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# INVESTIGATING THE EFFECTS OF BIODIESEL FROM WASTE COOKING OIL AND ENGINE OPERATING CONDITIONS ON THE DIESEL ENGINE PERFORMANCE BY RESPONSE SURFACE METHODOLOGY*

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**Abstract–** In this research, the application of response surface methodology (RSM) was highlighted to investigate the effects of biodiesel (from waste cooking oil) in fuel mixture (biodiesel and diesel fuel No.2) and engine operating parameters on performance characteristics (brake power, brake torque and BSFC) of a diesel engine. The experiments were conducted on a four cylinder direct-injection diesel engine based on three-factor five-level central composite rotatable design. The developed mathematical models were helpful to predict the response parameters, and further, to identify the significant interactions between the input factors on the responses. Results showed that the use of biodiesel reduces brake power and brake torque up to 18% and 17% respectively. On the other hand, BSFC increases 18 to 24% by using net biodiesel. Also, results showed that an increase in engine load appeared to cause an increase in the brake power and torque up to 68 and 69% respectively. On the other hand, BSFC is higher at low engine load and increases up to 15% by reducing the engine load.

**Keywords–** Engine performance, biodiesel, diesel engine, RSM, engine operating conditions

## 1. INTRODUCTION

In order to meet the growing energy needs as a consequence of the spiraling demand and diminishing supply, in today’s world renewable energy and biomass sources, mostly biofuels, are receiving greater attention. Moreover, because of the environmental pollution from internal combustion engines, the increasing global concern has caused a focus on the oxygenated diesel fuels [1]. Biofuels such as alcohols and biodiesel have been proposed as alternatives for diesel engines [2]. Biodiesel can be produced from various vegetable oils, waste cooking oils and animal fats. In particular, biodiesel has received wide attention as a replacement for diesel fuel because it is biodegradable, nontoxic and can significantly reduce toxic emissions and overall life cycle emission of $CO_2$ from the engine when burned as a fuel [3]. Biodiesel can form blends with petroleum diesel fuel at any ratio and thus has the potential to partially, or even totally, replace diesel fuel in diesel engines. There is a great deal of literature to study the effect of pure biodiesel on engine power, and most of them agree that, with biodiesel (especially with pure biodiesel), engine power will drop [4, 5, 6]. However, the results reported show some fluctuation [7, 8]. It was reported that there was no significant difference in engine power between pure biodiesel and diesel [9, 10]. Further, it was also reported that there were surprising increases in power or torque of engine for pure biodiesel [11, 12]. Although the basic trends of engine power performance with load or speed were similar

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for biodiesel engine and diesel engine, there exists offset of maximum value of torque and power for biodiesel compared to diesel [10, 13]. For BSFC, many researches compared the blends with different content biodiesel. Most of them [14-18] agree that the fuel consumption of an engine fueled with biodiesel becomes higher. Some authors [16, 19, 20, 21] believed that, with increasing the content of biodiesel, engine fuel consumption will increase. Although a few authors [10, 12, 22] agreed that the effect of biodiesel content on BSFC exists, they found no similar trend and observed that the effect of the blend(s) with certain content biodiesel might be highlighted. Of course, there are very few researches that showed an opposite trend [23, 24]. On the contrary, it was reported in [11, 25] that fuel consumption was decreased for biodiesel compared to diesel. A few others [26, 27] found no significant difference between pure biodiesel and diesel. Several researchers reported with increase in load, the BSFC of biodiesel decreases [16, 17, 18, 28]. Further, it was reported that the increase in BSFC values at full load was higher than those at partial loads for biodiesel compared to diesel [29]. However, it was shown that the BSFC increased with the increase in engine speed [30, 31].

The objective of this research work is to investigate the effects of biodiesel percentage of in fuel mixture (biodiesel and diesel fuel No.2) as fuel parameter and engine speed and engine load as the engine operation parameters on changes in performance characteristics of a diesel engine. Response Surface Methodology (RSM) is employed to develop mathematical relationships between biodiesel fuel blends, engine speed and engine load as the independent variables and brake power, brake torque and brake specific fuel consumption (BSFC) as the responses. In addition, using response surface plots, the interaction effects of process parameters on the responses are analyzed and discussed. Also, the cylinder pressure versus crank angle for biodiesel fuel and its blends with diesel at full load measured and analyzed.

## 2. MATERIALS AND METHODS

### *a) Biodiesel preparation and fuel properties*

Since biodiesel from waste vegetable cooking oil is a more economical source of the fuel, in the present investigation, biodiesel was produced from this source [32]. In the present research, biodiesel was produced by a transesterification process which was catalyzed by KOH (as Alkali catalyst) and methanol (as alcohol) at Tarbiat Modares University biofuels laboratories. Then, biodiesel was analyzed by an established research institution following the ASTM D6751 standard. The important properties of waste vegetable cooking oil and No. 2 diesel are shown in Table 1.

