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Influence of engine operating variable on combustion to reduce exhaust emissions using various biodiesels blend

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This study focused mainly on the behavior of biodiesel operated under various operating conditions. The experiment was conducted with B20 of three potential biodiesel sources, namely, rice bran, *Moringa* and sesame oil. A significant outcome was observed from the test results, which showed that the brake thermal efficiency of the biodiesel blend was about 3.4% lower under constant speed running conditions than constant torque operating conditions. Similarly, about 6.5% lower exhaust gas temperatures under constant speed running conditions with lower peak pressure were found than under constant torque testing conditions. On the subject of emission, it is seen that the testing conditions also have an influence on exhaust emission. For instance, under constant speed running conditions, the engine produces about 19.5% lower NO and 19% higher HC than under constant torque running conditions. A similar influence was also found in the pressure and heat release rate. However, there is a clear variation found in the results under different operating conditions. Therefore, it is necessary to test the fuel under various operating conditions, such as constant torque, constant speed, variable injection timing, for the optimal use of biodiesel.

1. Introduction

The sustainable production of biofuels is a valuable tool in stemming climate change and boosting local economies, particularly in lesser-developed parts of the world and enhancing energy security for all. Biodiesel has been found unambiguously to be a notable option for substituting conventional fuels due to its availability in nature from various renewable biological sources. In addition to its valuable advantages, biodiesel has a couple of difficulties when using 100% in engines, such as high viscosity, high density, low volatility, and low heating value,[1] which will lead to problems in pumping, atomization, gumming, injection fouling, and piston ring sticking.[2] Consequently, biodiesel blending (biodiesel and diesel) brings a new topic in the research arena.[3–5]

Among the available sources of biodiesel, very few are used commercially in different countries. For instance, canola and soybean are used in USA, palm oil in Malaysia and rapeseed oil in Europe.[1,6] However, numerous studies have been conducted and are still ongoing in various sources, such as *Jatropha*, rice bran, *Moringa*, coconut, corn, mustard, tallow, karanja, neem, *Pongamia*, linseed, and rubber seed, to identify another valuable source for biodiesel. However, different studies have shown different results. In particular, the operating parameters have a significant impact on biodiesel when tested in engines. For example, Niemi *et al.*[7] tested mustard oil at variable injection timing and found a lower NO_x than diesel but A. Sanjid *et al.*[8] found higher NO_x emission when tested under variable speed conditions. Saravanan *et al.*[9] have shown that rice bran biodiesel possesses lower thermal efficiency and better emission characteristics except for a marginal increase in NO_x. John & Kumar[10] studied the effect of the load on the performance and found that rice bran biodiesel resulted in a higher brake thermal efficiency than diesel. Patel *et al.*[11] observed that rice bran biodiesel possessed about 40–50% less HC and significantly lower CO and NO_x. R. S. Kumar *et al.*[12] reported that at a constant speed, all the emissions were lower than diesel except for NO_x. Similarly, Altun *et al.*[13] found that all the emissions and exhaust temperature of sesame biodiesel were lower than diesel. Banapurmath *et al.*[14] reported that at a constant speed, all the emissions of sesame methyl ester had a higher value than diesel except NO.

However, regarding the abovementioned study, it is clear that the study on biodiesel testing under one operating condition can hardly provide exact results, which will make it possible to use commercially. It is essential to conduct tests under various operating conditions for a particular biodiesel, which will help better choose the best biodiesel for commercial purposes. Moreover, during the road load test, an engine always operates at variable operating parameters such as constant speed with variable load or constant load with variable speed.

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Based on the fact, this study is categorized as an investigation of the detailed performance parameters and emission gases under two operating conditions such as constant torque with a variable speed and constant speed with a variable load. Finally, an analysis of in-cylinder combustion, such as ignition delay, pressure rise rate, heat release rate, and fuel mass burning fraction of the three biodiesel blend in CI engine, was performed.

2. Material and methods

2.1 Measurement of the physicochemical properties of crude oil and their biodiesel

According to ASTM, the physicochemical properties of crude oils and their biodiesel were tested. The chemical properties were tested through a chemical testing service. The cetane number (CN), iodine number (IV) and saponification value (SV) were calculated using the following equations.

$$\mathrm{CN} = 46.3 + \left(\frac{5458}{\mathrm{SV}}\right) - (0.225 \times \mathrm{IV}) \quad (1)$$

$$\mathrm{SV} = \sum \frac{(560 A_{\mathrm{i}})}{M_{\mathrm{wi}}} \quad (2)$$

$$\mathrm{IV} = \sum \frac{(254 A_{\mathrm{i}} D)}{M_{\mathrm{wi}}} \quad (3)$$

where A_{i} = the percentage of each fatty acid component; D = the number of double bonds; M_{wi} = the molecular mass of each component.

