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Research Article

Spark ignition engine performance analysis with low octane gasoline and Methyl tert-butyl ether additive for optimum operation

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ABSTRACT

Fuel quality is considered an important indicator for ensuring maximum output power. Hence, using commercial fuel that didn't meet the standard specifications may result in engine performance deterioration. In this study, Methyl tert-butyl ether additive has been introduced as an octane enhancer with local low-octane gasoline. Five samples were prepared by adding MTBE additive at 3%, 6%, 9%, 12% and 15% to commercial gasoline and tested at constant half load and increasing engine speed. Response surface method optimization and ANOVA analysis have been conducted using the obtained engine test results to indicate the optimum engine performance conditions and the significance of the variations respectively. Optimization results show that the output responses are linked statistically with the engine speed. The optimum operation conditions obtained at an engine speed of 3126 rpm and 3% additive ratio by 2356 W for brake power, 0.187857 g/W.hr for brake-specific fuel consumption and 38.3% for the brake thermal efficiency. According to the chosen significant level, ANOVA results shows significant influence of engine speed on the different obtained responses, On the other hand, the optimum response achieved at 3% additive ratio with insignificant influence for increasing additive ratio in the fuel mix.

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INTRODUCTION

The internal combustion engine has been considered one of the most important inventions used in all walks of life for many decades. The first successful commercial internal combustion engine was created in 1860 and operated using a mixture of coal and gas, then diesel and gasoline have been used as a standard liquid fuel for compression and spark ignition engines respectively. These fuels are depleting with time due the limited resources and increasing demand. These challenges result in a rapid increase of fuel prices with time which requires ensuring efficient utilization of the fuel in the operation of internal combustion engine to mitigate the impact of the fuel world crises [1,2]. Spark ignition engine commonly used in high-speed road cars, is operated with gasoline fuel that is composed of many different types of hydrocarbons

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including naphthenes, paraffin's and aromatics. The quality of gasoline fuel depends on the crude oil source and the refining processes in addition to the type and percentage of the chemical additives [3]. Several standards have been adopted to indicate the required specifications for gasoline engine properties. Among the different properties of gasoline fuel, the most significant effective property on the SI engine performance was found to be the octane number due to their direct impact on knock control in the engine. For many decades, low-octane gasoline fuel used to operate low compression ratios SI engines. After that and with the development of SI engine which implies high compression ratio of the engine, it was essential to improve the value of the octane number to suit the new engine design. This engages the researchers to investigate the different ways to improve the octane number [4].

Fuel additives have been suggested as one of the most valuable ways adapted by researchers to enhance engine performance and efficiency through improving fuel quality to meet the standard specifications [5]. Different additives have been suggested by various researchers to improve gasoline fuel properties. During recent decades, many types of alcohol and ether have been used as a blend with gasoline to reduce the dependence on gasoline and also as an additive to enhance fuel quality. Among these additives, Methyl tert-butyl ether (MTBE) was introduced as a viable octane enhancer for gasoline [6] and at the same time efficient in reducing emissions due to their clean burning. During the recent few decades, an increment in MTBE utilization has been observed due to concerns about environmental pollution [7,8].

Methyl tertiary-butyl ether is a volatile organic compound which has been considered as an octane booster and emission controller with gasoline in some countries for a couple of decades. It is produced from the chemical reaction of isobutylene and methanol. In USA, MTBE widely produced with a production rate in 1999 of over 200000 barrels/day. Moreover, it has been used as an octane booster since 1979 in the USA [9,10]. Many researchers introduced MTBE as one of the most cheapest and viable ether additives for gasoline with easy production and favorable handling in addition to their proper blending characteristics [11] that contribute to lowering harmful emissions [8]. Blending MTBE with gasoline has been investigated by Sezer and Bilgin [12]. The results reveal an enhancement in the SI engine performance with a reduction in CO emissions. The study results found that the best value of brake mean effective pressure (BMEP) reported at 10% MTBE addition with 90% gasoline which in turn improves the engine brake thermal efficiency up to a 15% MTBE addition ratio. Increasing the fuel octane number has been reported by Douihit et al. [13] when adding 15% of MTBE with gasoline. Similarly, increasing in the octane number of gasoline fuel has been obtained with the addition of ethanol at different ratios to gasoline fuel with a significant deterioration in the heating value [14]. In another study by Hsieh et al. [15] the fuel raid vapor pressure has been observed to increase with 10% ethanol addition and decrease after this ratio. The impact of oxygenates additives and non-oxygenate additives on fuel raid vapor pressure and octane number has been investigated by Da Silva et al. [11] at an addition ratio of 5, 10, 15 and 25% with two samples of Brazilian gasoline with different chemical compositions. Their results reveal an increment in the fuel octane number with all additives, however, the raid vapor pressure increases significantly with some additives and decreases with others depending on the gasoline type. The impact of the concentration of methane in biogas on the different properties of the fuel has been investigated by Porpatham et al. [16] through lowering the Carbon dioxide (CO_2) content from 41% to 30% and 20% in biogas. They reported a significant increase of 68.3% in the heating value with 20% CO_2 concentration. The impact of locally produced and commercial fuel additives on gasoline fuel characteristics has been investigated by Sheet [17] and Alptekin [18]. The results show an enhancement in the fuel octane number and a noticeable deterioration in the heating value with the used additives.

Simulation and modelling software has been introduced in many applications [19–22]. Response Surface Methodology (RSM) has been implemented as an efficient method for the evaluation and optimization of fuel blending ratio and engine operation parameters. It may be considered to achieve the optimum performance of engine performance at low exhaust emissions with minimizing experimental tests [23–27]. Recent studies reported that RSM can be implemented efficiently to evaluate and optimize engine performance [24]. On the other hand, RSM may be implemented as an efficient way in indicating the optimum blending ratio to achieve the best engine performance [23].

