

Research Article

Optimization of SI Engine Performance Operating with Low Octane Gasoline and Fuel Additives from Waste

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Fuel additives from waste have been suggested to enhance low octane commercial gasoline in this study. Four samples were prepared in addition to pure commercial gasoline and denoted as GF0, GF4, GF8, GF12, and GF 16 which refer to fusel oil addition ratio of 0%, 4%, 8%, 12, and 16% respectively. Engine speed was controlled and increased manually from 1000 rpm to 3000 rpm at an increment of 500 rpm. Design of experiments is used to indicate the optimum additive dosage through response surface method optimization. Obtained results show that increasing engine speed significantly impacts the engine brake power, brake-specific fuel consumption, and brake thermal efficiency with a slight change for fusel oil ratio. Accordingly, it can be concluded that the maximum increase in output variables is statistically linked with the engine speed. The output response values at optimized conditions were 2.61812 kW brake power, 0.2431 kg/kW.hr brake-specific fuel consumption, and 36.5303% brake thermal efficiency. Based on the *P*-value, ANOVA data indicate that engine speed was a significant factor influencing output responses, while the fusel oil ratio was insignificant. However, fusel oil ratio of 8% has a significant effect on the brake thermal efficiency and BSFC.

1. Introduction

Petroleum fuels (gasoline fuel) have been considered as one of the most widely used fuels in spark-ignition engines, which is a mixture of different types of hydrocarbons such as paraffins, naphthenes, and aromatics. Its components vary depending on the source of crude oil and the refinery operations and chemical additives [1, 2]. Petroleum fuels are classified according to several standard specifications: evaporation rate at different temperatures, quantity of additive enhancers, sulfur content, and octane number which is considered to have the most effect on the performance level of spark-ignition engines. At the beginning of the 20th century, low octane fuel was used in the low compression ratios engines. In the second half of the last century, there was a need to use high octane fuel due to the development of

engines with high compression ratios leading to widespread interest by researchers in obtaining a highly efficient fuel through the use of various fuel additives.

Several types of additives have been found that contribute to improving the properties of gasoline fuel. Douihit et al. 1988 [3] reported an increase in the fuel octane number with the addition of MTBE at a 15% ratio with gasoline. On the other hand, ethanol addition with gasoline fuel at different ratios was effective in increasing the octane number with a noticeable reduction in the heating value [4–6]. Hsieh et al. [5] observed an increment in the fuel raid vapor pressure with the addition of ethanol by 10% which decreased after this ratio. Da Silva et al. [7] investigated the influence of addition oxygenates and nonoxygenates additives on octane number and raid vapor pressure. The investigated additives were adopted in four addition ratios in

this study by 5%, 10%, 15%, and 25% with two samples of gasoline produced locally in Brazil and have different chemical compositions. The results reveal an increase in the octane number with all additives while some additives were effective in increasing the raid vapor pressure which decreased with using other additives depending on the gasoline type. Porpatham et al. [8] studied the influence of the concentration of methane in biogas on fuel properties by reducing the content of CO₂ from 41% to 30% and 20% in biogas. The study results reveal an increase in heating value by 68.3% when reducing the concentration of CO₂ to 20%. Sheet [9] investigated the utilization of adopting locally produced octane enhancers on the characteristics of gasoline fuel. The study results reported an increase in the octane number decrease in the heating value with the addition rates of 2.5% to 15% based on volume percentage. Alptekin [10] studied the influence of commercial fuel additives on the characteristics of gasoline fuel. They observed an improvement in the octane number with a reduction in the gasoline gum formation. Fusel oil has been suggested in many studies as a viable fuel blend and fuel additive from waste products.

In many countries, low octane gasoline is used in the local petrol stations as a fuel for vehicle drives with SI engines. This results in inefficient engine performance and high fuel consumption in addition to incomplete fuel combustion which results in increased emissions and pollutants. Though different additives have been suggested by researchers, by-product additives represent the cheapest and most viable option for enhancing gasoline fuel properties [11–14]. It has comparable fuel properties to that of gasoline with an extremely higher octane number [14, 15]. Surveyed studies investigated the optimum operating parameters of SI engines using response surface methodology (RSM). These studies reported that RSM can be considered as a useful method for estimating and optimizing the engine operation parameters for achieving optimum engine performance with lower exhaust emissions at a minimum number of experimental tests [11–15]. The reported finding from previous studies recommended more focus on to optimization of gasoline fuel blend with increasing fusel oil ratio. Similarly, it has been found that RSM can be considered as a useful method for estimating and optimizing the engine operation parameters for achieving optimum engine performance using fusel oil and gasoline blend at different ratios [12]. The same concept of optimization has been used with RSM to indicate the optimum operating parameters at 10% and 20% fusel oil ratio with gasoline [11]. In this study, fuel additives from waste have been suggested to enhance engine performance with low octane commercial gasoline. Optimization was performed using the response surface method (RSM) to analyze the relationship among the input (independent variables), including engine speed and fusel oil ratio on output (dependent variables).