2.2 Test fuel and operating condition

In this study, one blend, namely, B20 (biodiesel 20% vol + diesel 80% vol), of the three feedstock, such as rice bran, *Moringa oleifera* and sesame oil, were prepared and tested. The experiment was carried out under two operating conditions. First, at a constant torque (20 N m) with varying speed from 1000 rpm to 1800 rpm with a step of 200 rpm and secondly, at a constant speed (1400 rpm) with a variable load from 10 N m to 25 N m with a step of 5 N m. Diesel was used as baseline fuel, afterward blended biodiesel such as R20 (rice bran biodiesel 20% vol), M20 (*Moringa* biodiesel 20% vol) and S20 (sesame biodiesel 20% vol) were tested under the same operating condition. During the running condition, the engine ran satisfactorily throughout the entire test. To enhance the accuracy of the study, each test point was repeated twice to derive an average reading.

2.3 Engine test

The experimental investigation was carried out in the Tribology Laboratory of the Department of Mechanical Engineering, University of Malaya, on a single-cylinder, water-cooled, naturally aspirated, direct injection and four-stroke diesel engine. The schematic and engine specification is shown in Fig. 1 and

Table 1 Specifications of the engine

Parameter		Units
Displacement	638	cm^3
Bore × stroke	92 × 96	mm × mm
Compression ratio	17.7 : 1	
Rated power	7.8	kW
Rated speed	2400	rpm
D/H_{BOWL}	2.81	
Combustion chamber	Re-entrant type	
Fuel injection type	Mechanical cam driven injection	
No. of injection holes	4	
Nominal injection nozzle diameter	0.26	mm

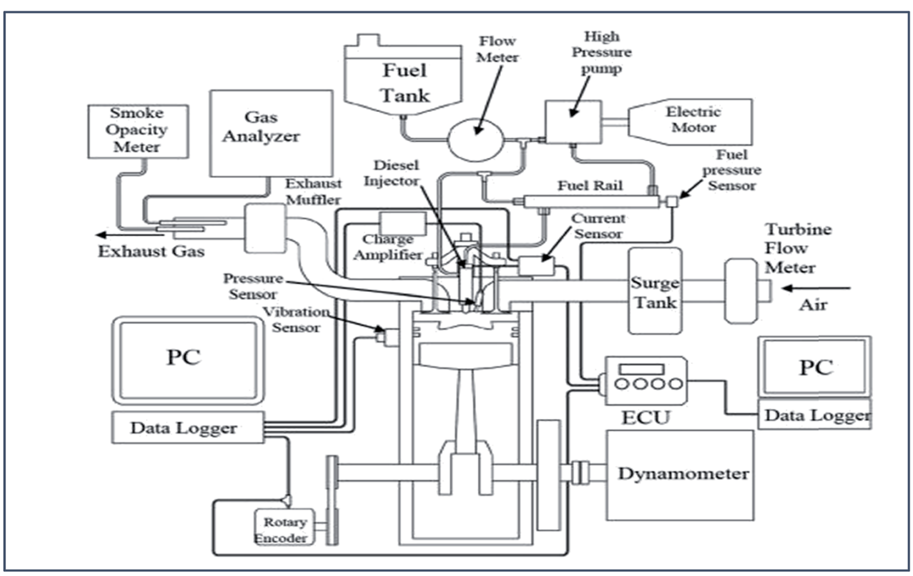

Fig. 1 Schematic of engine test bed.

Table 2 Specifications of the emission analyzer

Equipment	Method	Measurement	Upper limit	Accuracy
BOSCH gas analyzer	Non-dispersive infrared	CO	10.00 vol%	±0.02 vol%
	Non-dispersive infrared	HC	9999 ppm	±1 ppm
BOSCH RTM 430	Photodiode receiver	Smoke opacity	100%	±0.1%
AVL DICOM 4000	Electrochemical	NOx	5000 ppm	±1 ppm