In some countries, low octane fuel is produced from the oil refinery and supplied to the local petrol station to be used as a fuel for vehicles operated with SI engine. Inefficient engine performance and operation problems like knocking are observed as a result of low-octane fuel utilization. Though many additives have been investigated in recent studies, the optimum blend and engine conditions still need to be detected [23–27]. MTBE has been introduced as a suitable octane booster with low gasoline fuel in many studies [28,29]. Hence, the current study aims to optimize the utilization of MTBE with local gasoline fuel. Engine performance parameters (brake power (BP), brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE)) have been investigated using experimental engine tests and optimized with RSM at different MTBE ratios of 3%, 6%, 9%, 12%, and 15% with low octane gasoline fuel to indicate the optimum engine operation with the investigated fuel samples. Analysis of Variance (ANOVA) has been adopted for analyzing the statistical difference and interaction among group means for the investigated variables.

METHODOLOGY

Experimental Setup

The current study includes the investigation of adding MTBE with low-octane gasoline to enhance fuel quality and engine performance. Commercial gasoline was provided by a local petrol station and MTBE was supplied by a local chemicals supplier. The preparation of fuel samples has been performed in the lab under controlled conditions. Magnetic stirrer has been used to mix the prepared fuel samples with a mixing time of 20 minutes in which MTBE was added gradually to the commercial gasoline at the desired ratio as shown in Figure 1. Five samples were prepared through adding MTBE additive to gasoline by 3%, 6%, 9%, 12% and 15% to commercial gasoline and denoted as GMTBE3, GMTBE6, GMTBE9, GMTBE12, and GMTBE15. Table 1 lists the properties of local gasoline fuel and MTBE additive used in this study. A spark ignition single cylinder, 4-stroke gasoline engine (Model TD110) has been used to conduct the experimental test of the prepared fuel samples as shown in Figure 2(A). Engine torque and power have been measured during the engine test using prepared fuel samples at increasing engine speed and constant half-throttle opening (HTO) and the data collected from the control panel screen shown in Figure 2(B). The engine uses portal fuel injection and has a compression ratio of 9.5:1 with a 230 cc total displacement, 66 mm cylinder bore and 57 mm piston stroke. The maximum power produced by the engine is 3600 W at 3600 rpm engine speed. To apply the required load, a hydraulic dynamometer has been coupled to the engine and a regulating valve is used to regulate the flow rate of the pumped water as presented in Figure 2(C). A 16 ml pulp flow meter with a stopwatch has been used to measure the consumed fuel rate. Engine speed has been increased from a minimum speed of 1000 rpm to a maximum speed of 3000 rpm with a constant increment of 500 rpm. The engine has been warmed for 15 minutes at the beginning of each test to ensure a steady state operation. After that, engine test was conducted and repeated three times to ensure more accurate results through taking the average value. The fuel test matrix considered for the engine test in this study is listed in Table 2.