2. Methodology

Fuel preparation was conducted in the chemical lab of the Kirkuk Technical College/Northern Technical University.

Local gasoline was supplied from a governmental petrol station, and fusel oil was purchased from Eskisehir sugar refinery company and provided by a commercial company from Turkey. Table 1 lists the fuel property for both local gasoline and fusel oil used in this study to prepare the blended fuel sample. Blending has been conducted using a mechanical stirring for 20 minutes after adding the investigated fuel at the desired ratio. Four samples were prepared in this study in addition to pure commercial gasoline and denoted as GF0, GF4, GF8, GF12, and GF 16 which refer to fusel oil addition ratios of 0%, 4%, 8%, 12, and 16%, respectively. Table 1 lists the fuel property for both local gasoline and fusel oil used in this study in addition to the prepared blended fuel samples. Fuel samples were tested using a single-cylinder gasoline engine with specifications shown in Table 2. Engine coupled to a hydraulic dynamometer that applies the desired load using a regulating valve to control the pump water flow rate is shown in Figure 1. Fuel flow was measured using 16 ml pulp connected to the fuel line from the fuel tank to the engine fuel port carburetor. A stopwatch has been used to indicate the time taken for the measured fuel consumption. Measured parameters include engine torque and power in addition to the temperature collected from the sensors that are fixed on different locations of the engine has been indicated using digital meters panel. In this study, engine speed was controlled and increased manually from 1000 rpm to 3000 rpm at an increment of 500 rpm and constant wide throttle opening (WTO). Before starting collecting data in each experiment, the engine was run for 15 minutes to reach a steady operation state, and then, the test was repeated in triplicate, and the average was considered for each case to ensure accurate results. Table 3 presents the experimental design matrix adopted in this study.

Optimization was performed using the response surface method (RSM) to analyze the relationship among the input (independent variables), including engine speed (A) and fusel oil ratio (B) on output (dependent variables), such as brake power (Y1), brake specific fuel consumption (Y2), and brake thermal efficiency (Y3) to indicate the optimum operating conditions. Table 3 lists the coded and uncoded levels for the RSM design adopted in this study using a central composite design (CCD) and quadratic model. In this study, the CCD method is selected as it requires a less experimental runs compared to other methods like full factorial design. The design has the ability to resolve the essential high-order connection influences of the polynomials model with desirable output response results [16]. Equation (1) was used to code the independent variables' real level.

$$Z = \frac{Z_o - Z_c}{\Delta Z}, \quad (1)$$

where Z and Z_o indicate coded and real levels of independent variables, respectively, and ΔZ represents step change while z_c indicates the actual value at the central point. The above equation was used to derive the specific equation for each independent variable and code their actual values.

TABLE 1: Fuel property for both local gasoline and fusel oil.

Property	GF0	GF4	GF8	GF12	GF16	Fusel oil
Oxygen cc	—	—	—	—	—	18
H/C ratio	2.25	—	—	—	—	—
Density(kg/m ³) at 20 C	765	766	768	769	771	800.3
Lower heating value(MJ/kg)	41.8	41.5	41.3	41.0	40.8	35.32
RON	86	—	—	—	—	98.7
Cetan number	10	—	—	—	—	42
Latent heat <i>T</i> 298 K(KJ/kg)	500	—	—	—	—	874
Flashpoint (c)	38	38	38	38	39	42
Viscosity, (mm ² /s) at 40°C	0.467	0.6	0.8	0.9	1.1	4.162
Auto ignition temperature, °C	~300	—	—	—	—	416

TABLE 2: Gasoline engine specifications.

Model	TD110
Compression ratio	9.5:1
No of stroke	4
Total displacement	230 cc
Cylinder bore	66 mm
Piston stroke	57 mm
Maximum power	3.6 kW @ 3600 rpm
Injection type	Portal fuel injection

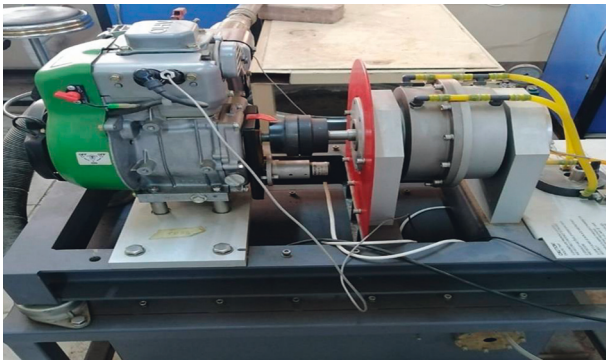


FIGURE 1: Engine and dynamometer test rig.

TABLE 3: Experimental design matrix.

Fuel sample	Composition
GF0	100% commercial gasoline + 0% fusel
GF4	96% commercial gasoline + 4% fusel
GF8	92% commercial gasoline + 8% fusel
GF12	88% commercial gasoline + 12% fusel
GF16	84% commercial gasoline + 16% fusel

TABLE 4: Levels and experimental range of independent variables.