Table 1. Properties of diesel and biodiesel fuels used for present investigation

| Property | Method | Units | Biodiesel | Diesel |
|---|---|---|---|---|
| Flash point | ASTM-D93 | °C | 176 | 61 |
| Pour point | ASTM-D97 | °C | -4 | 0 |
| Cloud point | ASTM-D2500 | °C | -1 | 2 |
| Kinematical viscosity, 40°C | ASTM-D445 | $mm^2/s$ | 4.15 | 4.03 |
| Copper strip corrosion | ASTM-D130 | -------- | 1a | 1a |
| Density | ASTM-D4052 | $kg/m^3$ | 880 | 840 |
| Lower heating value | ASTM-D240 | kJ/kg | 38730 | 42930 |
| Cetane number | ASTM-D613 | -------- | 62 | 57 |

### *b) Test engine experimental setup and procedure*

The engine tests were carried out on a 4-cylinder, four-stroke, turbocharged, water cooled and naturally aspirated DI diesel engine (OM 314). The major specifications of the engine under the test are shown in Table 2. The diesel engine was fuelled with blends of waste vegetable cooking oil and No. 2 diesel fuel. The fuel blends were used at the different engine speeds and engine loads. In each speed test run, the maximum engine torque was reached for each fuel. The engine speed was measured by a digital tachometer with a resolution of 1 rpm. Figure 1 shows a schematic diagram of the engine test setup and its instrumentation. As is seen in Fig. 1, the engine was coupled to an E400 ferromagnetism dynamometer to provide brake load and a system with scale method was used for determination of consumed fuel. The engine was allowed to run for a short time until the exhaust gas temperature, the cooling water temperature, the lubricating oil temperature, attained steady-state values and then the data were recorded. The cylinder pressure was measured by a Kistler model 6053C pressure sensor which was mounted on the cylinder head. Crankshaft position was obtained using a Kistler model 2614A crankshaft angle sensor to determine In-cylinder pressure as a function of crank angle. The cylinder gas pressures were recorded for B0, B20, B50, B80 and B100 at 1800 rpm and full engine load.

Table 2. Specifications of the test engine

| Engine type | Diesel OM314 |
|---|---|
| Cylinder number | 4 |
| Stroke(mm) | 128 |
| Bore(mm) | 97 |
| Compression ratio | 16:1 |
| Power (hp/rpm) | 110/2800 |
| Torque (Nm/rpm) | 340/1800 |
| Cooling system | Water cooled |

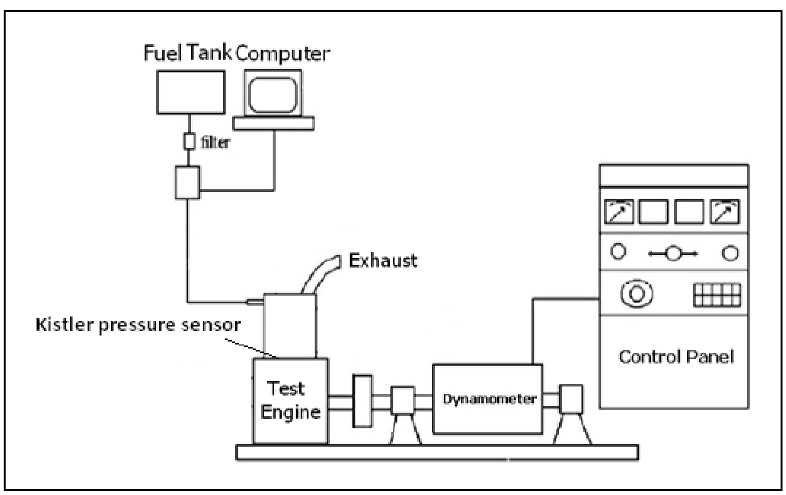


Fig. 1. The engine test set up

### *c) Experimental design and statistical analysis*

The standard RSM design using central composite design (CCD) was employed to examine the relationship between the response variables and set of quantitative experimental factors. The independent variables were percentage of biodiesel in fuel mixture ($x_1$), engine speed ($x_2$) and engine load ($x_3$). Each independent variable had coded levels of -1, 0 and 1. The experimental designs of the coded (x) and actual (X) levels of variables are shown in Table 3. The three responses (Y) were brake power, brake torque and BSFC. The response functions ($Y_1$, $Y_2$ and $Y_3$) were related to the coded variables ($x_i$, i = 1, 2, 3) by following second-order polynomial equation [33]. The coefficients of the polynomial were represented by $b_0$ (constant term); $b_1$, $b_2$ and $b_3$ (linear effects); $b_{11}$, $b_{22}$ and $b_{33}$ (quadratic effects); and $b_{12}$, $b_{13}$ and $b_{23}$ (interaction effects):