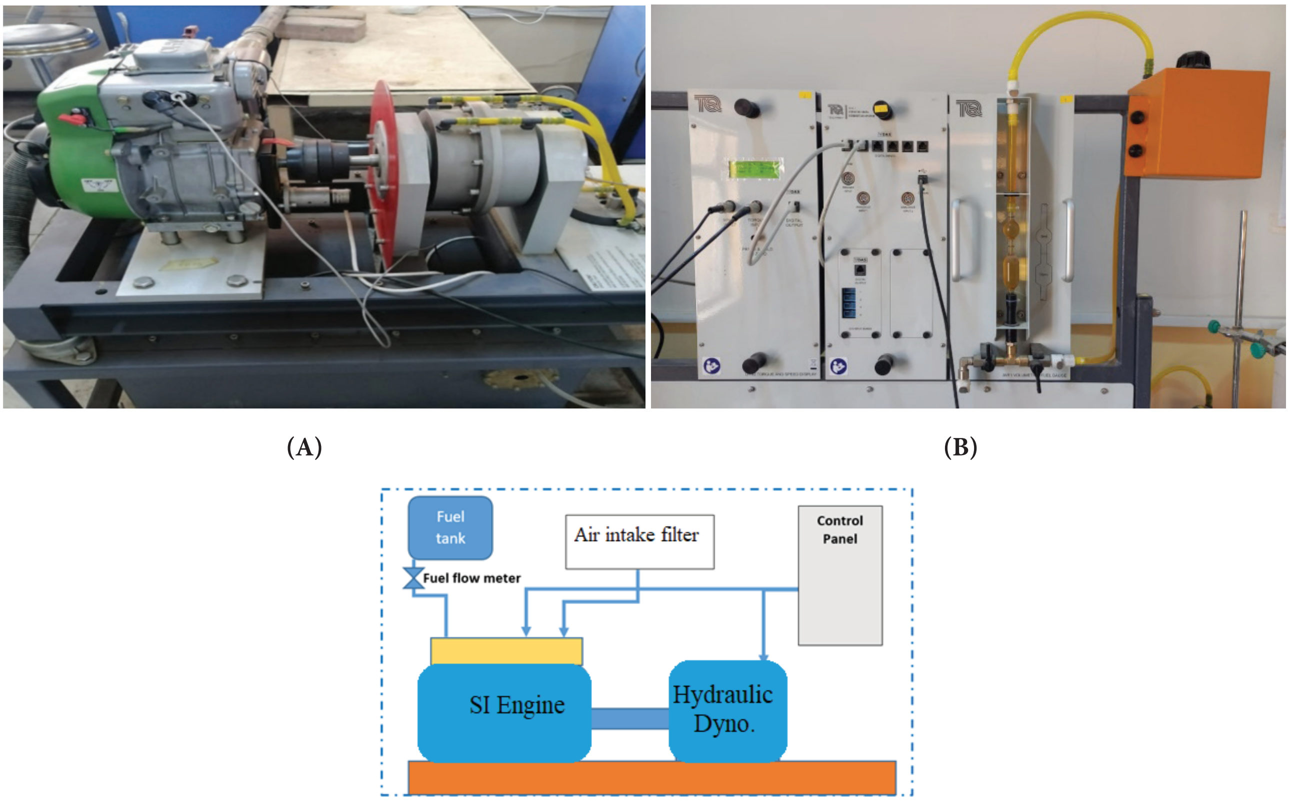
RSM Optimization

Optimum engine performance has been investigated using Design Expert Software version 8.0.6, Response Surface Method (RSM). The coded and uncoded RSM design levels implemented in the current analyses are presented in Table 3 using a central composite design (CCD) and quadratic model. As a comparison, less experimental runs are needed in the method of CCD than other RSM methods therefore it has been chosen. The implemented design efficiently resolves the essential polynomial model influences of high-order connection with desirable output response results [30]. The independent variables' real level has been coded based on the following equation [31]:

$$Z = Zo\text{-}Zc/\Delta Z \tag{1}$$

Where Z presents the coded level of independent variables, Zo presents the real level of independent variables, Zc presents the actual value at the central point and ΔZ represents step-change. A specific equation for each independent variable has been derived based on the above equation for coding their actual values.

Figure 1. Fuel samples preparation.



(A) (B)

(C)

Figure 2. Experimental engine and dynamometer (A) Test rig, Control panel (B) and (C) schematic diagram.

The following equation can be used to represent the general form of the statistical model and calculate the output based on the considered input [30].

$$Y=f(X1, X2, X3, X4, X5, X6, X7, X8, \ldots\ldots\ldots\ldots Xn + \varepsilon \quad (2)$$

In the responses function, the calculation of output (Y) is performed depending on the independent variables (X1, X2, X3, X4, X5, X6, X7, X8, ……..Xn) through considering the percentage of error ε in consideration. The above equation is implemented in different forms for the cases of regression with the following general form of the polynomial quadratic function [30].

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

Where β_o is a constant, β_i is the linear coefficient, and β_{ij} is the interactive coefficient.

Table 1. Local gasoline and MTBE additive properties

Property	Unit	GMTBE3	GMTBE6	GMTBE9	GMTBE12	GMTBE15	MTBE
Density at 20 C	kg/m^3	765	766	768	769	771	800.3
Oxygen cc	Cc	---	---	---	---	---	18
H/C ratio	---	2.25	---	---	---	---	---
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 T 298 K	KJ/kg	500	---	---	---	---	874
Flashpoint	°C	38	38	38	38	39	42
Auto ignition temperature	°C	~300	---	---	---	---	416
Viscosity at 40 °C	mm^2/s	0.467	0.6	0.8	0.9	1.1	4.162

Table 2. Experimental design matrix

Fuel sample	Composition
GMTBE3	97% Gasoline + 3% MTBE
GMTBE6	94% Gasoline + 6% MTBE
GMTBE9	91% Gasoline + 9% MTBE
GMTBE12	88% Gasoline + 12% MTBE
GMTBE15	85% Gasoline + 15% MTBE

Table 3. Levels of independent variables with experimental range

Independent variable		Codes factor levels				
		-α	-1	0	+1	+α
Engine speed (rpm)	A	1085.79	1500	2500	3500	3914.21
MTBE (%)	B	0.00514719	0.03	0.09	0.15	0.174853

ANOVA Statistic

Moreover, in this study, analysis of Variance (ANOVA) has been adopted for analyzing the statistical difference and interaction among group means. The degree of freedom value describes in this statistical analysis by DF represents the probability distribution in repeating sampling. A significance level of 0.95 is implemented in the current analysis which indicates maximum probability >F at 0.05. In the groups for each sample, the significant variation difference can be detected from the high F-value. The percentage contribution has been considered an effective indicator of the importance of each term in the model within the current study.

RESULTS AND DISCUSSION

Fitting of the Model

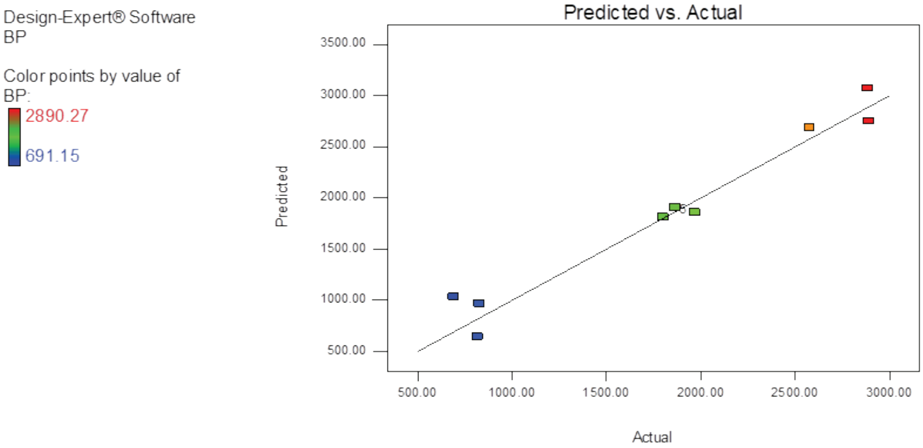
In this study, engine performance has been investigated using engine speed and additive ratio as the controlled variables. The output response includes brake power (BP) which represents the first output response that can be calculated directly from the measured engine speed and engine torque. Fuel consumption is the second response which represents another important indicator for the fuel quality to produce the desired output power. Brake thermal efficiency (BTE) represents the third response which is the most useful indicator for fuel conversion efficiency and combustion quality [32]. The level of independent variables can be optimized through the developed model using the theoretical, statistical and mathematical methods through the technique of response surface method (RSM). To indicate the values of the response variables, the polynomial equation coefficients have been determined based on the data obtained from experimental tests. The response variables BP, BSFC, and BTE regression equations are represented by equations 4, 5, and 6 respectively obtained from the RSM. These equations show the relationship between the input variables (independent), including the speed of the engine (A) and the additive ratio of MTBE (B); and output variables (dependent), including engine brake power, brake-specific fuel consumption and brake thermal efficiency for optimum engine operating conditions.