Table 1. In order to provide a load to the engine and controlling speed, a ST-7.5 model 7.5 kW A.C. synchronous dynamometer was used. An air flow meter of 2–70 L s^{-1} for the intake airflow measurement, A K-type thermocouple for monitoring the exhaust gas temperature, and a positive displacement gear wheel flow meter (model: DOM-A05H) for fuel flow rate were used. All the necessary sensors were fitted with the test system for combustion analysis. A Kistler6125B type pressure sensor was used for in-cylinder gas pressure measurement. To eliminate the cycle to cycle variation in each test, the average data were calculated from 100 consecutive combustion cycles of pressure data. To reduce noise effects, smooths data using SPAN as the number of points used to compute each element were applied to the sampled cylinder pressure data. A Bosch BEA-350 exhaust gas analyzer was used for engine emissions analysis of HC, CO, CO_2, and NO. A Bosch RTM 430 smoke opacity meter was used to measure the smoke opacity. The specifications of the emission analyzer are given in Table 2. The same method was applied for all blends.

2.4 Analysis of cylinder pressure data and heat release

To obtain quantitative information on the progress of combustion, the data of the cylinder pressure *versus* crank angle are significant.[15] For proper analysis of the heat release rate, the average value of 100 cycles was considered, because the average of *N* measurements is a more reliable estimator for the average pressure at that crank angle than any individual cycle measurement. The heat release rate, $\frac{dQ}{d\theta}$ per degree crank angle derived from the first law of thermodynamics can be calculated by eqn (4).

$$\frac{dQ}{d\theta} = \frac{\lambda}{\lambda - 1} P \frac{dV}{d\theta} + \frac{1}{\lambda - 1} V \frac{dP}{d\theta} \quad (4)$$

where $\frac{dQ}{d\theta}$ = rate of heat release (J per °CA), V = instantaneous cylinder volume (m^3), θ = crank angle (°CA), P = instantaneous cylinder pressure (Pa), γ = specific heat ratio which is considered constant at 1.35.

3. Results and discussion

3.1 Characterization of crude oils and their biodiesel

The basic properties of the crude oils and their biodiesel are shown in Table 3. Rice bran biodiesel possesses relatively more density and viscosity than sesame and *Moringa* biodiesel. The cetane number calculated for rice bran biodiesel was higher (76.1) than sesame (54.3) and *Moringa* (51.3). The oxygen content of all the biodiesel is about 11% with about 12% hydrogen. The flash point of sesame biodiesel was comparable to rice bran and *Moringa* biodiesel.

3.2 Effect of the operating parameters on the engine performance, emission and combustion

3.2.1 Brake specific fuel consumption. BSFC analysis is imperative because the fuel economy is commonly assessed in terms of the distance for transportation vehicles. Fig. 2 shows the variation of the BSFC under two operating conditions such as constant torque and constant speed. The average BSFC of all biodiesel blends was about 3.11% higher than diesel under each operating condition. The reason might be the slightly higher density and lower calorific value of biodiesel.[16,17] For the same volume of fuel injection, the amount of injected biodiesel is higher than that of diesel.[18] A higher required amount and

Table 3 Physicochemical characteristics of the crude oils and biodiesels[a]

Property	Unit	CRBO	CMOO	CSO	RME	MME	SME	ASTM D6751	EN 14214	Diesel
Kinematic viscosity at 40 °C	$mm^2\ s^{-1}$	52.225	32.004	34.087	5.3657	4.1264	4.3989	1.9–6.0	3.5–5.0	3.1818
Density at 15 °C	kg m^{-3}	924.3	923.4	923.6	886.9	885.8	884.8	n.s	860–900	849.1
Higher heating value	MJ kg^{-1}	39.548	39.868	39.386	39.957	39.888	39.996	n.s	n.s	45.315
Flash point	°C	300.5	263.5	280.5	174.5	176.5	208.5	>130	>120	73.5
Cetane number		N/D	N/D	N/D	76.1	51.3	54.3	47 min	51 min	N/D
Iodine value		N/D	N/D	N/D	92.88	127.55	108.03			N/D
Saponification value		N/D	N/D	N/D	143.53	161.93	168.93			N/D
Oxygen content	wt%	N/D	N/D	N/D	11	11.9	10.7	11	n.s	0.6
Carbon content	wt%	N/D	N/D	N/D	76.1	75.8	76.5		n.s	84.6
Hydrogen content	wt%	N/D	N/D	N/D	12.9	12.3	12.8	12	n.s	14.8

[a] n.s ≡ not specified; N/D ≡ not determined, CRBO ≡ crude rice bran oil, CMOO ≡ crude *Moringa* oil, CSO ≡ crude sesame oil, RME ≡ rice bran biodiesel, MME ≡ *Moringa* biodiesel SME ≡ sesame biodiesel.

