^3, 61.26kJ/m^3, 50,64kJ/m^3 and 45.36kJ/m^3 respectively. The peaks of B10, B20 and B30 seem to be synchronous to diesel fuel.

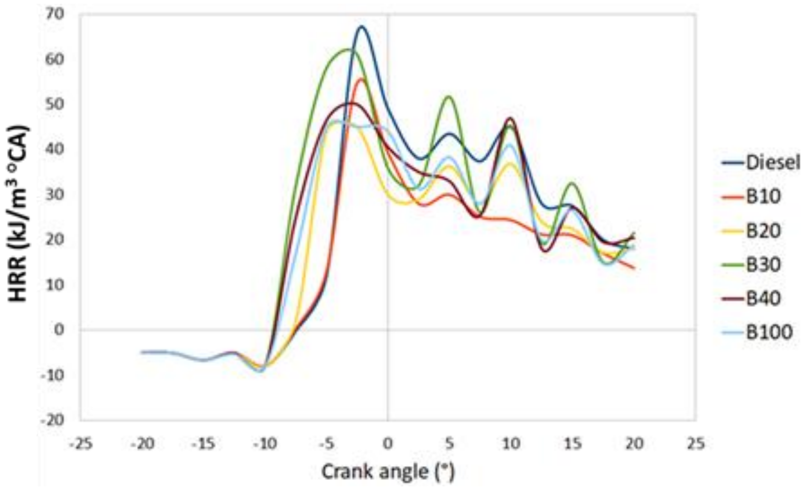

Figure 6: Variations in heat release rate against crank angle at full load condition for all test fuels

3.3. Engine emissions analysis

The exhaust gas that comes out of the engine after combustion mainly constitutes emission such as CO, HC, SOx, NOx and PM.

3.3.1. Carbon monoxide emissions.

The variations in CO emission at different percentages of full load for different combinations of fuel type are shown in Figure 7.

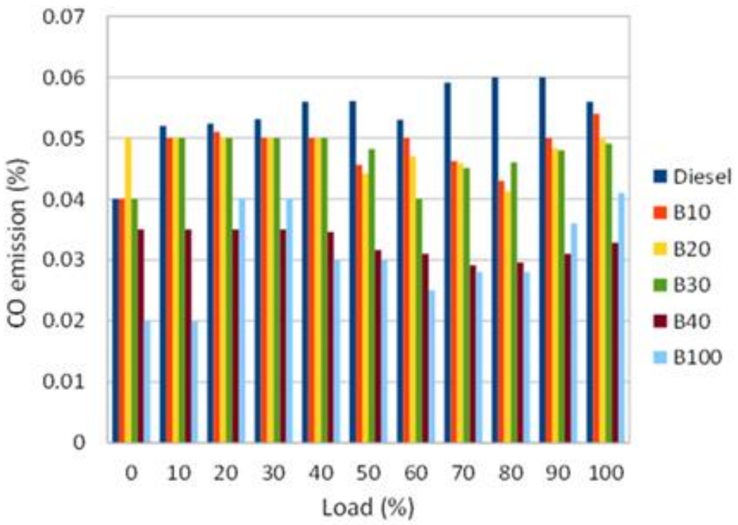

Figure 7: CO emissions with varying loads of different blends

It can be observed that the CO emission will decrease with usage of biodiesel-diesel blends as a fuel in diesel engine. Among all test fuels, several of the B20, B30 and B40 blends have shown decreased CO. B100 have lower CO emission than diesel with a decrease of 26.79 %, due to the higher oxygen content leading to higher temperature in the combustion chamber and resulting in more conversion of CO to CO_2.

3.3.2. Carbon dioxide emissions.

Figure 8 shows the variation in carbon dioxide (CO_2) emission for different combinations of fuel.

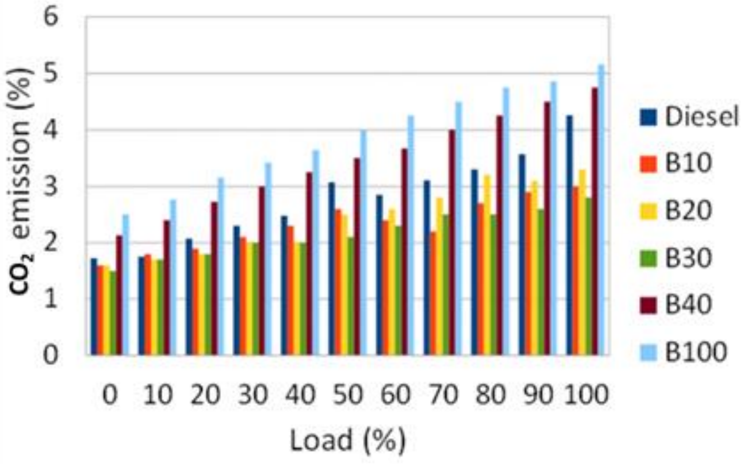

Figure 8: CO_2 emissions with varying loads of different blends

It can be seen that the CO_2 emission for biodiesel-diesel blends is higher than that of diesel (up to 5.16 %). This is due to the high O_2 content in biodiesels. The high O_2 content in biodiesel will increase the availability of oxygen for combustion. This improves the fuel combustion and leads to high CO_2 emission. However, the CO_2 emission of B100 of all test samples was found to be low in most cases, even if it contained high O_2 when compared to other test fuels. This is due to the high viscosity and low calorific value of B100, which decreases the fuel atomization and hence leads to poor combustion of fuel inside the cylinder.