$$BP = 1860.70 + 858.18 * A + 33.40 * B \tag{4}$$

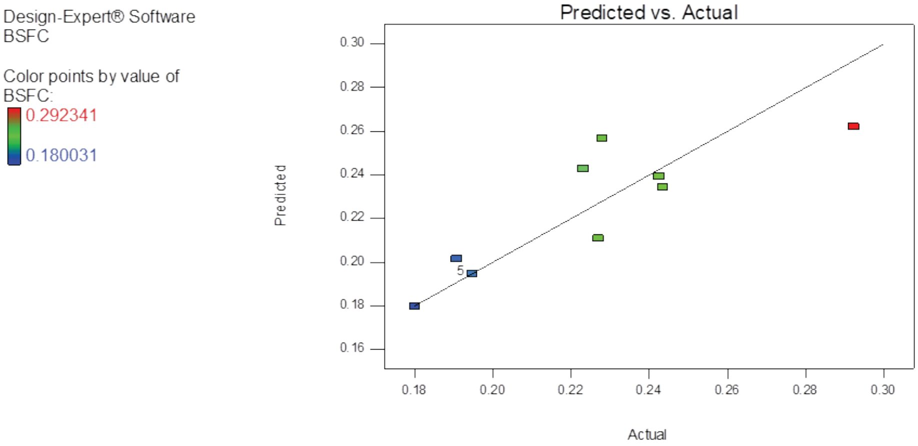
$$\begin{gathered} BSFC = 0.19 - 8.016E\text{-}003\ A + 0.022\ B \\ - 3.399E\text{-}003\ AB + 0.025\ A2 + 8.272E\text{-}003\ B2 \end{gathered} \tag{5}$$

$$\begin{gathered} BTE = 37.19 + 1.10\ A - 3.02 * B - 0.21\ AB \\ - 3.71\ A2 - 1.26\ B2 \end{gathered} \tag{6}$$

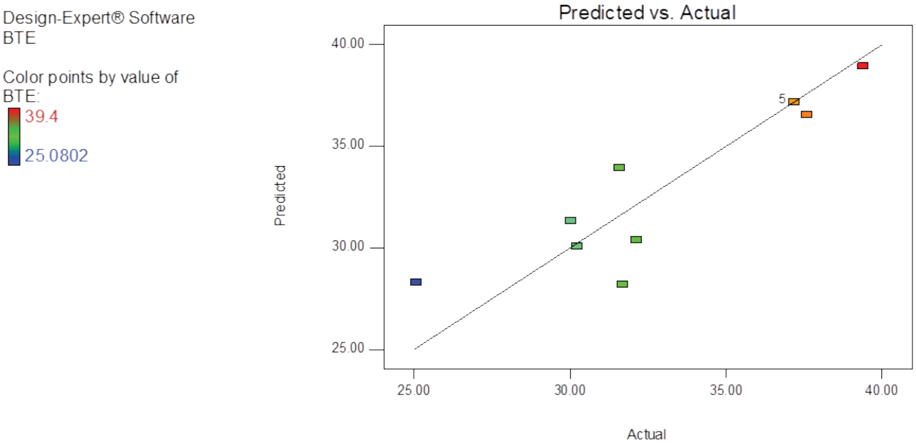
The residuals represent predicted and actual values variation [33]. The plot in Figure 3 shows the actual and predicted values for the output responses of BP, BSFC and BTE. The plot shows that the deviation from actual and predicted data reveals an approximately acceptable value of error at a slight deviation. Furthermore, a Confidence level of 95% has been adopted to obtain the model of regression for all responses to be statistically significant. The energy content of the fuel mix represents the ratio of fuel mass consumed to the engine BP [34] and has a direct impact on BSFC [14,35]. Brake-specific fuel consumption is an important indicator of the suitability of the fuel for engine operation with different fuel samples [36]. The combustion efficiency of the fuel mixture to produce certain output engine power can be assessed through the BSFC evaluation. Theoretically, two conflict factors indicate the final engine BTE with ether fuel additives which include the lower heating value and the higher-octane number compared to gasoline fuel which influence directly the fuel consumption for the same engine output power and the combustion efficiency of the fuel mixture [37].