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \quad (1)$$

Table 3. The central composite experimental design matrix

| Experiment number | Percentage of biodiesel in fuel mixture (%) | Engine speed(rpm) | Engine load (%) |
|---|---|---|---|
| | $X_1$ ($x_1$) | $X_2$ ($x_2$) | $X_3$ ($x_3$) |
| 1 | 20(-1) | 1365(-1) | 40(-1) |
| 2 | 80(1) | 1365(-1) | 40(-1) |
| 3 | 20(-1) | 2435(1) | 40(-1) |
| 4 | 80(1) | 2435(1) | 40(-1) |
| 5 | 20(-1) | 1365(-1) | 80(1) |
| 6 | 80(1) | 1365(-1) | 80(1) |
| 7 | 20(-1) | 2435(1) | 80(1) |
| 8 | 80(1) | 2435(1) | 80(1) |
| 9 | 0(-1.682) | 1900(0) | 62.5(0) |
| 10 | 100(1.682) | 1900(0) | 62.5(0) |
| 11 | 50(0) | 1000(-1.682) | 62.5(0) |
| 12 | 50(0) | 2800(1.682) | 62.5(0) |
| 13 | 50(0) | 1900(0) | 25(-1.682) |
| 14 | 50(0) | 1900(0) | 100(1.682) |
| 15 | 50(0) | 1900(0) | 62.5(0) |
| 16 | 50(0) | 1900(0) | 62.5(0) |
| 17 | 50(0) | 1900(0) | 62.5(0) |
| 18 | 50(0) | 1900(0) | 62.5(0) |
| 19 | 50(0) | 1900(0) | 62.5(0) |
| 20 | 50(0) | 1900(0) | 62.5(0) |

Minitab software version 15.0 was used to develop the mathematical models and to evaluate the subsequent regression analyses and analyses of variance (ANOVA). The developed mathematical models were effectively used to predict the range of parameters used in the investigation. Based on these models, the main and interaction effects of the process parameters on the exhaust emissions characteristics were computed and plotted in contour plots as shown in Figs. 2 to 4.

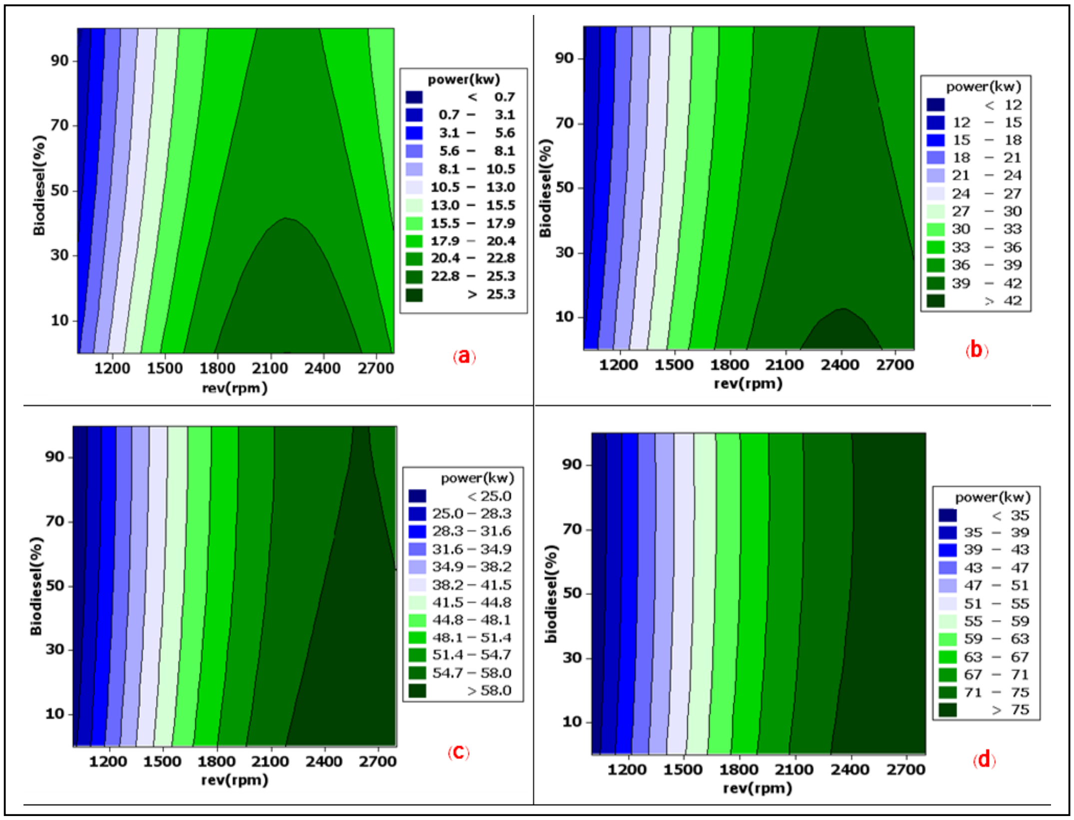


Fig. 2. Effect of percentage of biodiesel in fuel mixture and engine speed on brake power at 25% (a), 50 % (b), 75% (c), full (d) engine load

