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Research Article

Investigation of the Effects of JP-4 Addition to Biodiesel-Diesel Blends on the Performance Characteristics of a Diesel Engine

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ABSTRACT

In this study, the effects of JP-4-biodiesel-diesel blends and engine operating parameters on the performance characteristics of a diesel engine were investigated. The experimental tests were performed on a four-cylinder DI diesel engine. The Mixture-RSM method was applied to develop the mathematical models based on the experimental data. The results showed that the fitted models could be properly applied to predict the performance characteristics of the engine. According to the results, the brake power and torque decreased with increasing the biodiesel amount in the fuel mixture due to the lower energy content and higher viscosity of biodiesel than diesel fuel No.2. However, the brake power and torque increased slightly with increasing JP-4 in the fuel blend. The results also indicated that the BSFC increased with the higher proportion of biodiesel in the mixture at all engine speeds. The results indicated that there was no considerable difference in BSFC values while JP-4 was added to the fuel mixture, especially at higher engine speeds. Moreover, the difference of brake power values for fuel blends included biodiesel and neat diesel decreases at higher engine speeds due to the positive role of oxygen content in the molecular structure of biodiesel. Based on the results, brake power and torque increased at the higher engine load as a result of higher temperatures and better combustion conditions. Moreover, JP-4 caused an improvement in brake thermal efficiency compared to biodiesel, especially at lower and medium engine speeds. Generally, it is indicated that the application of JP-4 can improve engine performance.

1. INTRODUCTION

Population growth has increased demand for fossil fuels in recent decades. Increasing global concerns about environmental problems have also increased interest in alternative diesel fuels every day [1]. Today, petroleum fuels are the main resource for energy supply. Petroleum reserves are coming to be finished because of high demand in the world. Therefore, alternative energy sources have become more prominent these years. Among the alternative fuels, biodiesel is the most important liquid biofuel that is extracted from animal fat and vegetable oil feedstocks [2-4]. Many studies have been performed on the performance parameters of CI engines with biodiesel-diesel mixtures [1, 2, 5].

Özener et al. [1] investigated the effects of diesel and biodiesel blends (B10, B20, and B50) on the performance of a diesel engine. The results showed that BSFC increased up to 9 % from B10 to B50 when compared with pure diesel.

In another study [4], engine performances of five different types of biodiesels produced from corn, sunflower, soybean, canola, and hazelnut oil were compared with each other and with neat diesel. Biodiesel-diesel blends included 20 %, 50 %, and 100 % (volume basis) of biodiesel in the fuel mixture. The performance characteristics (brake power, SFC, and thermal efficiency) were determined for each fuel during engine test. The results showed that the best performance belonged to the fuel blend containing 20 % hazelnut biodiesel.

Seraç et al. [5] conducted some tests on a diesel engine power generator using diesel fuel and soybean-based biodiesel blends to evaluate the engine performance under different loads and a constant engine speed. The results showed that the maximum increase in BSFC was observed for D80B20 blend as about 8 % compared to neat diesel. Although the brake-specific fuel consumption of biodiesel is high on low loads compared to the neat diesel, both types of fuel showed almost the same results. The results also indicated that the maximum increase in BTE compared to diesel fuel was around 3 % when the engine ran with D80B20 blend at 10.8 kW.

On the other hand, there are fewer studies in the literature related to the use of jet fuels in diesel and other types of engines [1, 6, 7]. For example, in some papers, the effects of JP-8 on the combustion and spray characteristics of diesel engines were investigated [8-11]. Moreover, there are some ongoing research studies on JP-5 as an alternative of JP-8 along with diesel and biodiesel for use in CI engine [12].

Given the environmental problems and the existence of strict requirements for CI engines, it is necessary to study the application of new alternative fuels in the engines.

Kouremenos et al. [13] conducted an empirical study to investigate the use of JP-8 as an alternative fuel instead of diesel in an engine. The results showed that the application of JP-8 fuel enhanced combustion pressures because of the JP-8 properties that affect the injection parameters.

Arkoudeas et al. [14] applied two types of methyl ester with a percentage of 50 % in a diesel engine to measure the fuel consumption. The results indicated that the performance of the engine did not change using these fuels.

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Papagiannakis et al. [15] performed an experimental study to determine the performance of the direct injection and indirect injection engines fueled with JP-8 fuel. According to the results, JP-8 has a considerable impact on the combustion pressure in comparison with normal conditions.

In another study [8], the combustion parameters of a CI engine fueled with JP-8 and petroleum fuel were investigated. In this research, macroscopic spray images were applied to obtain the basic spray characteristics. The results showed that the spray angle and spray tip penetration were wider and shorter, respectively, than those of petroleum fuel when the engine was fuelled with JP-8. It is due to the faster vaporization property of jet fuel than diesel. Moreover, JP-8 has a longer ID than that of diesel as a result of the lower cetane number of JP-8.

Gowdagiri et al. [16] determined the BSFC and ignition delay of a diesel engine using petroleum and hydro-processed and Fischer-Tropsch as the diesel and aviation fuels, respectively. The results showed that ID was reduced with increasing cetane number. It was also observed that other fuel properties were not dependent on ignition delay. The results also indicated that BSFC decreased with increasing cetane number because the ignition delay reduced in the fixed-injection-timed condition.

Roy et al. [17] investigated the performance of an engine fueled with kerosene, biodiesel, diesel, and Wintron XC 30 (additive). The tests were carried out to analyze engine parameters by utilizing various blends of biodiesel and kerosene. The results indicated that methyl ester-kerosene blends improved performance at higher engine loads.

Lee et al. [10] investigated the impact of multiple injection strategies and EGR on the combustion characteristics of a light-duty diesel engine fueled with JP-8. The results showed that the ignition delay changed when the engine ran with JP-8 under the single-injection condition. Otherwise, the ignition delay of JP-8 and diesel is approximately equal when the tests are done under multiple injections due to the higher combustion temperature. Moreover, it was reported that more EGR levels could be used when an engine was fueled with JP-8 compared to conventional diesel combustion.

Labeckas and Slavinskas [18] performed the tests on a diesel engine fueled with biodiesel, JP-8, and diesel mixtures to examine combustion parameters of the engine. The results showed that maximum HRR and autoignition delay decreased when the engine operated with J5, J10, J20, and J30 blends at a rated speed in comparison with neat jet fuel. In this condition, in-cylinder pressure and BTE were higher although the BSFC did not change significantly.

Bhowmik et al. [19] investigated the effects of ethanol-diesel-kerosene blends on the performance parameters of an indirect injection diesel engine. In this research, an ANN model was employed according to the empirical data to find an accurate relationship between kerosene and ethanol amounts, as well as between engine load as the input variables and BSEC and BTE as the output variables. The researchers implied that the addition of ethanol to the fuel mixture had a positive impact on the BTE and BSEC of the diesel engine.

Given that there is not any research on the use of JP-4 blended with biodiesel-diesel mixture in diesel engines, the purpose of this study is the investigation of the impact of various JP-4-biodiesel-diesel blends and engine operating parameters (load and speed) on the performance characteristics of a CI diesel engine. Mixture-Response Surface Methodology (RSM) was also applied to develop models between performance (brake power, torque, BSFC, and brake thermal efficiency) characteristics of the engine.