Independent variable		Codes factor levels				
		−α	−1	0	+1	+α
Engine speed (rpm)	A	585.786	1000	2000	3000	3414.21
Fusel oil (%)	B	0.69	4	12	20	23.31

The statistical model can be represented in the general form to calculate the output based on the considered input by the following equation:

$$Y = f(X_1, X_2, X_3, X_4, \dots, X_n + \epsilon, \quad (2)$$

where *Y* represents the output which is calculated based on the independent variables (*X*₁, *X*₂, *X*₃, *X*₄, ...*X*_{*n*}) in the response function by considering the error percentage ϵ . This equation is used in many forms for regression cases and can be written in the following general form of the polynomial quadratic function.

$$Y = \beta_o + \sum_{i=1}^n \beta_i X_i + \sum_{i=1}^n \beta_{ii} X_i^2 + \sum_{i=1}^n \sum_{j=i+1}^n \beta_{ij} X_i X_j + \epsilon. \quad (3)$$

To analyze the interaction among group means and their statistical difference, analysis of variance (ANOVA) was used. In this statistical analysis, the value of the degree of freedom is described by DF which indicates the distribution of probability in repeating sampling. In this study, the level of significance is set to be 0.95 interval of confidence which indicates probability > *F* to be maximum at 0.05. The high *F*-value indicates a significant difference in the variation in the groups for each sample. The importance of each model term was indicated by the percentage contribution as an effective guide in this study.

3. Results and Discussion

3.1. Model Fitting. The technique of response surface method (RSM) represents a theoretical, statistical, and mathematical method to build a model for optimizing the level of the independent variables. The polynomial equation coefficients were calculated based on experimental data to indicate the response variable values. Equations (2)–(4) represent the regression equations for the response variables BP, BSFC, and BTE, respectively, that were obtained from the RSM.

$$BP = -0.37243 + 1.09983E - 003A + 0.020223B - 1.15063E - 005AB, \quad (4)$$

$$BSFC = +0.33583 - 1.14223E - 004A - 6.54829E - 004B + 9.87297E - 008AB + 2.26632E - 008A2 + 1.54047E - 005B2, \quad (5)$$

$$BTE = +19.82648 + 0.019932A + 0.28811B - 2.20747E - 005AB - 4.04037E - 006A2 - 9.92663E - 003B2. \quad (6)$$

The variation between actual values and predicted values is known as residuals [16]. Figure 2 presents the plot of actual values and predicted values for BP, BSFC, and BTE. It is observed from the figure that, in general, the impression from actual data and predicted data shows an approximately acceptable error value with a slight deviation. Moreover, the regression models were obtained for all responses at 95% level of confidence to be