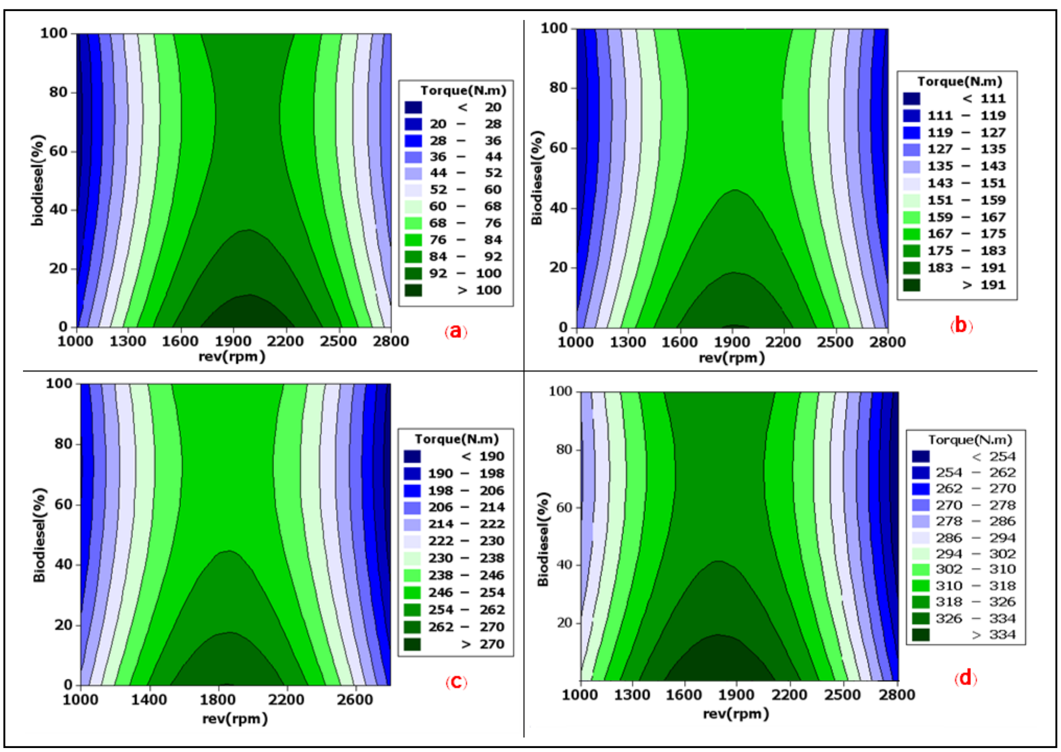


Figure 3. Effect of percentage of biodiesel in fuel mixture and engine speed on brake torque at 25% (a), 50 % (b), 75% (c), full (d) engine load