2. MATERIALS AND METHOD

2.1. Fuel preparation and properties

In this research, waste cooking oil methyl ester (biodiesel) was provided from biofuels laboratory. Moreover, JP-4 was supplied from NIOPD Company. Table 1 shows the properties of biodiesel, JP-4 and conventional diesel used in this study.

Table1. Properties of the fuels.

Property	ASTM	Unit	Biodiesel	Diesel	JP-4
Flash point	D93	°C	175	60	-10
Kinematic viscosity at 40 °C	D445	mm^2/s	4.15	4.03	No specification
Density (15 ºC)	D4052	kg/m^3	880	840	758
Lower heating value	D240	MJ/kg	38.7	43	42.8
Cetane index	D613	----	62	57	45

2.2. Tests setup

The tests were carried out on a direct inject, four-stroke and turbocharged diesel engine model OM364 (Figure 1). Table 2 shows the engine specifications. The engine was fuelled with various fuel blends including biodiesel, JP-4, and diesel fuel according to the design of experiment matrix (Table 4) and ran at the specified loads and speeds. Based on Figure 1, a dynamometer connected to the engine was used to supply brake load and the consumed fuel determined based on the gravimetric method. A closed graduated cylinder characterized by a total volume of 300 cm^3 has been previously filled with fuel and, while the engine operated in the prescribed conditions, a graduated cylinder was opened and a record of the time required for the given amount of fuel to be consumed was obtained. Engine speed was also measured by a digital tachometer. Table 3 also presents the specifications of the test instruments. At each speed, firstly, the maximum engine torque was reached for each fuel. After that, the test engine operated at different torques when different fuels were tested. According to the standard, the performance parameters were recorded when the operating parameters (temperature of cooling water, lubrication oil, and exhaust gas) reached constant levels.

2.3. Design of experiments and analysis

The experimental tests were designed by the design of experiments according to Mixture-RSM [20]. In this research, the mathematical models were extracted to determine the variables (dependent and independent) relationship. The independent variables include percentage of No.2 diesels (X_1), biodiesel (X_2), JP-4 (X_3) in the fuel blend, speed (X_4), and load (X_5). Table 4 shows the experimental designs of actual (X) amounts of the variables. In addition, brake power, torque and BSFC, and brake thermal efficiency (BTE) are the dependent variables (Y).

The mathematical models were developed by Design Expert software. Analyses of variance (ANOVA) and regression were also performed by this software [20]. In this study, the range of fuels was considered as 0 to 100 %, 0 to 100 %, and 0 to 20 % for biodiesel, diesel, and JP-4 in fuel mixture, respectively. Moreover, the engine speeds and loads were 20 to 100 % and 1200 rpm to 2600 rpm, respectively. Based on the mathematical models, the dependent variables were calculated and presented in the plots.

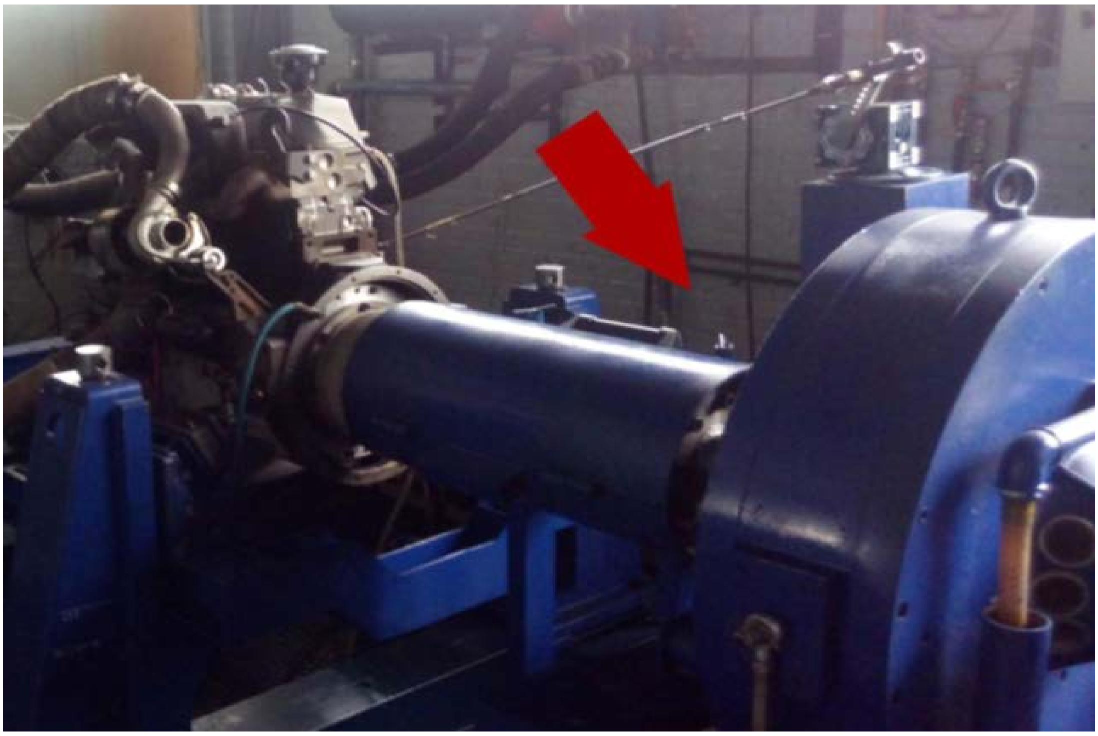


Figure1. The engine test setup.

Table 2. The test engine specifications.

Model	OM364
Number of cylinder	4
Stroke (mm)	133
Bore (mm)	97.5
Compression ratio	17:1
Maximum power	92 kW at 2400 rpm
Maximum Torque	455 N.m at 1450 rpm
Cooling system	Water

Table3. The specifications of testing instruments.

Variable	Range of measurement	Resolution
Torque	-	±1 (N.m)
Speed of engine	-	±1 (rev/min)