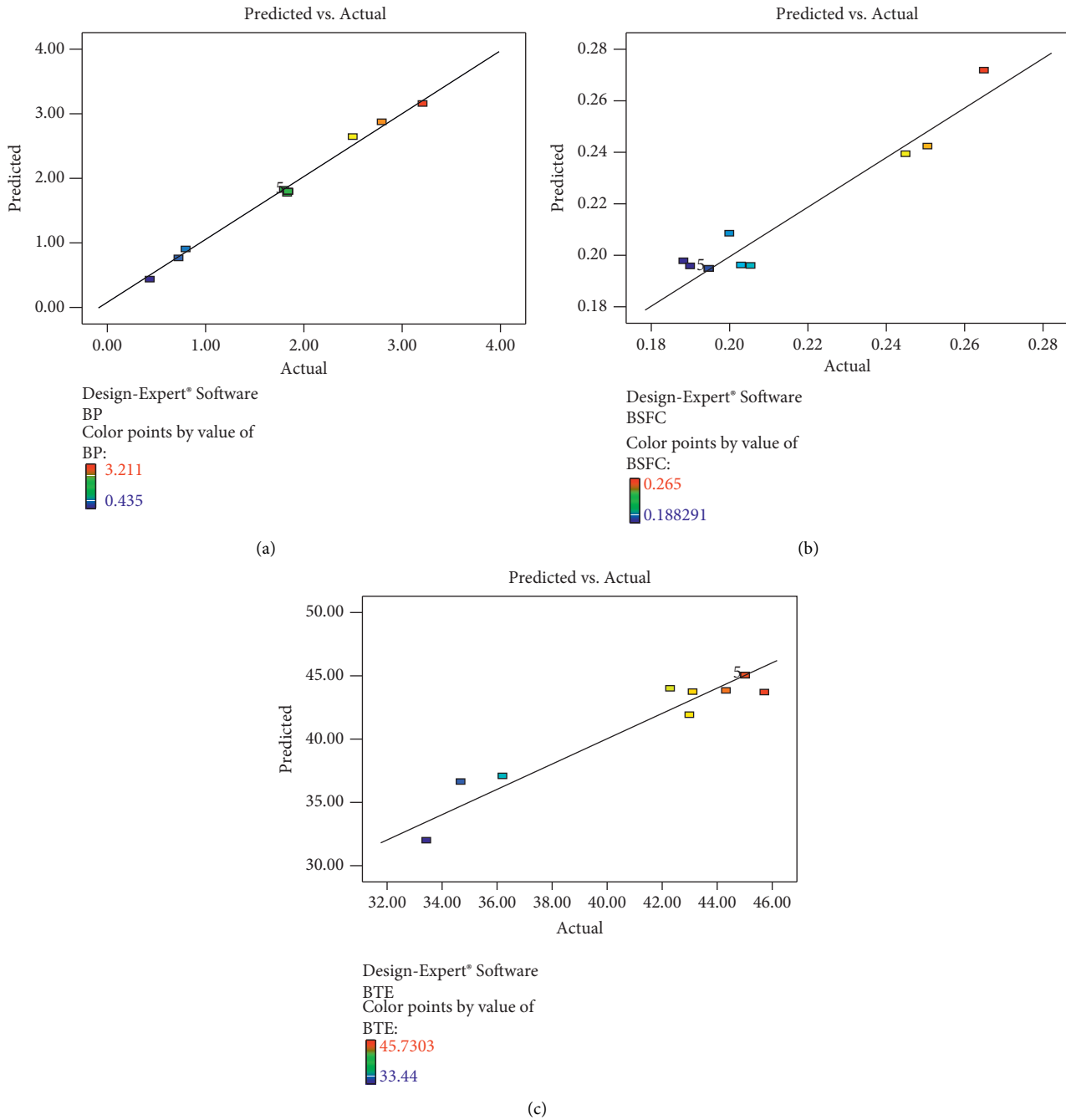


FIGURE 2: Distribution of experimental vs predicted values of the regression model of (a) BP, (b) BSFC, and (c) BTE.

statistically significant. The fuel energy content has a direct impact on BSFC [17, 18] which represents the ratio between consumption of fuel mass and BP [19]. Brake-specific fuel consumption can be considered as one of the significant factors when operating the engine using different fuels, which indicates the suitability of fuels [20]. It can be considered to evaluate the different fuel combustion efficiency to produce engine power in different engine speed as seen in Figure 3. Theoretically, using alcohol fuel additives leads to an increase in the fuel consumption for the same engine output power due to the effect of lower fuel energy content for the blend [21].

3.2. Optimization Results. Three-dimensional surface graphs are a useful method to depict the interaction impact between the investigated variables and responses. Figure 4 presents the three-dimensional surface plot for the interaction among the input variables (engine speed and fusel oil ratio) and output response (BP). It is observed that engine speed has a significant impact more than fusel oil ratio. The graph reveals that the highest value of BP achieved at high speed which is agreed with previous studies [22]. It is obvious that increasing engine speed significantly impacts the engine BP with a slight change for fusel oil ratio. Accordingly, it can be

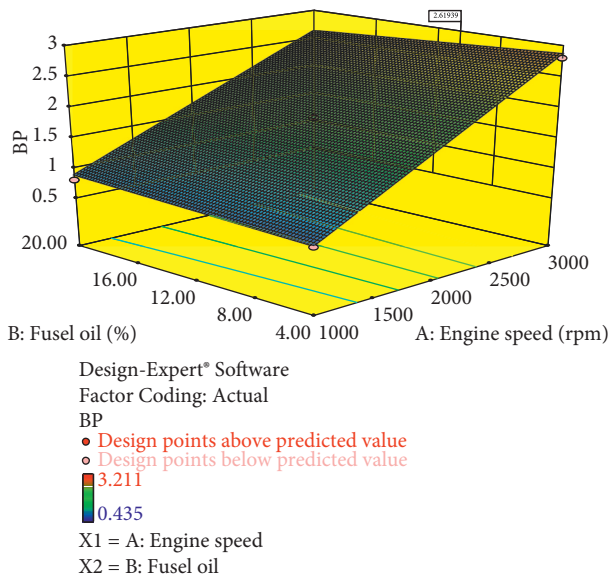


FIGURE 3: Three-dimensional surface plot of BP against engine speed and fusel oil ratio.

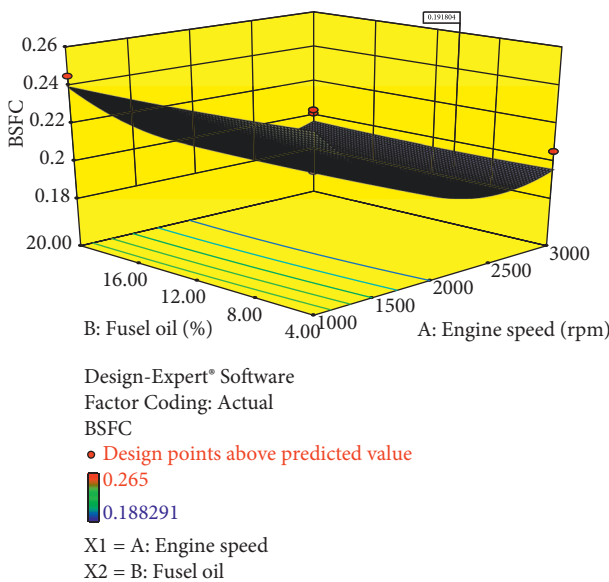


FIGURE 4: Three-dimensional surface plot of BSFC against engine speed and fusel oil ratio.

concluded that the maximum increase in engine BP is statistically linked with the engine speed.