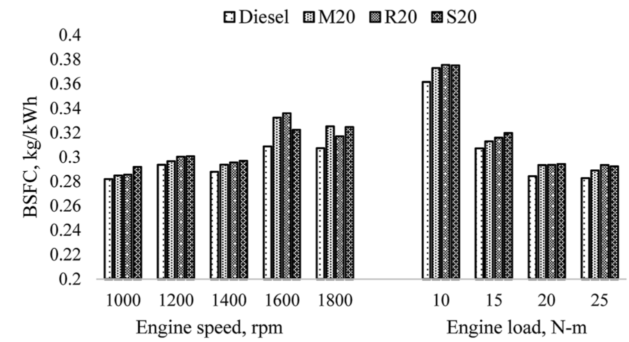

Fig. 2 Variation in the brake specific fuel consumption under various operating conditions.

a lower calorific value lead to higher volumetric consumption for the same brake power output.[19] BSFC is in an increasing trend as the speed increases, but a reversing trend is observed when load rises, as shown in Fig. 2. Frictional loss is the main cause of higher BSFC because with the increase in speed, frictional loss also increases, but at constant speed with increasing load, the decreasing trend of BSFC is dominated by the increasing mechanical efficiency as the bmep increases.[15] It was observed that BSFC at constant speed was about 4.38% higher on an average than the BSFC at constant torque. The calculated average BSFC at constant torque was 295.9, 306.5, 306.86 and 307.29 g kW^{-1} h^{-1} for diesel, M20, R20 and S20, respectively. On the other hand, at a constant speed, the values were 308.89, 317.02, 319.57, and 320.36 g kW^{-1} h^{-1} for diesel, M20, R20, and S20, respectively. In terms of the brake specific energy consumption, all fuels, including diesel, possess about 4.05% higher energy consumption under variable load conditions than at variable speed running conditions. However, all biodiesel possesses slightly higher specific energy consumption of about 1–1.5% than diesel. Moreover, it is observed that M20 provides lower energy consumption followed by R20 and then S20.

3.2.2 Exhaust temperature. The variation in the exhaust temperature with the variation in both engine speed and load for biodiesel blends are shown in Fig. 3. The exhaust gas temperature increases under both the aforementioned operating conditions. Such phenomena are the result of variations in the relative importance of heat transfer in the cylinder and heat transfer to the exhaust valve and port. The amount of fuel combusted in the combustion chamber within a unit time increases; consequently, the heat energy produced increases with increasing engine speed.[20] With increasing speed, the exhaust temperature for both diesel and biodiesel rise to 1–10.92% on an average, but such variations under constant speed conditions are larger than at variable speed, for instance, 12.38–20.42%. However, all biodiesel exhibited higher exhaust temperatures than diesel, for example, 2.53% at a constant torque and 1.05% at a constant speed on average. Such differences are due to a physical delay because proper atomization is retarded by the high density and viscosity.[21] However, on average, the exhaust temperature rise at constant torque is about 6.54% more than that under constant speed conditions.

3.2.3 Brake thermal efficiency. Brake thermal efficiency is mostly related to the BSFC and calorific value. Fig. 4 shows that brake thermal efficiency (BTE) for biodiesel blends follows the same trend line as diesel. It is found that biodiesel blends possess about 1.42% lower BTE on an average than diesel. The relatively higher fuel consumption and lower calorific value of biodiesel are the main cause for such a result. BTE at low and average speed is higher than that at higher speed because at lower speed, the minimum heat loss causes a lower fuel consumption but at higher speed, frictional loss dominates the situation. On the other hand, when the fuels are tested under constant speed keeping the load variable, it is seen that BTE is improving. At a constant speed, when the load is increasing, the brake power is also improving, which in turn increases the BTE. BTE at a constant speed is about 3.4% lower than that under constant torque operating condition on average.