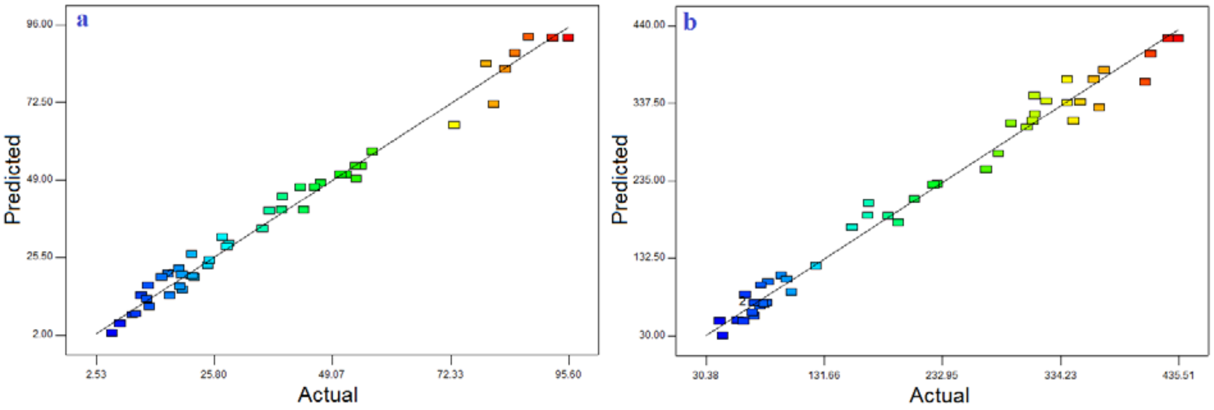
3. RESULTS AND DISCUSSION

3.1. Statistical analysis

The complete experimental tests were done according to the design matrix. The statistical analysis indicated that the model was sufficient without lack of fit. the R^2 values are adequate for all the dependent variables. The R^2 values for brake power, torque, BSFC, and brake thermal efficiency (BTE) were 98.4 %, 98.3 %, 96.1 %, and 91 %, respectively. Moreover, the results showed that all regression models were with significant p-values at 0.001 [21]. The experimental and model data were compared with each other to validate the mathematical models (Figures 2 to 5). It can be seen that the model data are in proper accordance with the experimental data.

Table 4. The design matrix for experimental tests.

Test number	Diesel percentage in fuel blend (%)	Biodiesel percentage in fuel blend (%)	JP-4 percentage in fuel blend (%)	Engine load (%)	Engine speed (rpm)
	X_1	X_2	X_3	X_4	X_5
1	0	80	20	100	2600
2	0	100	0	20	1900
3	0	80	20	100	1200
4	62.5	22.5	15	40	2250
5	100	0	0	60	1200
6	80	0	20	20	1900
7	100	0	0	100	1200
8	0	80	20	20	1200
9	50	50	0	100	2600
10	62.5	22.5	15	40	1550
11	22.5	62.5	15	60	1900
12	0	100	0	20	1200
13	100	0	0	100	2600
14	0	90	10	60	2600
15	80	0	20	100	1200
16	0	100	0	20	2600
17	100	0	0	80	1900
18	0	100	0	100	2600
19	80	0	20	20	2600
20	50	50	0	100	1200
21	90	0	10	100	2600
22	50	50	0	60	1200
23	0	80	20	20	2600
24	0	100	0	100	1200
25	0	90	10	100	1900
26	90	0	10	20	1200
27	0	80	20	60	1200
28	90	0	10	20	2600
29	80	0	20	20	1200
30	80	0	20	100	2600
31	80	0	20	60	1200
32	0	100	0	20	2600
33	0	100	0	60	1200
34	0	100	0	100	1200
35	100	0	0	60	2600
36	50	50	0	20	2600
37	0	80	20	100	1200
38	50	50	0	20	1200
39	90	0	10	100	1200
40	100	0	0	20	1200
41	0	80	20	20	1900
42	80	0	20	100	1200
43	50	50	0	20	1900
44	80	0	20	20	2600
45	100	0	0	20	1900
46	100	0	0	20	2600



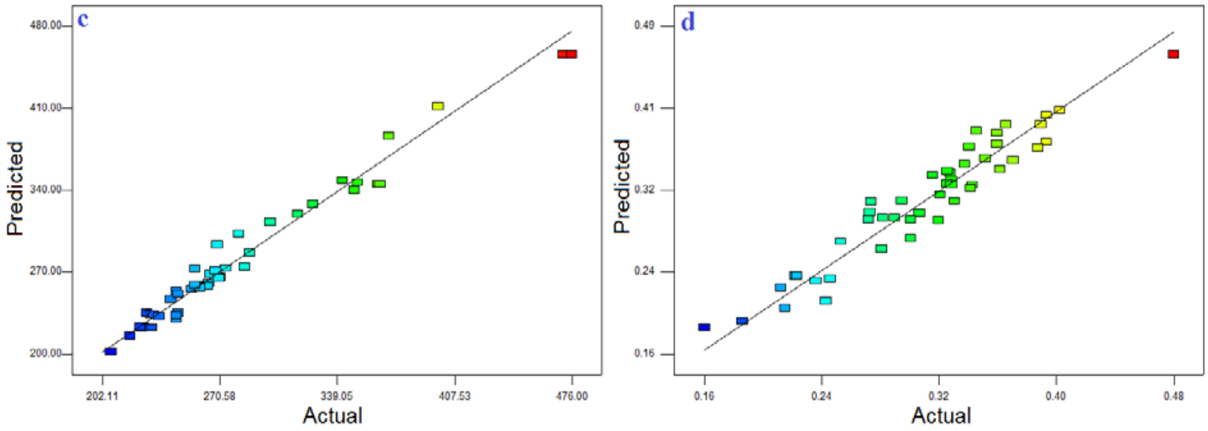


Figure 2. Predicted values versus actual values: a) brake power, b) torque, c) BSFC, and d) BTE.

3.2. Brake power

Figures 3 to 7 show the predicted values of brake power (kW) for various JP4-biodiesel-diesel blends at full load. Figure 8 shows the brake power values versus engine speed and load for D45B45J10 (diesel 45 %, biodiesel 45 %, and jet fuel 10 %) blend.

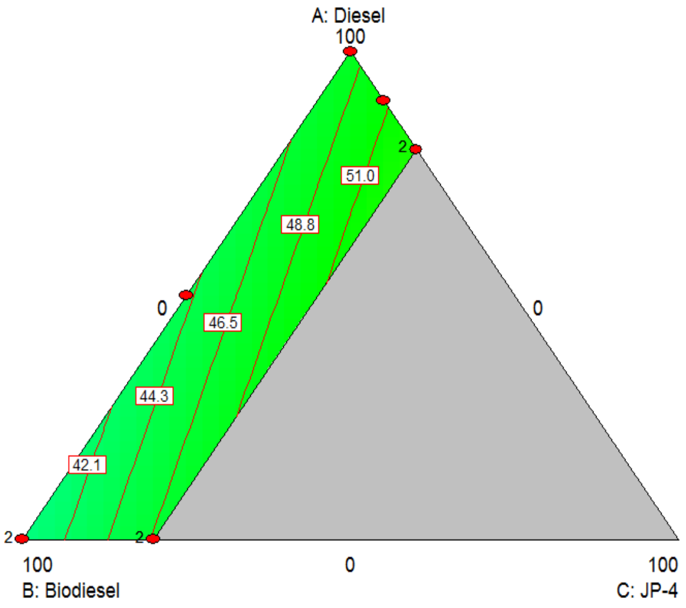


Figure 3. Brake power variations at a speed of 1200 rpm and full load.

Figure 4. Brake power variations at a speed of 1550 rpm and full load.