Figure 4 presents the three-dimensional surface plot for the interaction among the input variables (engine speed and fusel oil ratio) and BSFC. It is observed that engine speed has a significant impact more than fusel oil ratio. The graph reveals that the lowest value of BSFC has been achieved at a speed range between 2500 and 3000 rpm. It is obvious that increasing engine speed significantly impacts the BSFC with a slight change for fusel oil ratio.

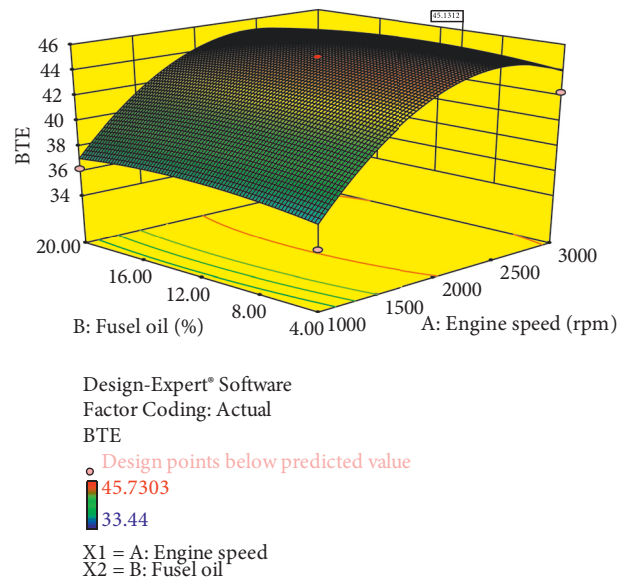


FIGURE 5: Three-dimensional surface plot of BTE against engine speed and fusel oil ratio.

Figure 5 presents the three-dimensional surface plot for the interaction between the input variables (engine speed and fusel oil ratio) and BTE. It is observed that engine speed has a significant impact more than fusel oil ratio. The graph reveals that the highest value of BTE is achieved at a speed between 2500 and 3000 rpm which is agreed with previous studies [22] that reported a significant impact of increasing engine speed on the engine BTE.

The counter surface plot in Figure 6 depicts the desired regain which indicates high power achieved at an engine speed range of 2500–3000 rpm and fusel oil ratio in the range of 8%–12%. Previous studies reported similar results in which the brake power of the SI engine increased with increasing the enginespeeds. Figures 7–9 present the contour graphs of the obtained response which included BP, BSFC, and BTE, respectively, at maximum desirability value after performing multiobjective optimization. Figure 6 presents the desirability value which can be considered to indicate the multiobjectives of optimization's parameters values. The BP increased as engine speed increased with a slight effect for increasing fusel oil ratio at a high engine speed above 2500 rpm. Accordingly, the highest BP was obtained with the highest speed and fusel oil addition ratio of 8% as shown in Figure 7. The minimum value of the BSFC with 8% fusel oil ratio and 2500 rpm engine speeds is presented in Figure 8. The BTE increased as engine speed increased within the range 2500 to 3000 rpm with a noticeable effect on the fusel oil addition ratio. Accordingly, the highest BTE was obtained with a fusel oil addition ratio of 8% as shown in Figure 9. The obtained results reveal significant changes observed on the surface plot at different engine speeds. Accordingly, based on the obtained results of statistical analysis, it is found that the variation in engine speed significantly influences all the output responses. On the other hand, the fusel oil ratio has less impact on the output responses compared to engine speed.