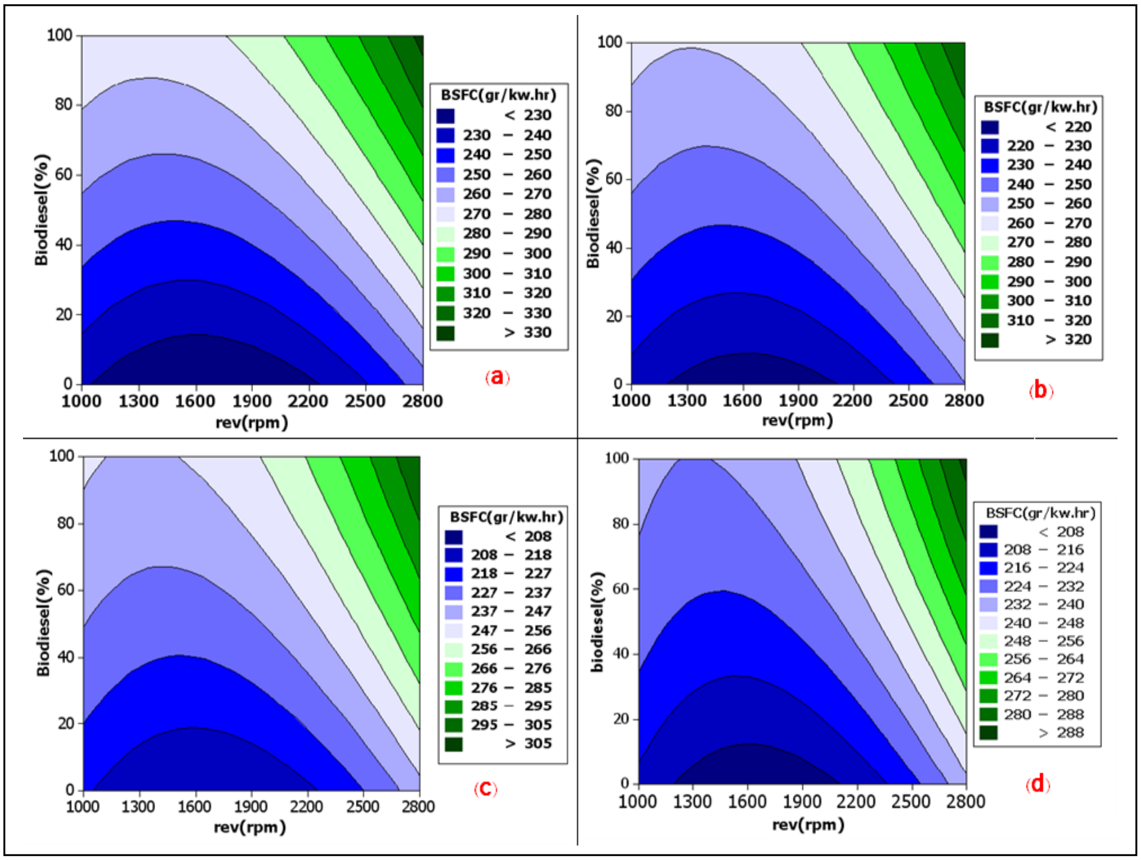


Fig. 4. Effect of percentage of biodiesel in fuel mixture and engine speed on BSFC at 25% (a), 50 % (b), 75% (c), full (d) engine load

## 3. ANALYSIS AND RESULTS

### *a) Statistical analysis*

All 20 experiments at design matrix (Table 3) were performed and the experimental data for the three responses (brake power, brake torque and BSCF of the diesel engine) are shown in Table 4.

Table 5 summarizes the results of each dependent variable with their coefficients of determination ($R^2$). The statistical analysis indicates that the proposed model was adequate, possessing no significant lack of fit and with very satisfactory values of the $R^2$ for all the responses. The $R^2$ values for brake power, brake torque and BSCF were 0.991, 0.988 and 0.964, respectively. The probability (p) values of all regression models were significant at 0.001, with no lack-of fit. The mathematical models were also inspected for its validity by comparing the experimental data and the predicted data given by the models. The predicted data in Table 4 proved that the model provided an accurate description of the experimental data, indicating the connection between the variables and output data. This data can be also observed using visual inspection by plotting the experimental data versus the predicted data corresponding to the respective responses in the DOE software. The results demonstrated that there are tendencies in the linear regression fit, and the model explains the experimental range studied adequately. The fitted regression equation showed good fit of the models and was successful in capturing the correlation between the three preparation variables.

Table 4. The experimental and predicted data for the three responses

| Experiment number | Experimental data | | | Predicted data | | |
|---|---|---|---|---|---|---|
| | Brake power (Kw) | Brake torque(N.m) | BSFC(gr/(Kw.hr) | Brake power (Kw) | Brake torque(N.m) | BSFC(gr/(Kw.hr) |
| | $Y_1$ | $Y_2$ | $Y_3$ | $Y_1$ | $Y_2$ | $Y_3$ |
| 1 | 22.2 | 130 | 234 | 21.8 | 125.08 | 230.6 |
| 2 | 20.3 | 126 | 258.6 | 19.49 | 115.42 | 258.7 |
| 3 | 37.2 | 130 | 245.8 | 34.47 | 131.35 | 248.8 |
| 4 | 33.5 | 117 | 288.3 | 32.16 | 121.69 | 288.5 |
| 5 | 43.9 | 282 | 219.5 | 42.28 | 274.19 | 217 |
| 6 | 41.6 | 266 | 241.6 | 41.03 | 264.53 | 236.3 |
| 7 | 67 | 252 | 238.7 | 65.93 | 262.45 | 235.2 |
| 8 | 67.8 | 251 | 265.9 | 64.69 | 252.72 | 266 |
| 9 | 49.9 | 232 | 210.5 | 46.45 | 231.77 | 213.1 |
| 10 | 45.4 | 213 | 261 | 43.46 | 215.53 | 262.7 |
| 11 | 18.5 | 153 | 237.4 | 17.63 | 156.95 | 242.7 |
| 12 | 51.4 | 157 | 284.3 | 48.18 | 152.35 | 283 |
| 13 | 20.8 | 83 | 257 | 21.25 | 87.84 | 256.4 |
| 14 | 71.5 | 326 | 220 | 65.82 | 323.46 | 226 |
| 15 | 43.9 | 213 | 238.6 | 44.3 | 214.6 | 241.2 |
| 16 | 45.4 | 215 | 242.8 | 44.3 | 214.6 | 241.2 |
| 17 | 43.9 | 216 | 250.8 | 44.3 | 214.6 | 241.2 |
| 18 | 46.8 | 225 | 236.4 | 44.3 | 214.6 | 241.2 |
| 19 | 41.1 | 205 | 241.2 | 44.3 | 214.6 | 241.2 |
| 20 | 44.7 | 214 | 239.6 | 44.3 | 214.6 | 241.2 |