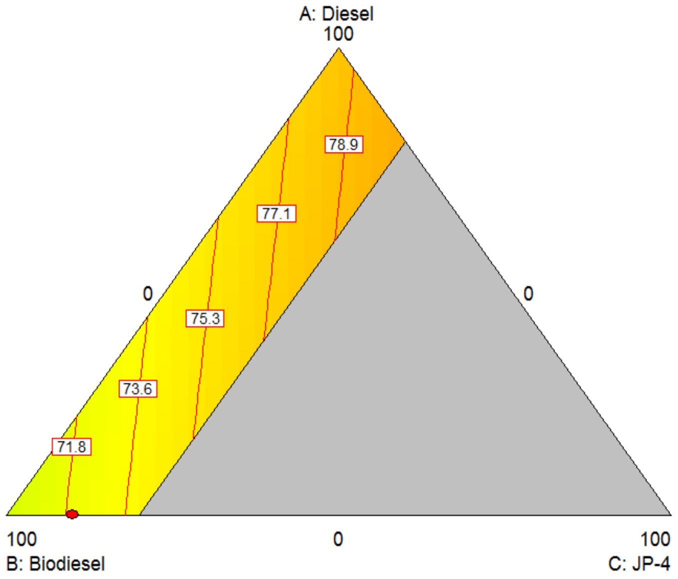


Figure 5. Brake power variations at a speed of 1900 rpm and full load.

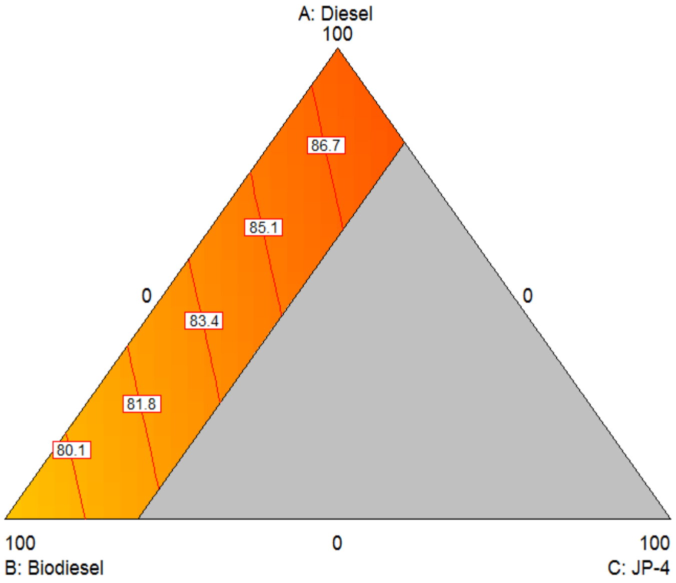


Figure 6. Brake power variations at a speed of 2250 rpm and full load.

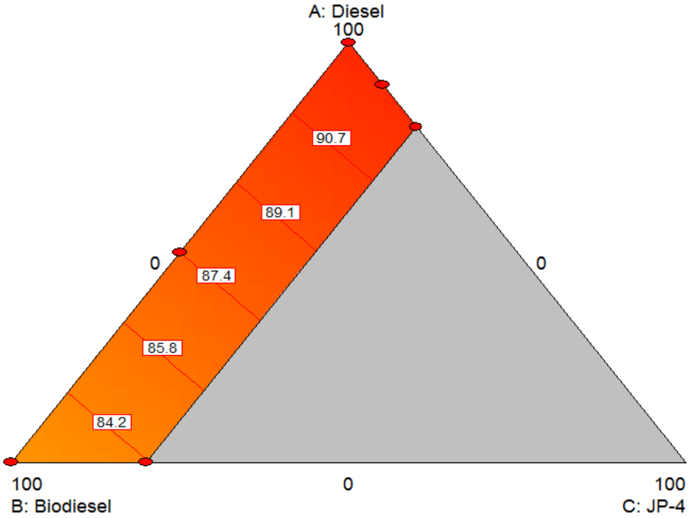


Figure 7. Brake power variations at a speed of 2600 rpm and full load.

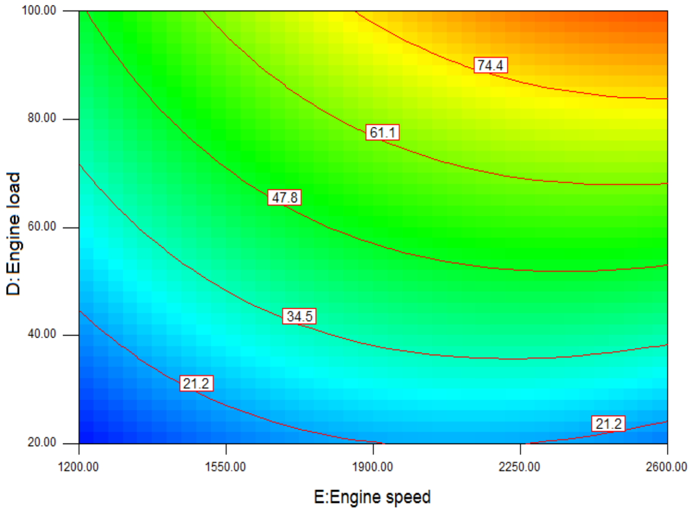


Figure 8. Brake power variations versus engine speed and load for fuel blend D45B45J10.

Based on the results, the maximum brake power with an approximate value of 92 kW belongs to neat diesel at 2600 rpm. Further, the minimum brake power (40 kW) was predicted for B100 at 1200 rpm. According to the results, brake power was reduced with the increasing biodiesel amount in the fuel mixture due to the lower heating value of this fuel in comparison with diesel No. 2 and JP-4 [1, 22-24]. In addition, higher viscosity of biodiesel causes poor atomization; then, the brake power decreases, especially at lower engine speeds [25]. According to the figures, the brake power increased slightly while the amount of JP-4 increased in the fuel blend. Accordingly, the energy content of JP-4 is more than that of biodiesel. In addition, the lower evaporate rate of biodiesel compared with jet fuel, which is related to the heavier hydrocarbons, impacts on the fuel-to-air ratio in the combustion process and engine power [18]. On the other hand, JP-4 resulted in better fuel-air mixing due to its lower cetane number and higher evaporation rate than biodiesel. This condition causes well distribution of fuel mixture under the premixed combustion stage and improves the brake power [8].

The results showed that the difference between brake power values of the blends including biodiesel decreased at higher engine speeds. This behavior may result from the presence of oxygen molecules in the biodiesel structure that leads to higher combustion efficiency and compensates the loss of heating value [26, 27]. Another possible explanation is the enhanced turbulence of airflow at higher speeds that causes better atomization of the fuel and tends to a more homogeneous fuel mixture; therefore, the brake power improves [26, 28].

In addition, the ignition delay of biodiesel combustion is shorter than that of JP-4 due to the higher cetane index of biodiesel [29, 30]. Therefore, there is no significant difference in the brake power between using JP-4 and biodiesel at higher engine speeds.

As shown in Figure 8, the predicted values for brake power were higher at higher engine loads because of enhanced temperature conditions that caused more complete combustion [1, 31]. Moreover, at higher engine loads, an increase in fuel consumption produces more heat energy that produces higher brake power [32]. However, the overall air-fuel mixture is lean at lower loads and causes lower brake power.

3.3. Brake torque

Figures 9 to 13 show the brake torque variations with full engine loads at different engine speeds. The variations of brake torque against engine speed and load are shown in Figure 14 for D45B45J10 (diesel 45 %, biodiesel 45 %, and jet fuel 10 %).