(a) BP



(b) BSFC



(c) BTE

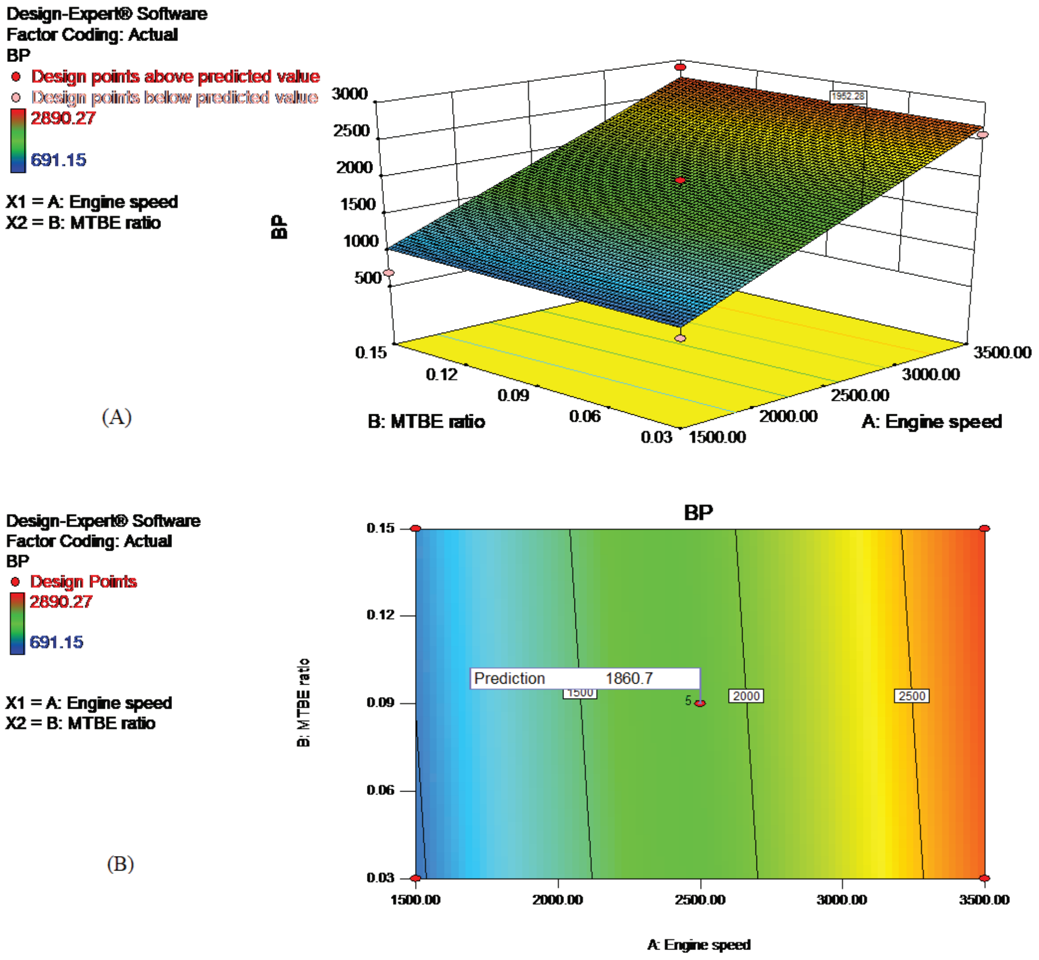
Figure 3. Experimental values distribution vs predicted values.

Optimization Results

The most useful way to show the impact of investigated variables interaction and the output responses is the three-dimensional surface plots. Figure 4(A) shows the interaction between the different input variables (engine speed, and MTBE additive ratio) and the brake power (BP) which represent the first output response that can be calculated directly from the measured engine speed and engine torque. The 3-D plot shows a significant impact of engine speed on the engine BP rather than the MTBE additive ratio. Figure 4(B) depicts the obtained contour plot for the achieved response of BP from the multi-optimization results at maximum desirability value. The plot indicates that increasing engine speed results in a significant increase in the engine output BP while the MTBE ratio shows slight influence at a high engine speed above 2500 rpm. Therefore, the maximum BP has been achieved at high engine speeds and an MTBE additive ratio of 9%. The obtained results show that the engine BP increased with increasing engine speed and the maximum value observed at an engine speed of 3500 rpm which is agreed well with the results from recent studies [38]. Based on the obtained results, it is obvious that there is a significant correlation between the engine speed and output BP increment.

Fuel consumption is another important indicator for fuel quality to produce the desired output power. The interaction between the different input variables (engine speed, and MTBE additive ratio) and the BSFC as the output response is shown in Figure 5(A). The 3-D plot shows a significant impact of engine speed on the BSFC rather than the MTBE additive ratio. The BSFC contour plot shown in Figure 5(B) achieves a minimum value at a 9% MTBE ratio and an engine speed of 2500 rpm. The obtained results show that the BSFC decreased with increasing engine speed and then start to increase again and the minimum value was observed at an engine speed of around 2500 rpm. Moreover, a significant impact for the engine speed increment on the BSFC is observed with a slight influence of the MTBE additive ratio.

Brake thermal efficiency (BTE) is the most useful indicator for fuel conversion efficiency and combustion quality. The interaction between the different input variables



(A)

(B)

Figure 4. (A) 3D-surface plot and (B) contour surface plot of engine brake power.