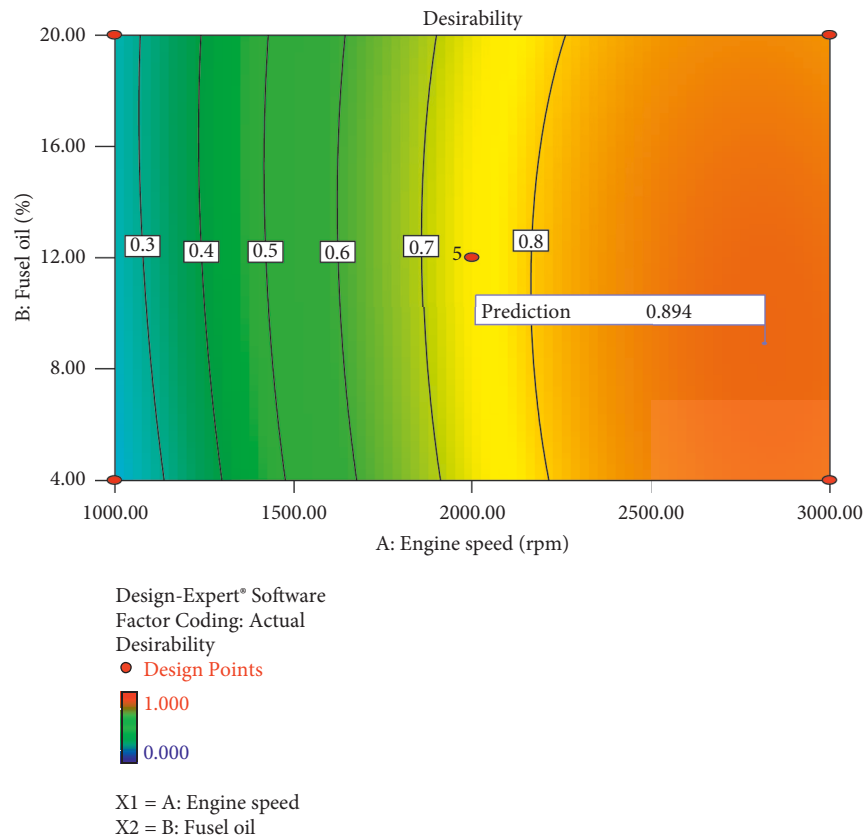


FIGURE 6: Counter surface plot of desirability values of parameters.

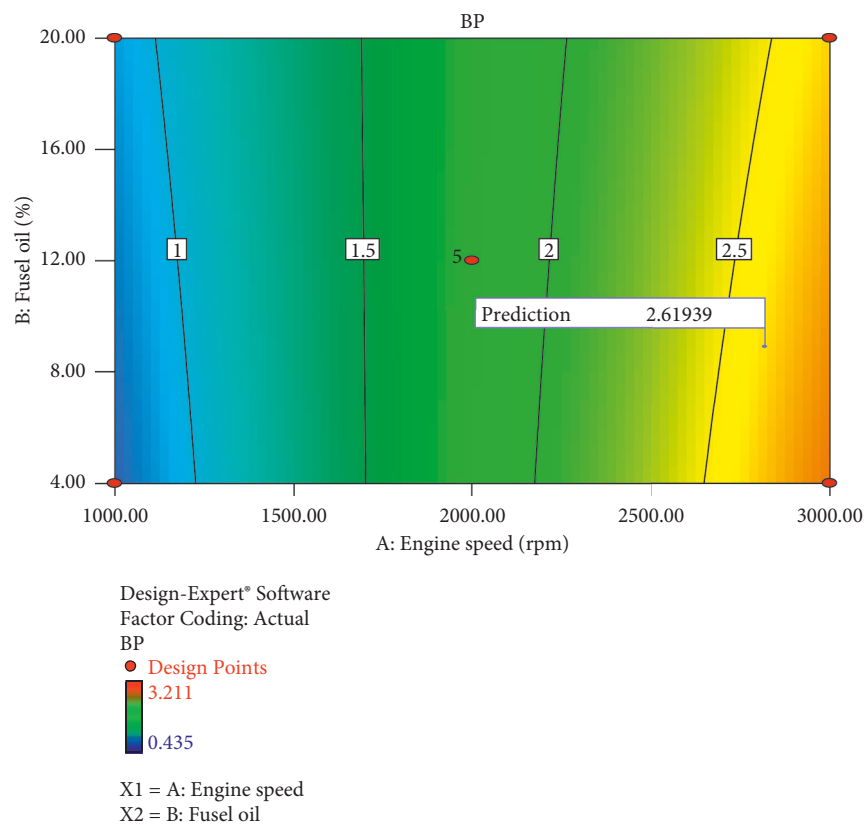


FIGURE 7: Counter surface plot of BP against engine speed and fusel oil ratio.