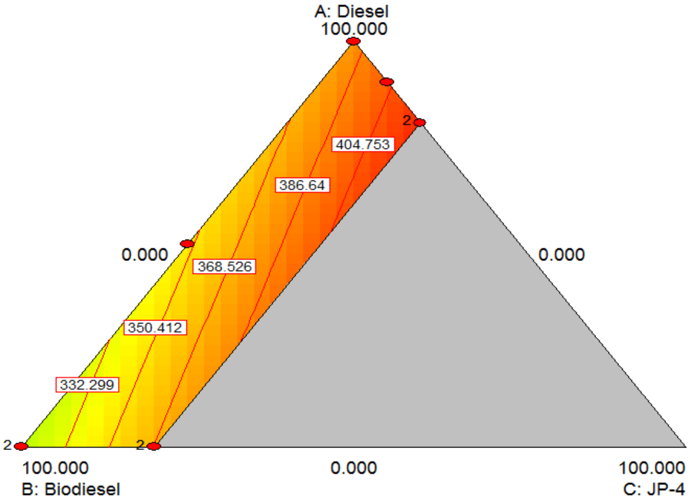


Figure 9. Brake torque variations at a speed of 1200 rpm and full load.

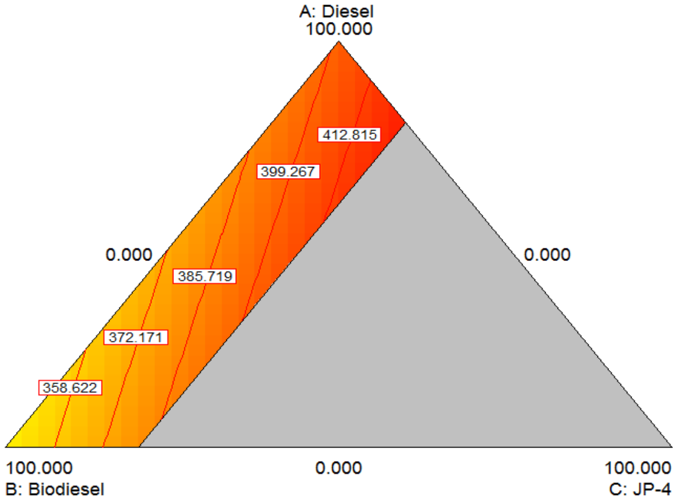


Figure 10. Brake torque variations at a speed of 1550 rpm and full load.

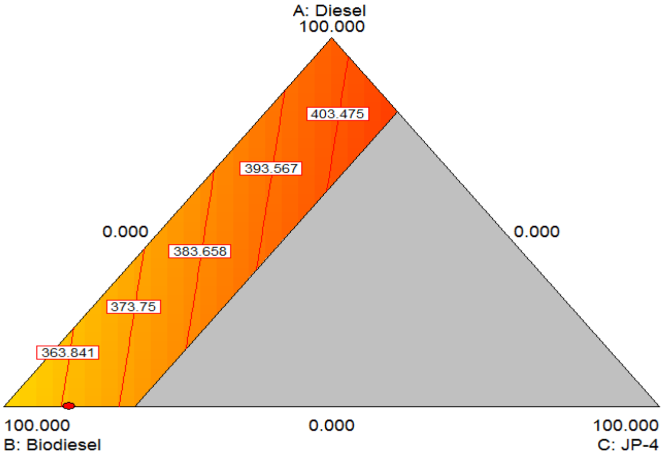


Figure 11. Brake torque variations at a speed of 1900 rpm and full load.

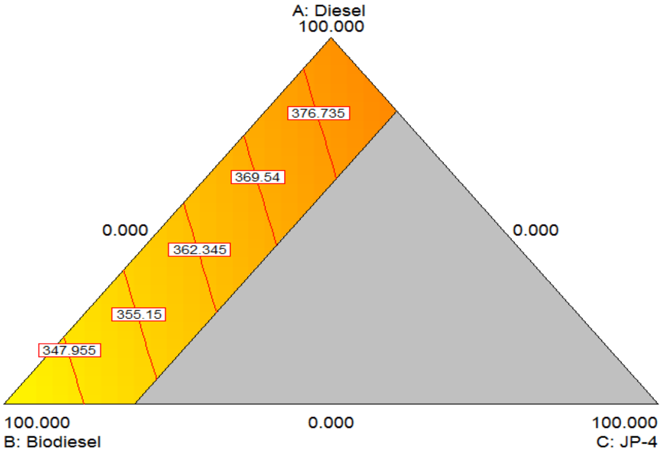


Figure 12. Brake torque variations at a speed of 2250 rpm and full load.

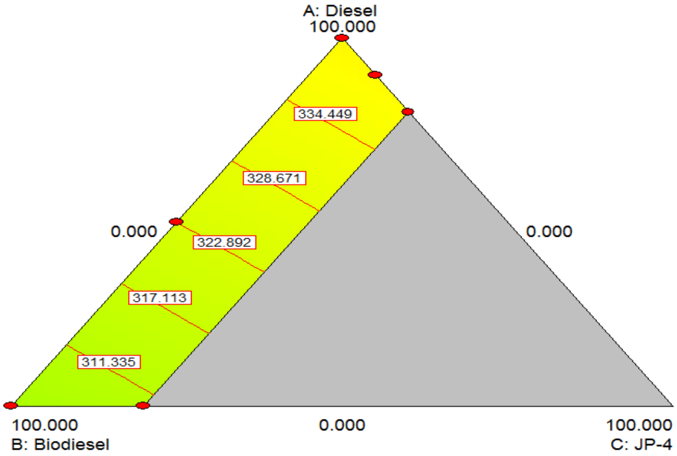


Figure 13. Brake torque variations at a speed of 2600 rpm and full load.

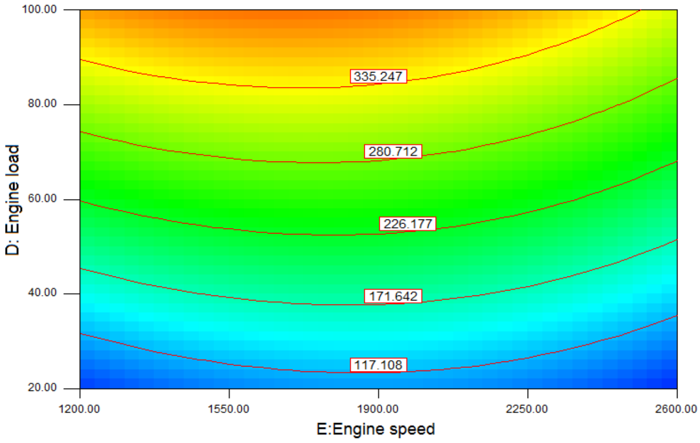


Figure 14. Brake torque variations versus engine speed and load for fuel blend D45B45J10.