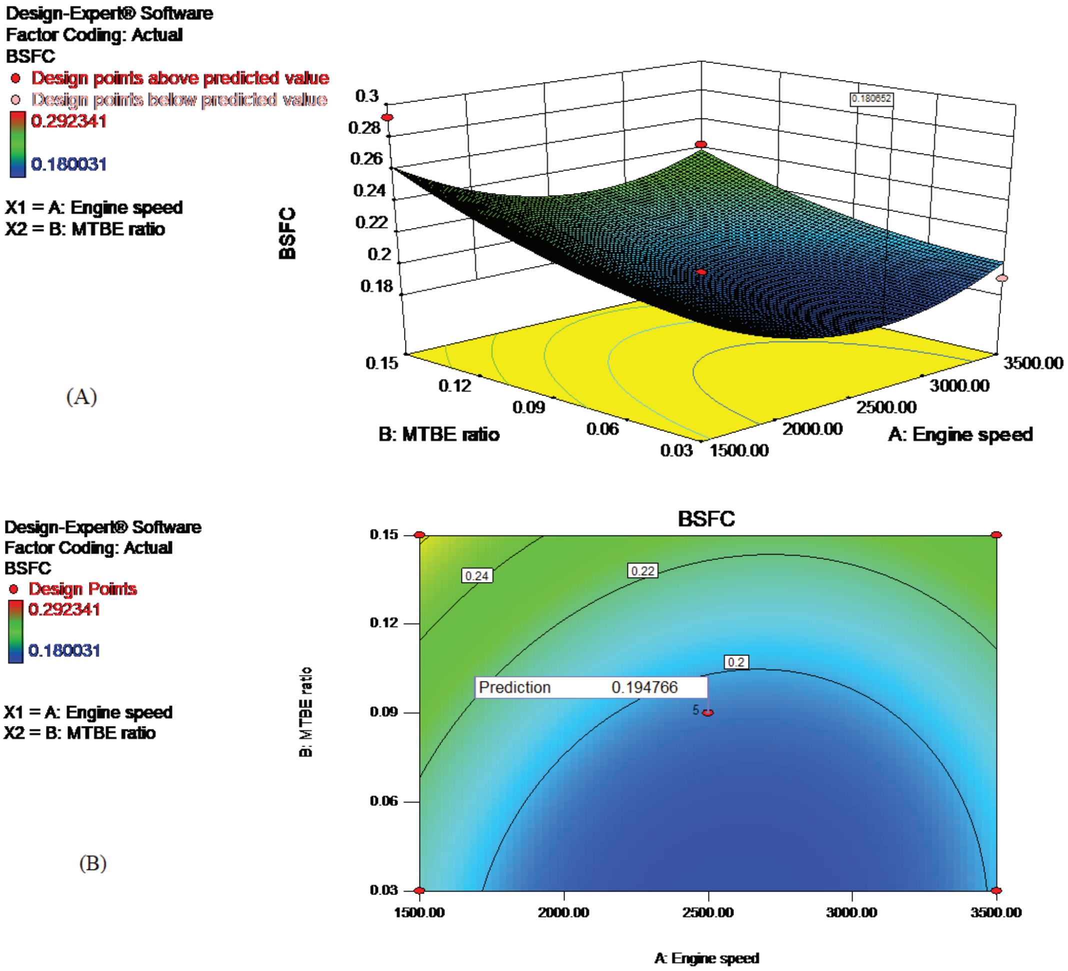


Figure 5. (A) 3D-surface plot and (B) contour surface plot of engine brake specific fuel consumption.

(engine speed, and MTBE additive ratio) and the BTE as the output response are shown in Figure 6(A). The 3-D plot shows a significant impact for engine speed on the BTE rather than MTBE additive ratio. The contour plot presented in Figure 6(B) indicates that increasing engine speed and MTBE ratio results in a significant increase in the engine output BTE. Therefore, the maximum BTE has been achieved at high engine speeds and an MTBE additive ratio of 9%. The obtained results showed that the BTE increased with increasing engine speed and then start to decrease again and the maximum value was observed at an engine speed of between 2500 rpm and 3000 rpm. Moreover, a significant impact for the engine speed increment on the BSFC is observed with a slight influence of the MTBE additive ratio.

Figure 7 depicts the plot of the contour surface for the desired regain that shows the achievement of high engine brake power at MTBE ratio and engine speed around 9% and 2500 rpm respectively. The contour plot shows the values of the multi objectives optimization's parameters based on the desirability value. A similar trend of increasing engine brake power with increasing engine speed with SI engine has been reported by many other researchers. In general, significant variation has been observed from the multi objectives optimization's surface plots at different engine speed. Moreover, it is found from the statistical analysis results that the engine speed variation's significantly impacts the whole output responses. However, the additive ratio of MTBE slightly influences the output responses.

Though the results reveal that the MTBE additive ratio slightly influences the engine output BP, it has a higher impact on the output responses of the BSFC and engine BTE. Accordingly, the results showed that 9% MTBE ratio has a statistically significant impact on improving the engine BTE at lower BSFC.

The Results of ANOVA

The ANOVA results for engine BP are listed in Table 4 with F-value and p-value of 99.28 and 0.0001 respectively for this model. P-value shows a lower value compared to the confidence level chosen for this analysis (0.05), which indicates significant variation in this model with a high R^2