Table 5. Regression coefficients, $R^2$, and p-values for three dependent variables for performance of the diesel engine

| Regression coefficient | Brake power (Kw) | Brake torque(N.m) | BSFC(gr/Kw.hr) |
|---|---|---|---|
| $b_0$ *(intercept)* | 47.3236 | -296.573 | 298.740 |
| $b_1$ | $-0.08^{*}$ | $-0.524334^{*}$ | $0.500932^{***}$ |
| $b_2$ | $0.05608^{***}$ | 0.302273 | $-0.0881057^{***}$ |
| $b_3$ | $0.205^{***}$ | $4.65396^{***}$ | $-0.236844^{***}$ |
| $b_{11}$ | $-2.5\times10^{-4*}$ | $0.00361894^{*}$ | $-0.00138634^{*}$ |
| $b_{22}$ | $-1.4079\times10^{-5***}$ | $-7.40156\times10^{-5***}$ | $-2.67088\times10^{-5***}$ |
| $b_{33}$ | $-5.4988\times10^{-4*}$ | $0.00636633^{*}$ | $-5.65169\times10^{-4}$ |
| $b_{12}$ | $-5.5548\times10^{-5}$ | $4.71405\times10^{-5}$ | $0.000180705^{*}$ |
| $b_{13}$ | $4\times10^{-4*}$ | $1.54590\times10^{-17}$ | $-0.00335640^{*}$ |
| $b_{23}$ | $2.3\times10^{-4***}$ | $-3.77124\times10^{-4*}$ | $2.09513\times10^{-5}$ |
| $R^2$ | 99.1% | 98.8% | 96.4% |
| *p*-value | $0.000^{***}$ | $0.000^{***}$ | $0.000^{***}$ |

Subscripts: 1 = Percentage of biodiesel in fuel mixture, 2 = Engine speed, 3=Engine load
$^{*}$ Significant at 0.05 level.
$^{**}$ Significant at 0.01 level.
$^{***}$ Significant at 0.001 level.

As shown in Table 5, brake power depends on the percentage of biodiesel in fuel mixture ($p < 0.05$), engine load and engine speed ($p < 0.001$) as its linear, and the quadratic effects of percentage of biodiesel in fuel mixture, engine load ($p < 0.05$) and engine speed ($p < 0.001$), the interaction effect between percentage of biodiesel in fuel mixture and engine load ($p < 0.05$), and the interaction effect between engine load and engine speed ($p < 0.05$) were significant, giving an overall curvilinear effect. Another factor that contributes to the brake power includes the interaction effect of percentage of biodiesel in fuel mixture and engine speed was found to be not significant. Besides the interaction effects and the quadratic effects of percentage of biodiesel in fuel mixture and engine load was found to be not significant.

The brake torque was found to be a function of the linear and quadratic effects of the percentage of biodiesel in fuel mixture ($p < 0.05$). The linear was negative, whereas the quadratic effect was positive. Engine speed had a quadratic effect on the brake torque ($p < 0.001$), the linear effects of engine speed was found to be not significant. As shown in Table 5, brake torque depends on engine load ($p < 0.001$) as its linear and the quadratic effects of engine load ($p < 0.05$) were significant. The interaction effect between engine speed and engine load was significant ($p < 0.05$). Besides, the other interaction effects were found to be not significant.

Engine speed had a pronounced effect on brake specific fuel consumption. The linear and quadratic effects ($p < 0.001$) were both negative, which explained the observed nature of the curve. The brake specific fuel consumption was linearly related ($p < 0.001$) to percentage of biodiesel in fuel mixture. Also, the percentage of biodiesel in fuel mixture had a quadratic effect on the brake specific fuel consumption. Brake specific fuel consumption depends on engine load linearly but the quadratic effect of engine load was insignificant. All of the interaction effects were found to be significant except the interaction effect between engine load and engine speed (Table 5).

Figures 2 to 4 show the interactions between the engine speed and responses in contour plot form. The graphical form plots were obtained by holding the value of engine load at 25%, 50%, 75% and 100% constant level in each related mathematical model. The X and Y-axis values of these figures are the real values.

### *b) Brake power*

The predicted brake power amounts for different fuel blends and engine speeds are shown in Fig. 2. As the Figure shows the maximum brake power is more than 75 Kw for diesel fuel No.2 at full load and engine speed between 2700 to 2800 rpm. Also, the minimum brake power (less than 0.7 Kw) happens at 25% engine load and 1000 rpm as engine speed for fuel blends included more than 95% biodiesel.

The brake power was decreased slightly with increasing the amount of biodiesel in the fuel blend. As can be understood from the percentages, the brake power level decreased with the proportion of biodiesel in the blend. Probably, the main reason for the higher brake power amounts for diesel fuel No.2 could be due to the lower heating value of biodiesel [5, 6, 34]. The fuel flow problems such as higher density and higher viscosity of biodiesel and decreasing combustion efficiency also have certain effects on decreasing brake power [34]. On the other hand, the higher oxygen content of biodiesel in combustion region provided more complete combustion. This means that biodiesel in the fuel mixture increases oxygen content of the blend; this causes higher combustion efficiency and compensates the loss of heating value of biodiesel [1, 9]. The main reason for increased brake power at high engine speeds is the increased atomization. At the same time, high engine speeds cause the increased inlet air flow speed or turbulence. This enhances the effect of atomization of the fuel in the cylinder, makes the mixture more homogeneous, and increases brake power [1]. For this reason, the beneficial effect of biodiesel as an oxygenated fuel was partially lost at high speeds [29]. As shown in Fig. 2 the brake power of the engine is relatively high at higher engine loads, because the increase in combustion temperature leads to more complete combustion during the higher load [6]. Also, at higher engine load, the beneficial effect of biodiesel as an oxygenated fuel was seen to generate more complete combustion, which means increased brake power. This indicates that the addition of oxygenated fuel is most effective in rich combustions [29]. However, at partial loads, the overall mixture was further leaned out. Therefore, addition of biodiesel had only a slight beneficial effect on the performance, and there were slight reductions in the engine power due to the lower heating value of biodiesel.