According to the results, the maximum torture (approximately 425 N.m) belongs to D80J20 at 1550 rpm. Moreover, B100 has the minimum value of brake torque (305 N.m) at 2600 rpm. The brake torque increases slightly with the increasing JP-4 content in the blend due to a higher heating value of JP-4. In the reverse trend, by increasing biodiesel content in the fuel mixture, the brake torque was reduced, especially at lower engine speeds [22, 26, 30, 33, 34]. Further, the lower cetane number and greater evaporation rate of jet fuels might result in a better chance for forming a premixed mixture near the stoichiometric condition and higher brake torque [8]. The shorter ignition delay, oxygen content in the biodiesel structure, and high lubrication properties of this fuel can compensate the lower energy content of biodiesel at higher engine speeds [32].

As shown in Figure 14, the brake torque increases at higher loads because of higher combustion temperatures that cause more effective combustion [1, 31].

3.4. Brake specific fuel consumption (BSFC)

Figures 15 to 19 show the effects of biodiesel and JP-4 addition to the fuel mixture on the BSFC at various speeds and full engine load. Figure 20 also shows the BSFC variations versus engine speed and engine load for 45B45J10.

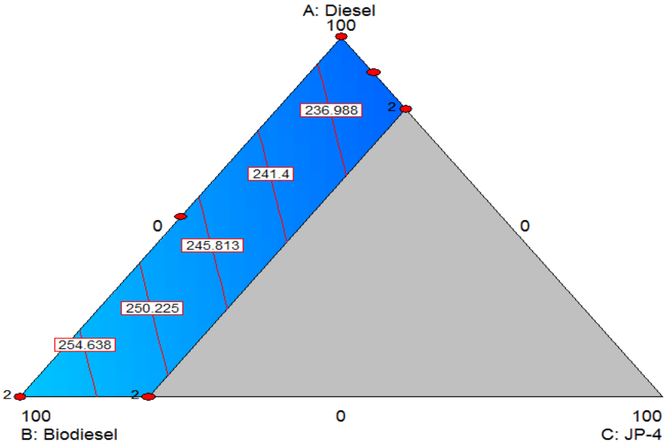


Figure 15. BSFC variations at a speed of 1200 rpm and full load.

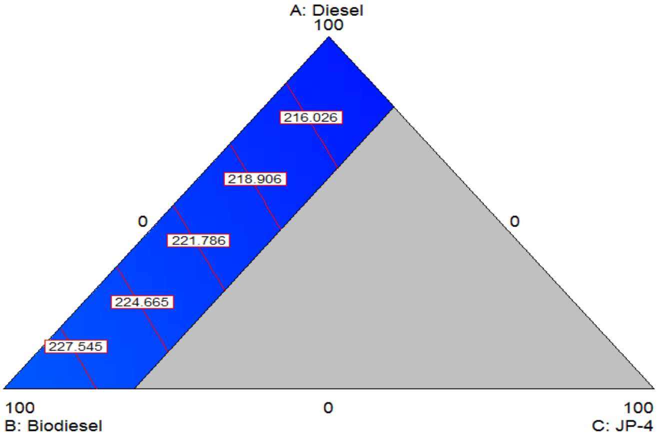


Figure 16. BSFC variations at a speed of 1550 rpm and full load.

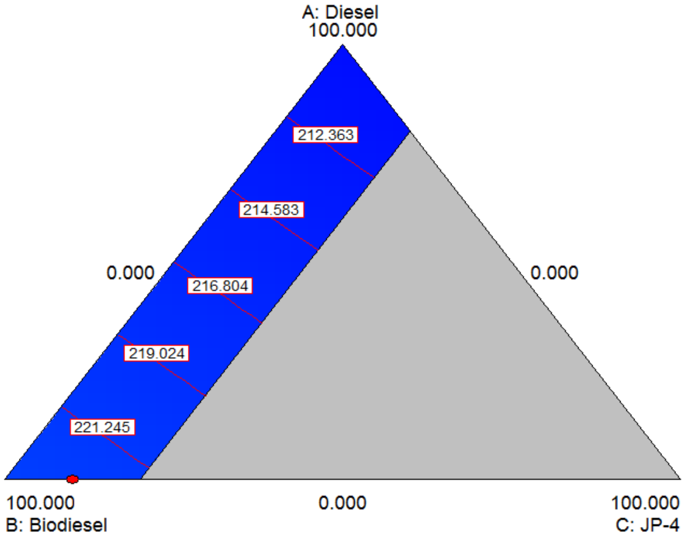


Figure 17. BSFC variations at a speed of 1900 rpm and full load.

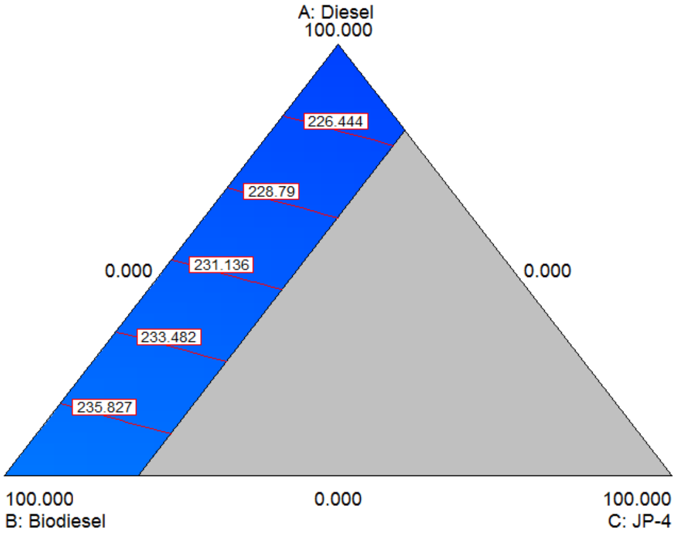


Figure 18. BSFC variations at a speed of 2250 rpm and full load.

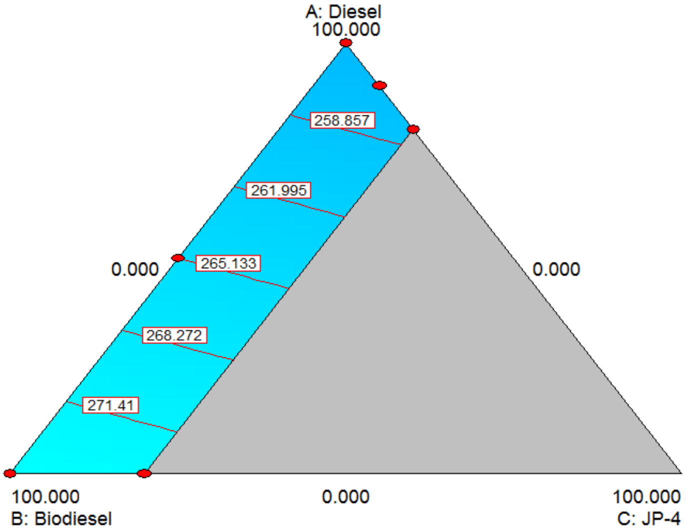


Figure 19. BSFC variations at a speed of 2600 rpm and full load.