3.3.3. Hydrocarbon emissions.

Figure 9 shows variation of unburned hydrocarbon (HC) emission for different blends of hybrid biodiesel and diesel for various loads. If combustion is improved the HC emissions decrease, and vice versa. Because of the high content of oxygen in the biodiesel it is expected that HC emission will decrease for blends of hybrid biodiesel and diesel. B100 has lower HC emission than diesel with a reduction in HC emissions of 41.06 % at full load.

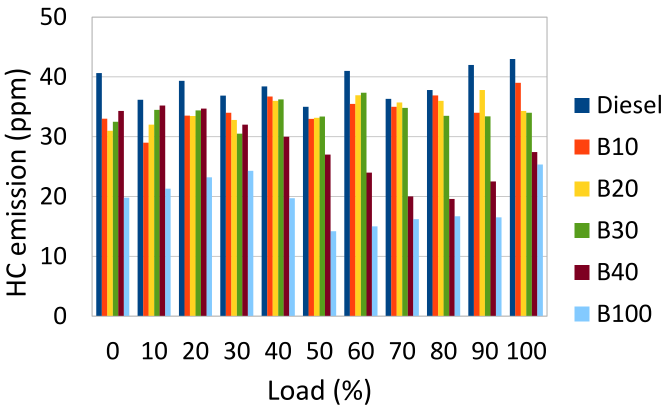

Figure 9: Variation in HC emission with load

3.3.4. *Oxides of nitrogen (NOx) emissions.*

The variations of NOx at different percentages of full load for different combinations of fuel types, are shown in Figure 10. The important parameters which affect the NOx emissions are flame temperature, ignition delay, availability of O_2 and N_2 in the mixture and fuel bound oxygen (Lin et Lin, 2007).

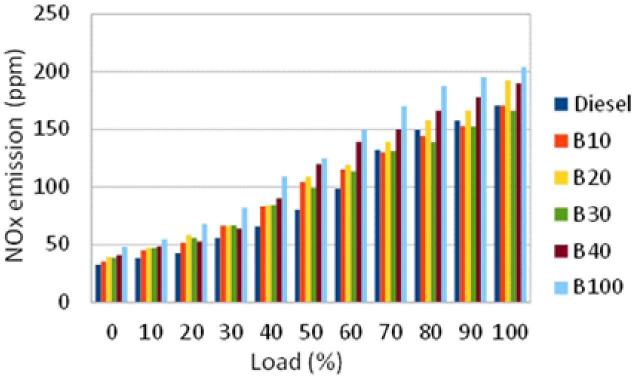

Figure 10: Variation in NOx emission with load

The tests show an increase in NOx emissions with the increase in engine load for all blends. It is found highest for biodiesel because of high oxygen content which results in complete combustion causing high combustion temperature. The NOx value of B100 at 100 % load is 15.8 % higher than diesel.

3.3.5. *Smoke opacity variation with engine load.*

Figure 11 presents the variations of smoke emissions for biodiesel-diesel test fuels. The peak smoke opacity at maximum load is almost 60 % with diesel fuel (B0), and 40 % with biodiesel (B100). Arun and Balasubramanian (2012) reported a peak value of smoke emission of 77 % with a dual biodiesel blends of neem and jatropha biodiesels. Goga *et al.* (2019) observed a peak smoke emission of 27.5 % with a blend of rice bran biodiesel and n-butanol.

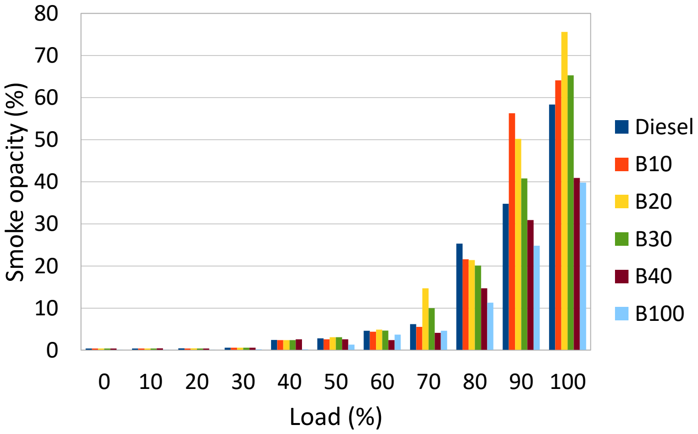

Figure 11: Smoke opacity variation of different blend with load

4. CONCLUSION

This work investigated the performance, combustion and emission characteristics of a hybrid biodiesel on a CI engine operation with various diesel blends. Among biodiesel test blends B10, B20 and B30 has shown engine performance (BTE, BSFC and EGT) close to those of conventional diesel. Fuel combustion characteristics (cylinder pressure and HRR) are almost synchronous to that of diesel. CO, HC and smoke emissions were lower for the tested biodiesel blends B10 and B20 as compared to diesel fuel. However, the impact of hybridizing the raw material to improve the performance characteristics of biodiesel is not obvious.

5. CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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