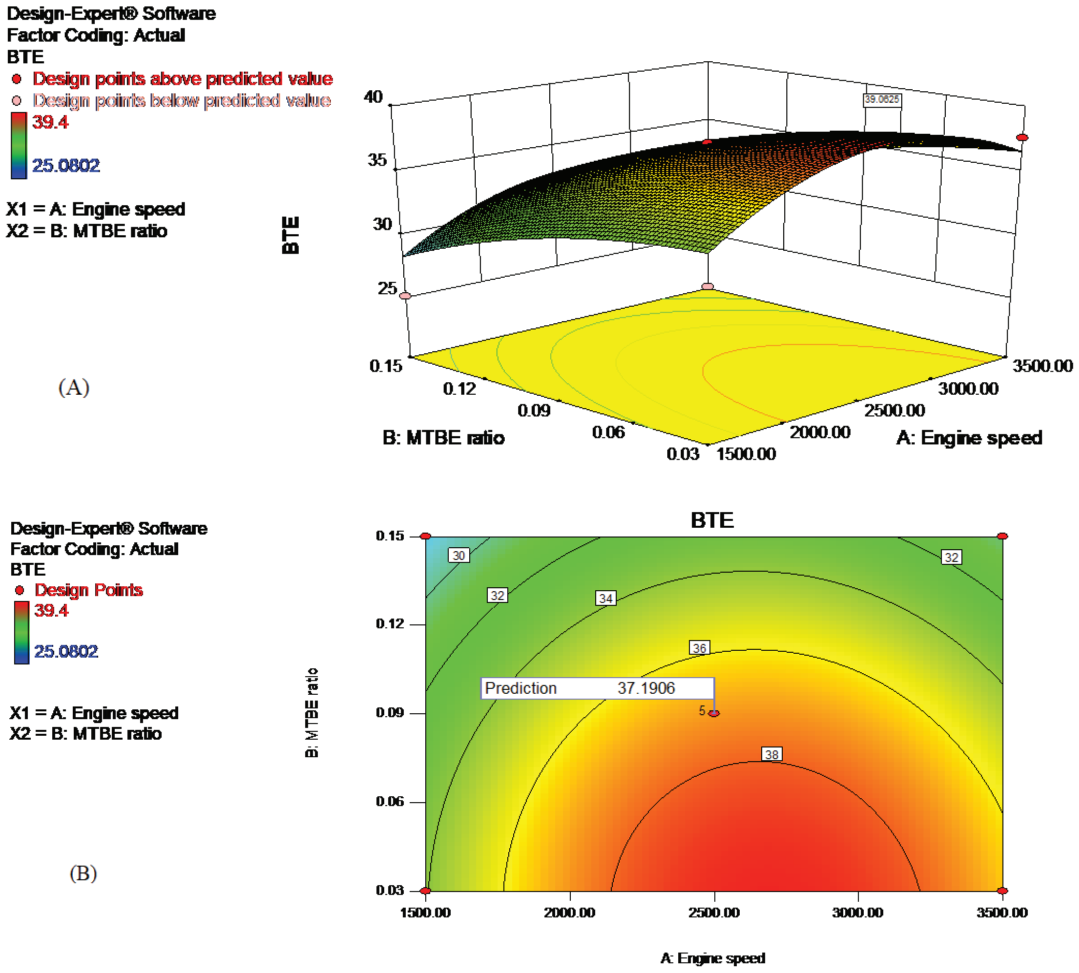


Figure 6. (A) 3D-surface plot and (B) contour surface plot of brake thermal efficiency.

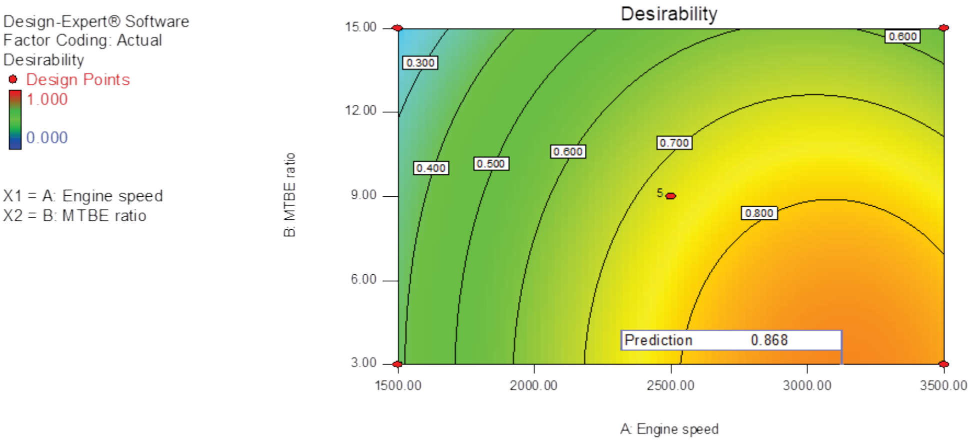


Figure 7. Desirability values contour surface plot of parameters.

value of 0.9923. This value of R^2 is desirable as it is close to 1 which indicates acceptable results from this analysis. Furthermore, R^2 value indicates the total variability response's after taking into consideration the accounted value and significant factors for the model's predictor's number. According to the p-value, ANOVA analysis results indicate a significant impact on the engine speed and an insignificant impact on the MTBE additive ratio.

Table 4. BP ANOVA results

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	5.901E+006	2	2.950E+006	99.28	< 0.0001
A-Engine speed	5.892E+006	1	5.892E+006	198.26	< 0.0001
B-MTBE ratio	8925.68	1	8925.68	0.30	0.5957
Residual	2.972E+005	10	29718.08		
Lack of Fit	2.972E+005	6	49530.14		
R-Squared	0.9521				

Table 5. BSFC ANOVA results

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	9.171E-003	5	1.834E-003	4.91	0.0300
A-Engine speed	5.141E-004	1	5.141E-004	1.38	0.2790
B-MTBE ratio	3.961E-003	1	3.961E-003	10.61	0.0139
AB	4.622E-005	1	4.622E-005	0.12	0.7353
A^2	4.476E-003	1	4.476E-003	11.99	0.0105
B^2	4.760E-004	1	4.760E-004	1.28	0.2960
Residual	2.613E-003	7	3.733E-004		
Lack of Fit	2.613E-003	3	8.710E-004		
R-Squared	0.7782				

The ANOVA results for engine BSFC are listed in Table 5. The F-value and p-value were 4.91 and 0.0300 respectively for this model. P-value shows a lower value compared to the confidence level chosen for this analysis (0.05), which indicates significant variation in this model with a high R^2 value of 0.7782. This value of R^2 is desirable as it is close to 1 which indicates acceptable results from this analysis. Furthermore, R^2 value indicates the total variability response's after taking into consideration the accounted value and significant factors for the model's predictor's number. According to the p-value, ANOVA analysis results indicate an insignificant impact on the engine speed and a significant impact on the MTBE additive ratio.

The ANOVA results for engine BTE are listed in Table 6. The F-value and p-value were 7.53 and 0.0097 respectively for this model. P-value shows a lower value compared to the confidence level chosen for this analysis (0.05), which indicates significant variation in this model with a high R^2 value of 0.8433. This value of R^2 is desirable as it is close to 1 which indicates acceptable results from this analysis. Furthermore, R^2 value indicates the total variability responses after taking into consideration the accounted value and significant factors for the model's predictor's number. According to the p-value, ANOVA analysis results indicate an insignificant impact on the engine speed and a significant impact on the MTBE additive ratio.