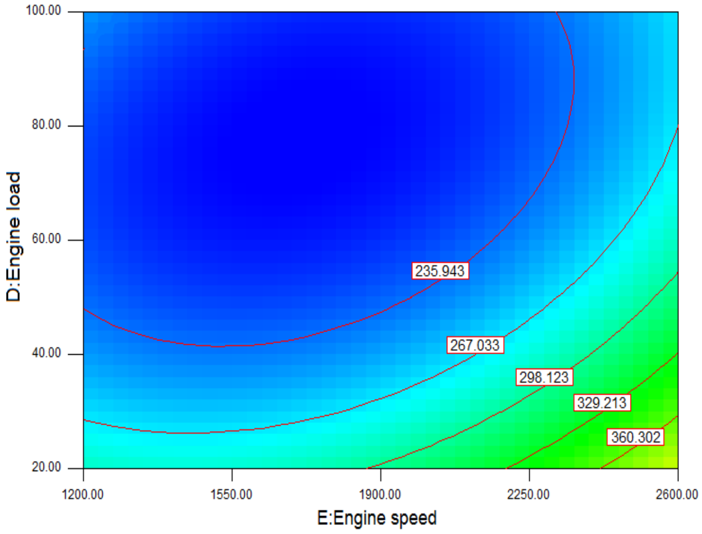


Figure 20. BSFC variations versus engine speed and load for fuel blend D45B45J10.

Based on the results, the maximum BSFC with an approximate value of 275 (gr/kW.hr) belongs to B100 at 2600 rpm. In addition, the minimum BSFC (210 (gr/kW.hr)) was predicted for the neat diesel fuel at 1900 rpm as a result of its higher heating value. According to the figures, at first, the BSFC was reduced with an increase in engine speed up to 1550 rpm; then, brake-specific fuel consumption reached a constant value at engine speeds between 1550 and 1900 rpm. At the speeds more than 1900 rpm, BSFC increased due to the enhanced friction losses and the lower volumetric efficiency of the engine that led to lower brake power [18, 24]. The BSFC increased with the higher proportion of biodiesel in the mixture at all engine speeds. The heat content of biodiesel is lower than that of diesel and JP-4. Therefore, the BSFC values will be higher by consuming more fuel amount to compensate the lower brake power produced with biodiesel [24, 33, 35-37]. In addition, the higher density of waste cooking oil methyl ester causes higher injection of the fuel into the cylinder based on the mass flow rate for the same volume injection. Moreover, some parameters such as injection pressure, atomization ratio, and viscosity have also very important roles in the BSFC and brake power values [27, 38]. However, there is no considerable change in the BSFC values while using JP-4 in fuel mixture, especially at higher speeds. However, the predicted values of BSFC were reduced slightly with the addition of JP-4 to the fuel blend at lower engine speeds [39]. Moreover, JP-4 with the lower density compared to biodiesel causes an improvement in BSFC [29]. At higher rpms, a better air swirl and turbulence condition accompanied by the oxygen content in the biodiesel structure tend to a better combustion condition; therefore, in this condition, the BSFC decreased for fuel blends containing biodiesel [40].

According to Figure 20, the brake-specific fuel consumption decreased with an increase in engine load. The understandable reason for this behavior is higher brake power, which overcomes fuel consumption in this condition [24, 35, 41].

3.5. Brake thermal efficiency (BTE)

Brake thermal efficiency (BTE) indicates the efficiency of chemical energy converted to mechanical energy. Figures 21 to 25 present the effects of biodiesel and JP-4 addition to the fuel mixture on the BTE at various speeds and full engine load. Figure 26 shows the BTE variations versus engine speed and load for 45B45J10.

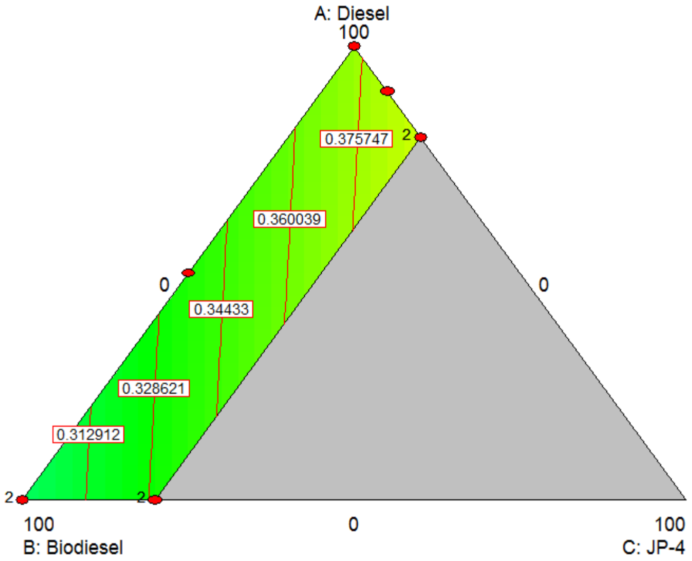


Figure 21. BTE variations at a speed of 1200 rpm and full load.

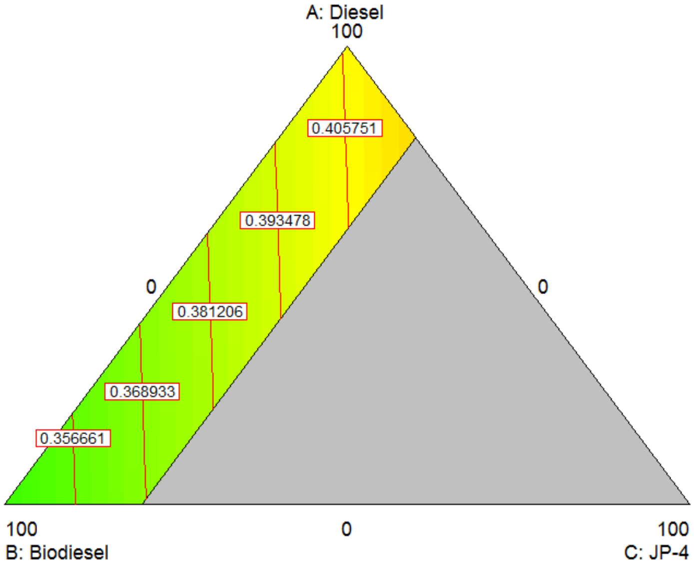


Figure 22. BTE variations at a speed of 1550 rpm and full load.

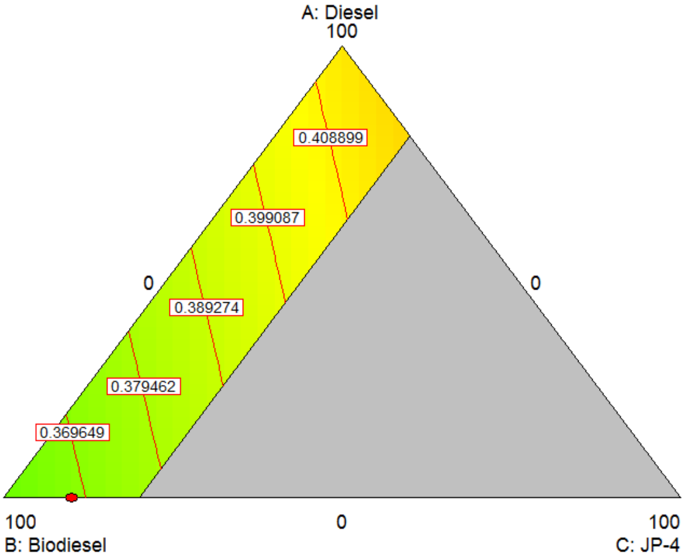


Figure 23. BTE variations at a speed of 1900 rpm and full load.