### *c) Brake torque*

Figure 3 shows the effects of biodiesel percentage and engine speed on the predicted brake torque of the engine at various load condition. As the figure shows, the maximum brake torque is more than 334 N.m for fuel blends including less than 15% biodiesel at full load and engine speed between 1700 to 1900 rpm. Also, the minimum brake torque (less than 12 N.m) happens at 25% engine load and 1000 rpm as engine speed for fuel blends including more than 60% biodiesel. The predicted values for the brake torques decrease slightly with the increasing amount of biodiesel in the fuel blend. These decreases are understandable, since the heat content of the fuel blend decreases with the increasing amount of biodiesel compared to that of diesel fuel No.2 [1, 4, 5, 35]. High lubricity and the higher oxygen content of biodiesel might result in the reduced friction loss and thus improve the brake effective torque and compensates the loss of heating value of biodiesel [15]. Figure 3 shows the brake torque increases with increasing engine load, because the increase in combustion temperature leads to more complete combustion during the higher load [6].

### *d) Brake specific fuel consumption*

Figure 4 shows the effects of biodiesel percentage and engine speed on the predicted brake specific fuel consumption of the engine at various load condition. As the figure shows, the maximum brake specific fuel consumption is more than 330 (gr/Kw.hr) for fuel blends including more than 95% biodiesel at 25% engine load and engine speed between 2700 to 2800 rpm. Also, the minimum brake specific fuel consumption (less than 208 (gr/Kw.hr)) occurs at full engine load and engine speed between 1500 to 1700 rpm for fuel blends including less than 10% biodiesel. According to the results, the BSFC initially decreased with increase in speed up to 1300 rpm and then BSFC remains approximately constant between 1300 rpm and 1900 rpm. For the range more than 1900 rpm, the BSFC increased sharply with speed [6]. The predicted values for the brake specific fuel consumption increase with the increasing amount of biodiesel in the fuel blend. The heating value of the biodiesel is lower than that of diesel fuel No.2. Therefore, if the engine was fueled with biodiesel or its blends, the BSFC will increase due to the produced lower brake power caused by the lower energy content of the biodiesel [1, 4, 5, 7, 15]. At the same time, for the same volume, more biodiesel fuel based on the mass flow was injected into the combustion chamber than diesel fuel No.2 due to its higher density. In addition to these parameters, viscosity, the atomization ratio and injection pressure should be considered since they have some effects on the BSFC and brake power values [9, 11]. As the figure shows, with increase in load, the BSFC of biodiesel decreases. One possible explanation for this trend could be the higher percentage of increase in brake power with load as compared to fuel consumption [14-18].

### *e) Variation of In-cylinder pressure with crank angle*

Figure 5 shows the variation of In-cylinder pressure with crank angle for diesel, biodiesel and its blends at 1800 rpm and full load conditions. According to the figure, the peak cylinder pressure is decreased with the increase of biodiesel addition in the blends. It is observed that the peak pressures of 60.4, 59.6, 58.9, 57.8 and 57.2 bar were recorded for B0, B20, B50, B80 and B100, respectively. The viscosity and volatility of the fuel have a very important role to increase atomization rate and to improve air fuel mixing formation [36, 37]. So the cylinder peak pressure of biodiesel and its blends is lower than that of standard diesel because of the higher viscosity and lower volatility. The pressure reduction can be explained with the expected effects of biodiesel viscosity on fuel spray, and reduction of air entrainment and fuel/air mixing rates. However, the cylinder peak pressure of biodiesel fuels was lower than that of diesel fuel or was close to diesel fuel due to the improvement in the preparation of air fuel mixture as a result of low fuel viscosity [36, 37].