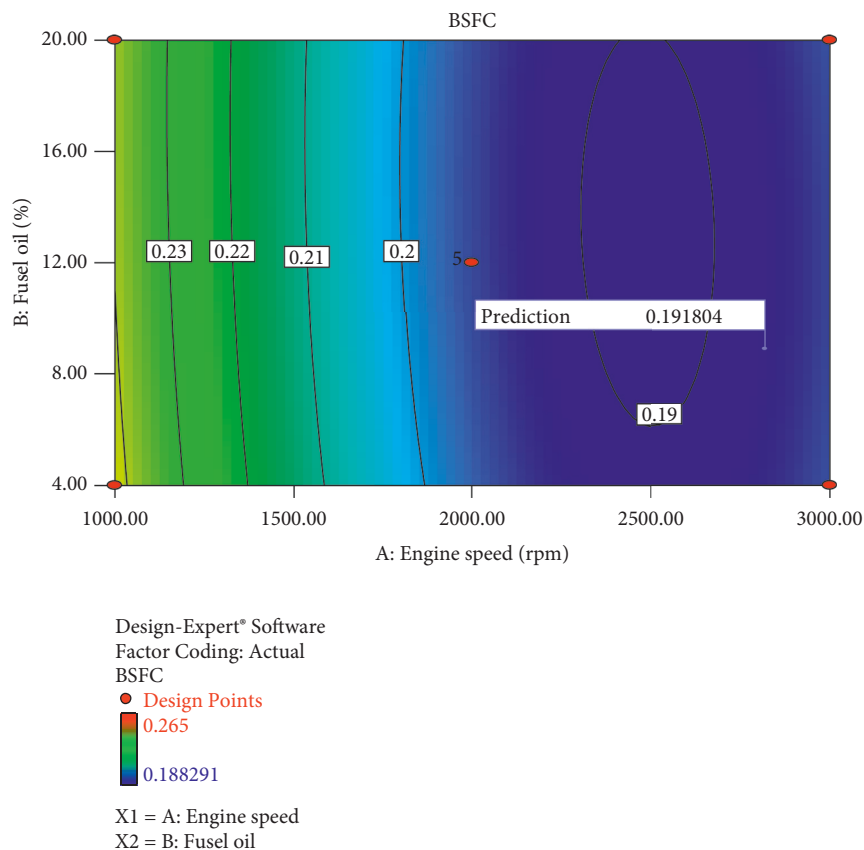


FIGURE 8: Counter surface plot of BSFC against engine speed and fusel oil ratio.

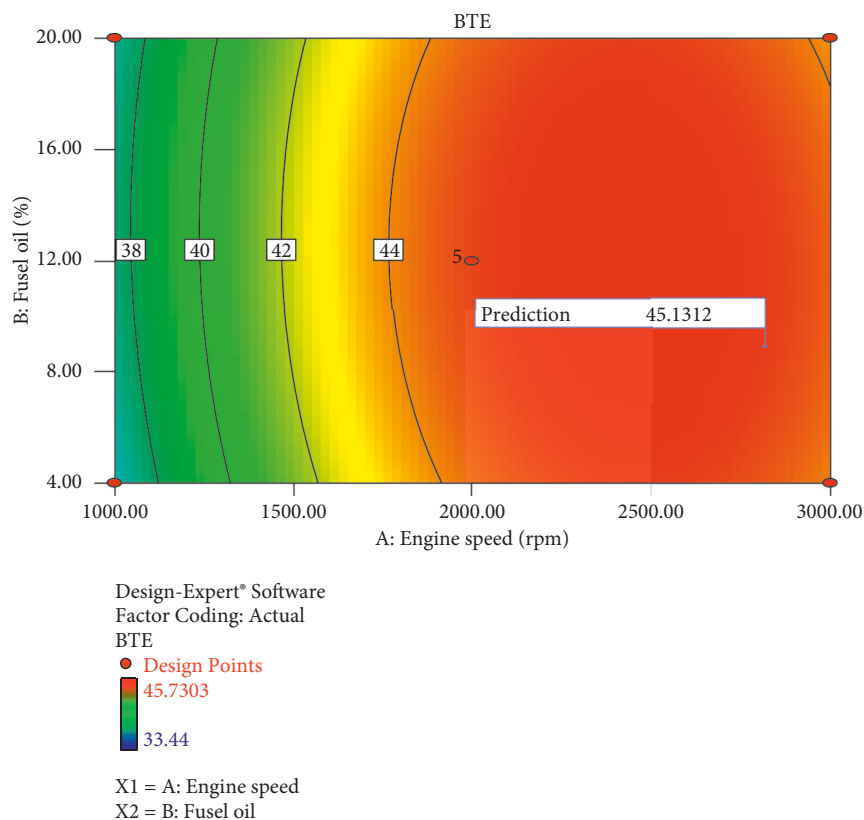


FIGURE 9: Counter surface plot of BTE against engine speed and fusel oil ratio ANOVA results.

The fusel oil ratio has a slight impact on BP while the highest impacts of the fusel oil ratio were on BSFC and BTE response. Fusel oil ratio of 8% has a statistically significant effect on increasing the brake thermal efficiency (BTE) and decreasing BSFC.

Table 5 lists the ANOVA data for BP. The F-value of this model was 385.30, and the p -value was 0.0001 which is less than 0.05; hence, the model is significant, and the high value of R^2 (0.9923) which is close to 1 is desirable and indicates reasonable analysis results. Moreover, the value of R^2 indicates the response's total variability after considering the significant factors and the accounted value for the model's predictor's number. Based on the P -value, ANOVA data indicate that engine speed was a significant factor, while the fusel oil ratio was insignificant.

Table 6 lists the ANOVA data for BSFC. The F-value of this model was 22.32, and the P -value was 0.0001 which is less than 0.05; hence, the model is significant, and the high value of R^2 (0.9410) which is close to 1 is desirable and indicates reasonable analysis results. Moreover, the value of R^2 indicates the response's total variability after considering the significant factors and the accounted value for the model's predictor number. Based on the P -value, ANOVA data indicate that engine speed was a significant factor, while the fusel oil ratio was insignificant.

Table 7 lists the ANOVA data for BTE. The F-value of this model was 19.24, and the p -value was 0.0003 which is less than 0.05; hence, the model is significant, and the high value of R^2 (0.9322) which is close to 1 is desirable and indicates reasonable analysis results. Moreover, the value of R^2 indicates the response's total variability after considering the significant factors and the accounted value for the model's predictor number. Based on the P -value, ANOVA data indicate that engine speed was a significant factor, while the fusel oil ratio was an insignificant factor.