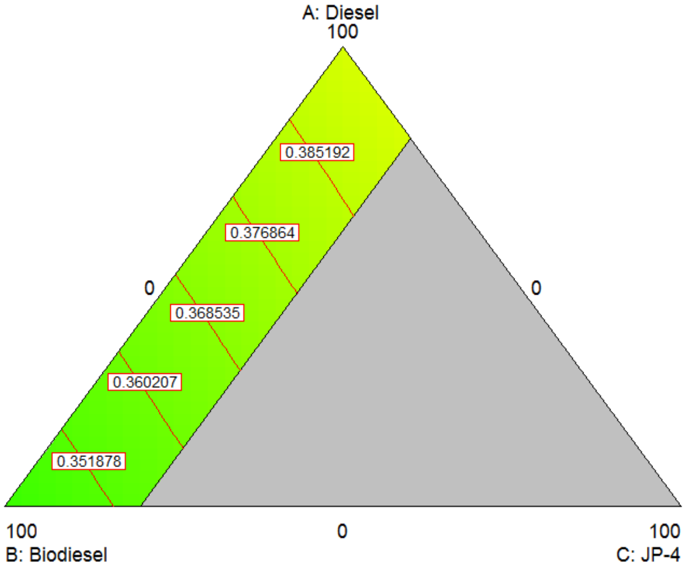


Figure 24. BTE variations at a speed of 2250 rpm and full load.

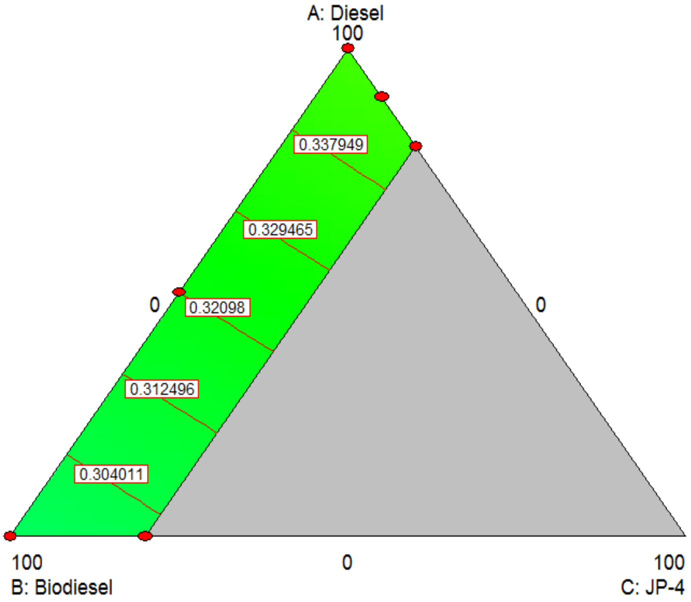


Figure 25. BTE variations at a speed of 2600 rpm and full load.

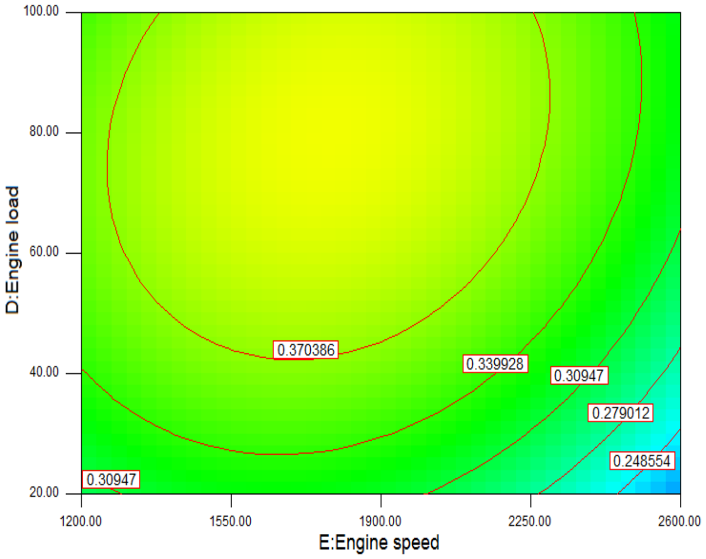


Figure 26. BTE variations versus engine speed and load for fuel blend D45B45J10.

Based on the results, the maximum BTE (approximately 41 %) belongs to D80J20 at 1900 rpm. Moreover, the minimum BTE (30 %) was predicted for the neat biodiesel at 2600 rpm. Given that the BTE is inversely related to the BSFC and lower heating value (LHV) of the fuels, JP-4 with lower BSFC and higher LHV than that of biodiesel causes an improvement in brake thermal efficiency in comparison with biodiesel, especially at lower and medium engine speeds.

Based on Figure 26, the BTE decreased at low and high engine speeds due to the lower values of BSFC. However, at medium engine speeds, the lower BSFC caused an improvement in BTE of the engine [40].

As seen in Figure 26, the brake thermal efficiency enhanced with a reduction in engine load due to the improvement in brake power, which causes lower BSFC in this condition [24, 35, 41].

4. CONCLUSIONS

In this research, the Mixture-RSM method was employed to develop models and determine the performance characteristics of the diesel engine fuelled with JP-4-biodiesel-diesel blends. It was concluded that:

a) The fitted models could be properly applied to predict the performance characteristics of the engine.
b) The brake power and torque were reduced with increasing the amount of biodiesel in the fuel mixture due to the lower energy content of biodiesel than diesel fuel No.2 and JP-4. The brake power increased slightly when the amount of JP-4 increased in the fuel blend. It is because the heating value of jet fuel is more than that of waste cooking oil methyl ester.
c) The difference between the brake power values of fuel blends included biodiesel and neat diesel decreased at higher engine speeds. This behavior can be related to the oxygen molecules in the biodiesel structure that causes greater complete combustion and compensates the heating value of biodiesel.
d) Based on the results, brake power and torque of the engine increased at higher engine loads due to higher temperature conditions, leading to the more complete combustion.
e) The predicted values of brake-specific fuel consumption improved with the increasing proportion of biodiesel in the fuel mixture at all engine speeds because of the lower energy content of biodiesel compared with petroleum diesel and JP-4 and also more fuel injected into the combustion chamber based on the higher density of biodiesel.
f) There was no considerable change in BSFC values, especially at higher speeds under JP-4 combustion. However, the BSFC reduced slightly with the addition of JP-4 to fuel blend due to the higher heating value of this fuel.
g) JP-4 caused an improvement in brake thermal efficiency in comparison with biodiesel, especially at lower and medium engine speeds.

According to the results, the application of JP-4 in biodiesel-diesel blends can improve the performance of the engine, especially at low and medium engine speeds. In addition, based on previous studies, the use of biodiesel in the fuel mixture has a positive effect on emission characteristics of the engine; therefore, the blends of JP-4-biodiesel-diesel could be useful when the engine runs at low and medium rpms.

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