3.2.4 Ignition delay. The ignition delay, which is an important phenomenon of combustion, is defined as the time interval between the start of injection and the start of combustion.[15] Both physical and chemical processes take place in the duration of the ignition delay, which largely depend on the fuel ignition characteristics (cetane number). The influence of the operating conditions on ignition delay is presented in Fig. 5. The ignition delay or delay period increases linearly when the operating speed increases. A change in engine speed alters the temperature/time and pressure/time relationships.[15] The negative impact is found when the fuels are tested under

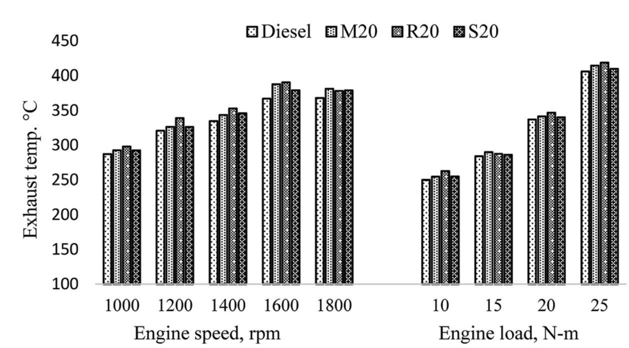

Fig. 3 Variations in the exhaust gas temperature under various operating conditions.

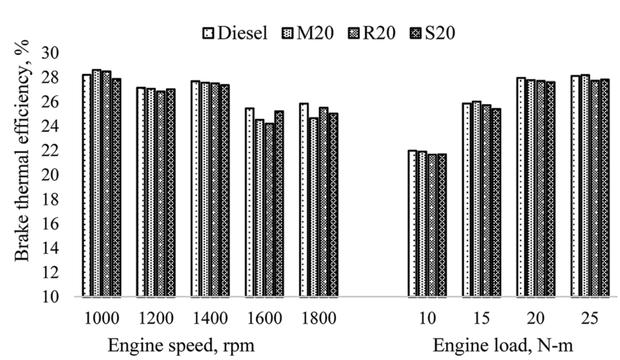

Fig. 4 Variations in the brake thermal efficiency under various operating conditions.

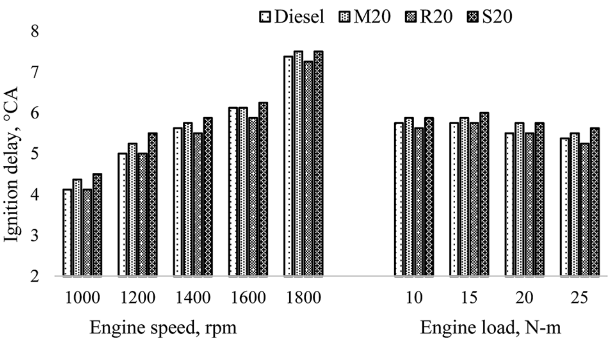

Fig. 5 Variations in the ignition delay under various operating conditions.

variable load conditions. The delay decreases linearly as the load increases. This is because with the addition of a load, both the residual gas temperature and wall temperature increase, which results in a high charge temperature at injection. This reduces the delay.[15]

3.2.5 **Peak pressure.** Fig. 6 shows the effect of the testing conditions on combustion peak pressure. The peak pressure of any fuel depends largely on the heating value and ignition delay. In some cases, biodiesel possesses a higher peak pressure than diesel because the relatively longer ignition delay of these biodiesel compensated for the negative impact of the lower calorific value. A longer ignition delay accumulates more oil to burn initially, consequently increasing the pressure.[22] However, both operating conditions have an influence on the peak pressure. Fig. 6 shows that the peak pressure increases with increasing speed, and the variation is maximized at a high speed except at the initial speed. The vital factor effecting such a variation is the ignition delay: as speed increases, the ignition delay increases.[15] On the other hand, under constant speed, when the load is increasing, the peak pressure also increases linearly, but not as sharply as under the constant torque condition. With increasing load, the mean effective pressure increases because of the improved mechanical efficiency. Therefore, the peak pressure is improved as the load increases, even though the load has negative impact on ignition delay. All the fuels gave a higher peak pressure under constant torque conditions than at a constant speed running, about 8.8% on an average.

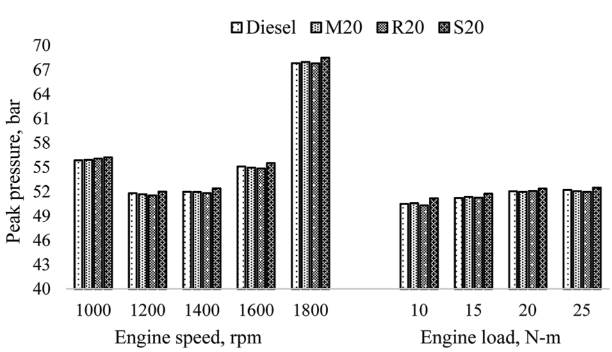

Fig. 6 Variation in the peak pressure under various operating conditions.