3.3. Independent Variables Optimization. To indicate the influence of engine speed and fusel oil ratio on response variables (BP, BSFC, and BTE), a desirability function was used to execute numerical optimization using DoE software. The selected target for optimizing engine speed and fusel oil ratio is to achieve maximum brake power and brake thermal efficiency at minimum brake-specific fuel consumption. Though different solutions were obtained that contain independent variables with different levels, the maximum desirability solution was chosen as the optimized engine performance conditions. The combined optimized conditions for engine speed and fusel oil ratio were 2818 rpm and 8.92%, respectively. The values of the response at optimized conditions were 2.61812 BP, 0.191787 BSFC, and 45.1353 BTE as listed in Table 7.

3.4. RSM Model Verification. Optimized engine performance conditions were used to ensure the suitability of the RSM model for calculating the output response values [15]. Validation of optimized engine operation conditions

TABLE 5: ANOVA results for BP.

Value source F	Sum of squares	Df	Mean squares	F Value	p-Prob >
Model	7.44	3	2.48	385.30	<0.0001
A	7.40	1	7.40	1150.01	<0.0001
B	3.985E-003	1	3.985E-003	0.62	0.4515
AB	0.034	1	0.034	5.27	0.0474
Residual	0.058	9	6.435E-003		
R-squared	0.9923				

TABLE 6: ANOVA results for BSFC.

Source F	Sum of squares	df	Mean squares	F value	P-value prob >
Model	7.616E-003	5	1.523E-003	22.32	
A 0.0001	4.009E-003	1	4.009E-003	58.76	
B 0.8171	3.934E-006	1	3.934E-006	0.058	
AB 0.8538	2.495E-006	1	2.495E-006	0.037	
A ² 0.0002	3.573E-003	1	3.573E-003	52.37	0.0004
B ² 0.7621	6.762E-006	1	6.762E-006	0.099	
Residual	4.776E-004	7	6.823E-005		
R-squared			0.9410		

TABLE 7: ANOVA results for BTE.

Value source > F	Sum of squares	df	Mean squares	F value	p-Prob >
Model	212.11	5	42.42	19.24	
A	98.32	1	98.32	44.58	
0.0003					
B	0.017	1	0.017	7.597E-003	
0.9330					
AB	0.12	1	0.12	0.057	
0.8188					0.0006
A ²	113.56	1	113.56	51.49	
0.0002					
B ²	2.81	1	2.81	1.27	
0.2964					
Residual	15.44	7	2.21		
R-squared			0.9322		

was achieved by conducting experiments under the same conditions. The output response values at optimized conditions were 2.61812 kW brake power, 0.2431 kg/kW.hr brake-specific fuel consumption, and 36.5303% brake thermal efficiency. The higher brake thermal efficiency obtained with using fusel fuel in the blend is due to the improvement of fuel mixture combustion resulting from the oxygen content and high octane number [23, 24]. On the other hand, the output response values at experimental conditions were 2.84 kW brake power, 0.21 kg/kW.hr brake specific fuel consumption, and 45.6% brake thermal efficiency. Predicted and experimental values of output responses show good agreement as listed in Table 8.

TABLE 8: Optimum conditions, experimental, and predicted values of response at optimized conditions.

Optimum conditions	Coded value	Actual value
Engine speed (rpm)	1.818	2818.05
Additive ratio (%)	−0.385	8.92
Response	Predicted values	Experimental values
BP (kW)	2.61812	2.84
BSFC (kg/kW.hr)	0.2431	0.243
BTE (%)	36.5303	36.5

4. Conclusion

The technique of response surface method (RSM) represents a theoretical, statistical, and mathematical method to build a model for optimizing the levels of the independent variables. Optimization was performed using the response surface method (RSM) to analyze the relationship among the input (independent variables), including engine speed and fusel oil ratio on output (dependent variables). The following conclusion has been addressed from the results of this study:

- (i) It is observed from the figure that, in general, the impression from actual data and predicted data shows an approximately acceptable error value with a slight deviation. Moreover, the regression models were obtained for all responses at 95% level of confidence to be statistically significant.
- (ii) Obtained results show that increasing engine speed significantly impacts the engine brake power, brake-specific fuel consumption, and brake thermal efficiency with a slight change for fusel oil ratio. Accordingly, it can be concluded that the maximum increase in output variables is statistically linked with the engine speed.
- (iii) The output response values at optimized conditions were 2.61812 kW brake power, 0.2431 kg/kW.hr brake-specific fuel consumption, and 36.5303% brake thermal efficiency. Based on the *P*-value, ANOVA data indicate that engine speed was a significant factor influencing output responses, while the fusel oil ratio was insignificant.
- (iv) The fusel oil ratio has a slight impact on BP while the highest impacts of the fusel oil ratio were on BSFC and BTE response. Fusel oil ratio of 8% has a statistical significance in increasing the brake thermal efficiency (BTE) and decreasing BSFC.
- (v) Finally, predicted and experimental values of output responses show good agreement in this study [23].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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