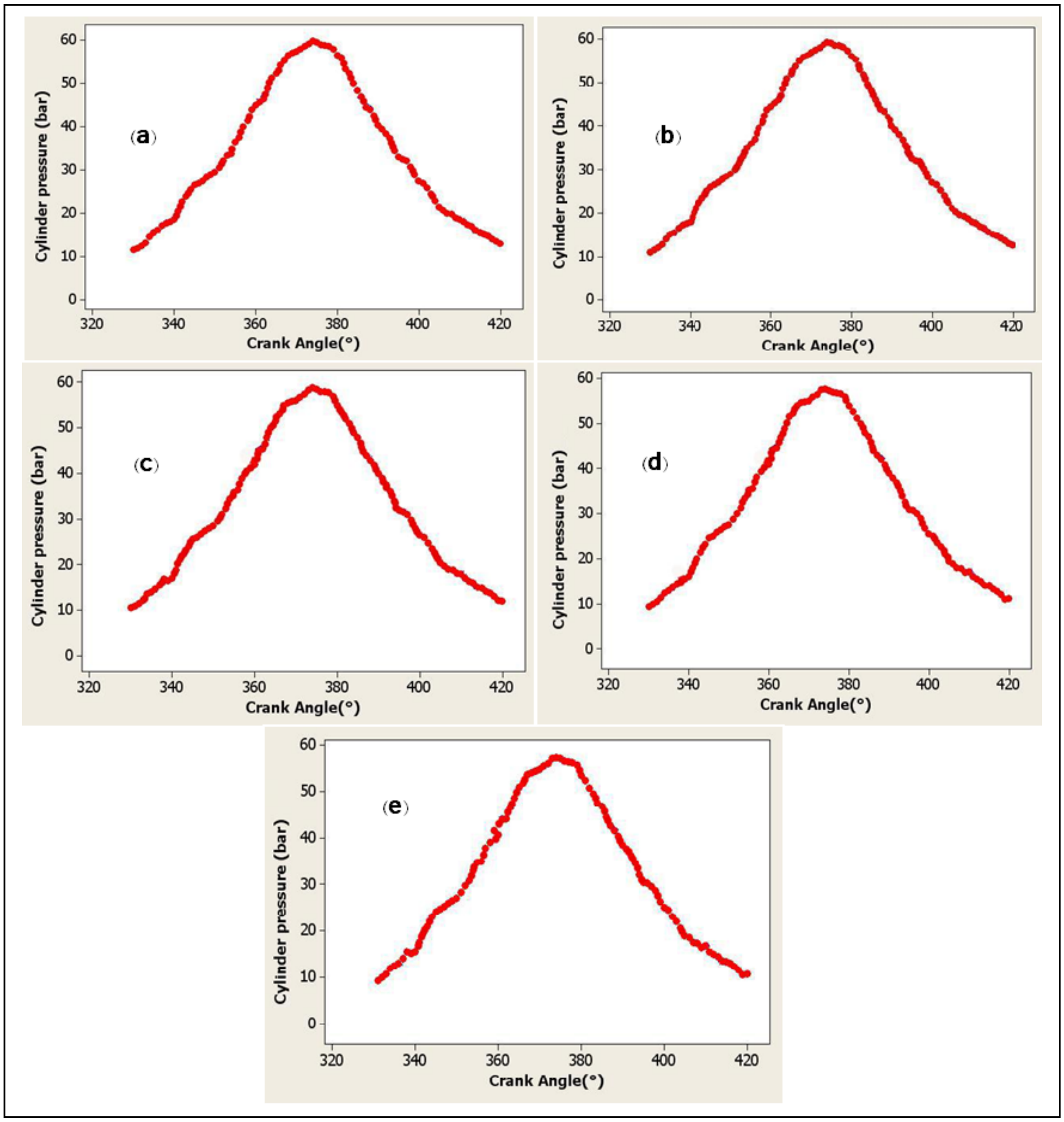


Fig. 5. Variations of the In-cylinder pressure with crank angle for B0 (a), B20 (b), B50(c), B80 (d), B100 (e) at 1800 rpm and full engine load

## 4. CONCLUSION

In this study, the mathematical models were developed using response surface methodology to estimate the brake power, brake torque and brake specific fuel consumption (BSFC) of the diesel engine. It was concluded that:

1- The statistical models as fitted can be effectively used to predict the engine performance. Also, the effect of biodiesel produced from waste cooking oil blends and diesel No.2 fuel on engine performance was investigated.

2- The brake power decreases with the increase of biodiesel in the blends, due to the lower heating value of biodiesel. Results showed that the brake power of diesel No.2 fuel is more than 4% and 18% than the brake power of net biodiesel at full and 25% engine load respectively.

3- The brake torque decreases with the increase of biodiesel in the blends, due to the lower heating value of biodiesel. Results showed that the brake torque of diesel No.2 fuel is more than 5% and 17% more than the brake torque of net biodiesel at full and 25% engine load respectively.
4- The brake specific fuel consumption increases with the increase of biodiesel in the blends, due to the lower heating value of biodiesel. Results showed that the brake specific fuel consumption of diesel No.2 fuel is 18 to 24% more than the brake specific fuel consumption of net biodiesel at various engine loads.
5- The brake power and torque at full engine load were 68 and 69% more than these characteristics at 25% engine load for all fuel blends.
6- The brake specific fuel consumption at 25% engine load was around 15% more than this characteristic at full engine load for all fuel blends.
7- The peak cylinder pressure is decreased with the increase of biodiesel addition in the blends because of the higher viscosity and lower volatility of biodiesel and its blends than that of diesel fuel.
8- These results are similar to those found in the literature and support that waste cooking oil methyl esters have similar properties with diesel fuel.
9- Also, the results of the study show that use of biodiesel blends with diesel had no significant change on performance of the diesel engine.

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