3.2.6 **Pressure rise, heat release rate and mass burnt fraction.** The pressure rise rate and heat release rate are significant in combustion analysis because these parameters can help sufficiently assess the engine performance and the effects of the operating conditions on the engine performance, as well as to compare the performance of different engines under the same operating conditions.[23] It was observed that the operating conditions have an influence on the maximum pressure and heat release developed (Fig. 7). For instance, on a crank angle basis, the maximum pressure rise at a constant torque forms at about 1.875°CA earlier (average data) than that under constant speed running conditions. On the other hand, the maximum heat release rate under constant torque conditions occur at about 2.5°CA later on an average than under constant speed conditions. The reason might be the time of residence. At a constant torque, as the speed increases, the residence time for fuels inside the cylinder decreases. Therefore, the proper combustion timing is redeemed by the longer crank rotation. At constant torque, the maximum pressure rises occur from 8.75°CA to 14.75°CA and the maximum heat release occurs from 7.125°CA to 13.75°CA. On the other hand, at a constant speed, the pressure rise maximizes from 10.75°CA to 16.5°CA and heat release maximizes at 6.875°CA to 7.875°CA. At a lower speed/load, the maximum pressure rise for biodiesel blends is few crank angle degrees later than diesel. Relatively higher viscosity, lower heating value and lower in cylinder pressure are responsible for these results. Another important finding from the experiment is that with increasing speed, the heat release rate is lesser than that at the lower speed. The maximum heat release occurs at the initial speed because of the starting condition of the engine, in which some gases are trapped in the crevice region, thereby increasing heat transfer.[15] In the case of fuel burning, the mass burnt fraction (MBF) curves of all biodiesel follow the same trend as that of diesel, the burning rate of all fuels increases with increasing speed/load because the burning interval remains constant on the CA basis.[15]

3.2.7 **Exhaust emissions**

3.2.7.1 Nitric oxide. The formation of nitrogen oxides depends largely on the peak flame temperature, high burning gas temperature, ignition delay, and availability of nitrogen and oxygen.[15] The present study deals with NO (nitric oxide) because it is the principal oxide of nitrogen. From Fig. 8, it is seen that the formation of NO is lower at an average speed than at the initial and final operating speeds. At 1000 rpm, NO is higher because at a lower speed, the residence time of the injected fuel is higher, which enhances the proper atomization and vaporization of fuels. This leads to the burning of fuels nearer to the peak combustion temperature and pressure,[15] resulting in an increase in NO formation. At 1800 rpm, combustion is enhanced by advanced injection, which prolongs the combustion, and thus NO formation again increases. On the other hand, at low load (Fig. 8), NO formation is lower because of the lower cylinder pressure and temperature.[24] However, as the load increases at a certain speed, NO formation also increases except at a high load. When the load increases, the fuel–air ratio also increases steadily with increasing bmep. The increased quantity

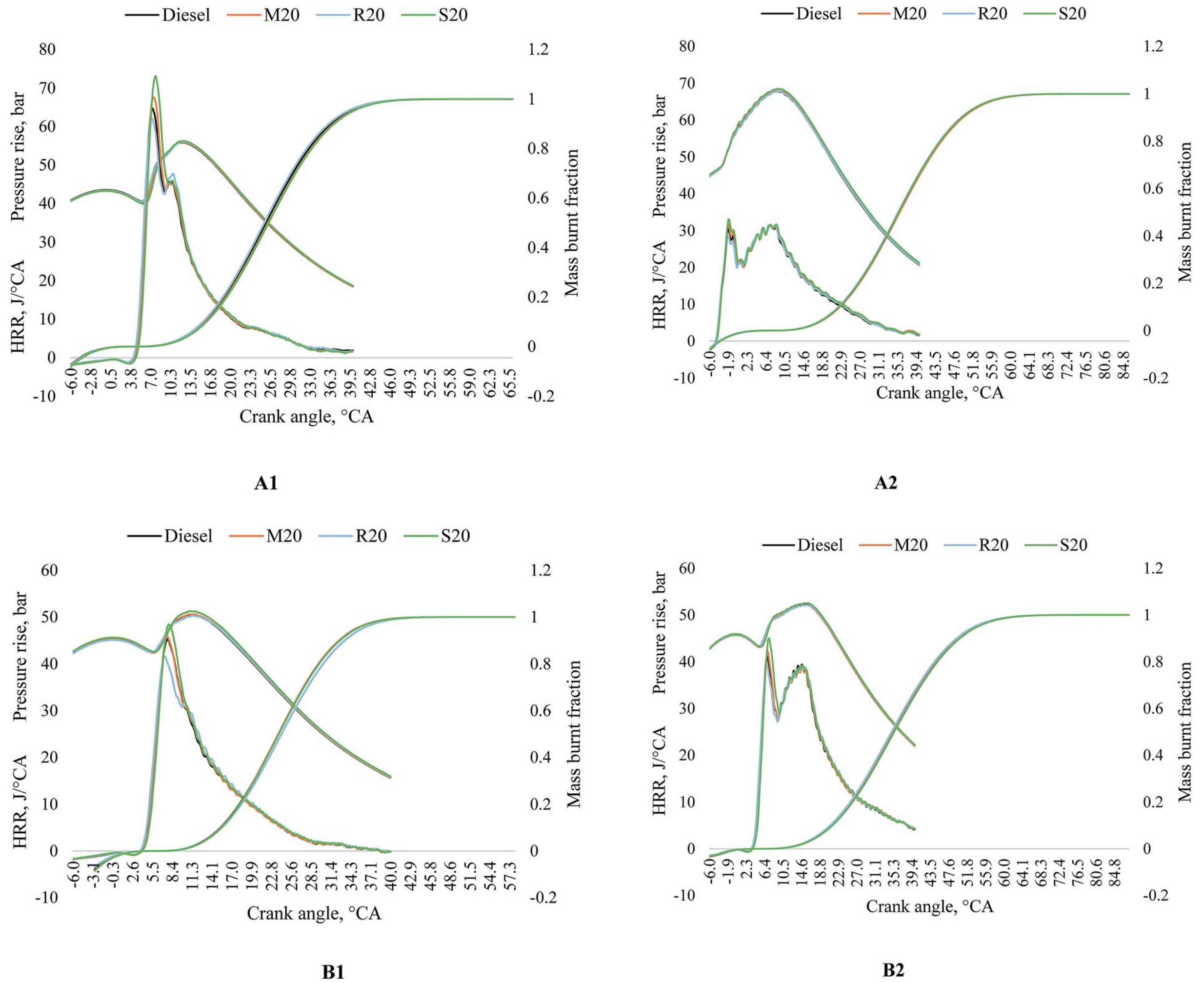

Fig. 7 Variations in the pressure rise, heat release and mass burning rate under various operating conditions (A1): at 1000 rpm, (A2): at 1800 rpm, (B1): at 10 N m, (B2): at 25 N m.

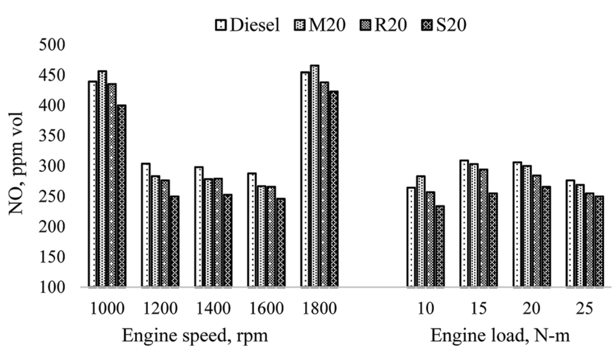

Fig. 8 Variations in nitric oxide under various operating conditions.

of fuel injected per cycle results in an increased amount of charge close to stoichiometric combustion, consequently near the peak pressure and temperature.[15] Thus, NO increases. On the other hand, when the load reaches the maximum, NO formation decreases. The increased amount of fuel injected at high load results in a rich mixture and lower volumetric efficiency due to the high in-cylinder temperature. These two phenomena are responsible for initially burning the fuel at a slower rate. This is in-turn leads to proper atomization and vaporization, which cause burning of fuel at the end of combustion with a sufficient amount of oxygen and results in a relatively low peak ignition temperature. Thus, NO formation decreases. NO formation at constant speed is about 19.5% lower than under constant torque operating conditions.

3.2.7.2 Hydrocarbon. Fig. 9 shows the variation of hydrocarbon (HC) under different operating conditions. HC formation increases with increasing speed. This finding can be attributed to over-fueling as the engine accelerates.[15] The sac volume (the small volume left at the tip of the injector after the needle seats) is filled with fuel, and because of over-fueling, it can hardly mix with air. Therefore, HC formation increases.[25] On the other hand, HC formation at a light load is higher than that at a higher load due to overleaning. This is because at a light load, the mixture is too lean to a stoichiometric ratio, which is one of the vital factors for higher HC[15]. Unburnt hydrocarbon formation under constant speed running conditions is about 19% higher than that under constant torque

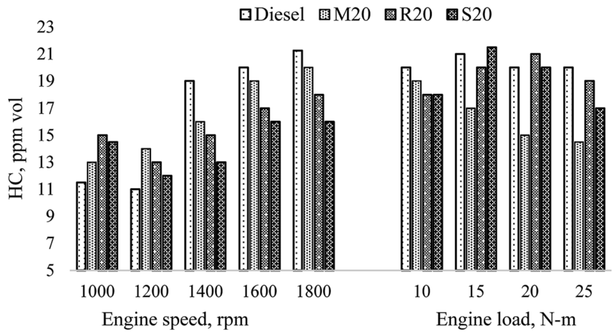

Fig. 9 Variation in the unburnt hydrocarbon under various operating conditions.

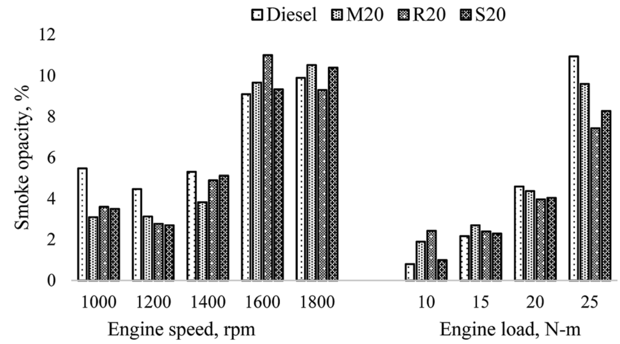

Fig. 11 Variations in the smoke opacity under various operating conditions.

operating conditions on an average. In addition, different operating conditions affect the biodiesel HC formation. For instance, M20 possesses a lower HC than R20 and S20 under constant speed running condition, but contrary results were found when operated under a constant torque.

3.2.7.3 *Carbon monoxide and smoke opacity.* The formation of CO and smoke are shown in Fig. 10. The data show that the formation of CO is depends largely on the operating conditions. As shown in the figure, CO of biodiesel blends under constant torque conditions is higher than diesel. On the other hand, at a constant speed, the formation of CO is lower than diesel on average except S20. With the increase in load, the residual gas temperature and wall temperature both increases, which increase the cylinder temperature. Thus, proper atomization is enhanced, which improve the complete combustion of biodiesel blends as biodiesel contains about 11% more oxygen than diesel (shown in Table 3). CO formation under the initial operating condition is higher than others. Improper combustion due to the idling and entrapment of some fuels in the crevice zone is the vital reason of such results.[15] CO formation for M20 was higher than R20 at variable speeds, but when tested at a constant speed, R20 showed higher CO formation than M20, especially at a high load.

The smoke from the exhaust tail pipe is usually visible as black smoke. The composition of smoke depends strongly on the type of fuel, engine operating condition and carbon residue.[26] At high speed and high load operating conditions, all the fuels, including diesel, possessed more smoke than that under normal operating conditions (Fig. 11). This is because the sudden acceleration from one speed to another causes over-fueling to ensure balance. This outcome initially results in a rich mixture, which in turn leads to smoke formation. The same results were obtained under high load operating conditions.

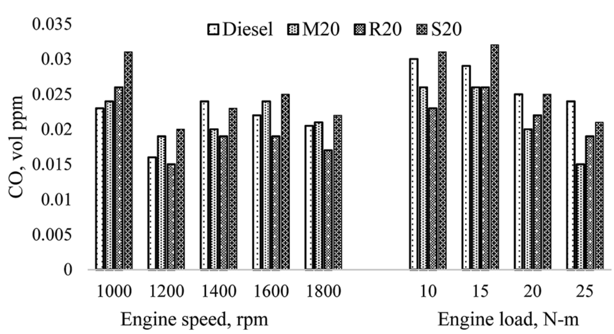

Fig. 10 Variations in carbon monoxide under various operating conditions.

4. Conclusion

Owing to the high demand of eco-friendly fuels for transportation, the search for new sources of biodiesel is ongoing. By consensus, this study was carried out under various operating conditions because of the limitation of a single operating condition, as mentioned above. The findings from the above-mentioned study showed that the operating parameters have a significant impact on both emission performance and combustion performance, but the impact is higher on emissions. To conclude, more than one test condition is needed to test biodiesel, if it is to be considered for commercial purposes.

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