Independent Variables Optimization

For the evaluation of the impact of MTBE additive ratio and engine speed on response variables that include; BP, BSFC and BTE, the adoption of a desirability function implies executing numerical optimization through the utilization of design of experiments (DoE) software. The chosen target for engine speed and MTBE additive ratio optimization is to obtain maximum engine BP and BTE at lower BSFC. The maximum desirability solution has been selected as the optimized engine performance conditions among the different obtained solutions that contain independent variables with different levels. The combined optimized conditions for engine speed and MTBE additive ratio were 3126 rpm and 3.0% respectively. The response values at optimized conditions were 2365.18 W for BP, 0.187857 g/W.hr for BSFC, and 38.3% for BTE as listed in Table 7.

Verification of the RSM Model

To verify the RSM model's suitability for the calculation of the output response values, optimization of engine performance conditions has been considered [27]. For validating the optimized engine operation conditions, experiments have been conducted under similar operation conditions. The obtained values of output response at optimized conditions including brake power, brake-specific fuel consumption and brake thermal efficiency found

Table 6. BTE ANOVA results

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	182.86	5	36.57	7.53	0.0097
A-Engine speed	9.70	1	9.70	2.00	0.2003
B-MTBE ratio	72.93	1	72.93	15.02	0.0061
AB	0.18	1	0.18	0.037	0.8529
A^2	95.79	1	95.79	19.73	0.0030
B^2	11.04	1	11.04	2.28	0.1752
Residual	33.98	7	4.85		
Lack of Fit	33.98	3	11.33		
R-Squared	0.8433				

Table 7. Experimental and predicted values for the optimum conditions

Optimum conditions	Actual value	Coded value
Engine speed (rpm)	3126	0.627
Additive ratio (%)	3.0	-1.00
Response	Experimental values	Predicted values
BP (W)	2384	2365.18
BSFC (g/W.hr)	0.16243	0.187857
BTE (%)	38.1	38.3

to be 2365.18 W, 0.187857 g/W.hr and 38.3% respectively. Increasing brake thermal efficiency value with introducing MTBE with commercial gasoline can be attributed to the high-octane number and oxygen content of MTBE additive which results in the enhancement of the combustion of fuel mixture [39]. The obtained values of the output response at experimental conditions including BP, BSFC, and BTE found to be 2384 W, 0.16243 g/W.hr and 38.1% respectively which show good agreement with predicted values as listed in Table 7.

CONCLUSION

In this study, the optimum MTBE additive dosage with low-octane gasoline has been indicated using Response surface method software. Five samples were prepared through adding MTBE additive to commercial gasoline by 3%, 6%, 9%, 12% and 15% and tested at constant half load and increasing engine speed. Response surface method optimization design implemented in the current analyses using central composite design (CCD) and quadratic model and conducted based on the obtained engine test results to indicate the optimum engine performance conditions. Optimization results show that the output responses are linked statistically with the engine speed as follows:

- The results reveal significant impacts for the engine speed on the output response with less effect for the MTBE ratio increment which results in a statistical correlation between the engine speed and the output variables maximum increase.
- The optimum operation conditions were obtained at an engine speed of 3126 rpm and 3% additive ratio by 2.356 W for brake power, 0.187857 g/W.hr for brake-specific fuel consumption and 38.3% brake thermal efficiency.
- The optimization results showed an acceptable error value at a slight deviation for the impression from actual and predicted data.
- The obtained regression models at a 95% level of confidence were found to be statistically significant.
- Based on the chosen significant level, ANOVA results show a significant influence of engine speed on the different obtained responses. On the other hand, the optimum response was achieved at a 3% additive ratio with insignificant influence for increasing the additive ratio in the fuel mix.
- Finally, good agreement is observed among the obtained experimental and predicted values within the range of MTBE addition adopted in this study. Accordingly, it's recommended to expand the study and increase the range of additives ratio for further understanding of the engine performance and to indicate the optimum operation conditions.

NOMENCLATURE

ANOVA	Analysis of Variance
MTBE	Methyl tert-butyl ether
RSM	Response Surface Methodology
BP	Brake power
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
HTO	Half throttle opening
CCD	Central composite design
Z	Coded level of independent variables
Zo	Real level of independent variables
Zc	Actual value at the central point
ΔZ	Step-change
Y	Calculated output variable
X	Independent variable
A	Engine Speed
B	Additive ratio

Greek symbols

ε	percentage of error
β_o	Constant.
β_i	Linear coefficient.
β_{ij}	Interactive coefficient.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Shankar S, Astagi HV, Hebbal O, Hotti SR. Effect of exhaust gas recirculation (EGR) on performance, emissions and combustion characteristics of a low heat rejection (LHR) diesel engine using pongamia biodiesel. J Therm Engineer 2016;2:1007−1016. [CrossRef]

[2] Karagöz Y. Emissions and performance characteristics of an SI engine with biogas fuel at different CO2 ratios. J Therm Engineer 2019;5:131−140. [CrossRef]

[3] Örs İ, Sayin B, Çiniviz M. An experimental study on the comparison of the methanol addition into gasoline with the addition of ethanol. Int J Automot Sci Technol 2020;4:59−69. [CrossRef]

[4] Rajak U, Nashine P, Verma TN. Comparative assessment of the emission characteristics of first, second and third generation biodiesels as fuel in a diesel engine. J Therm Engineer 2020;6:211−225. [CrossRef]

[5] Doori WHA, Ali OM, Ahmed AH, Koten H. Comparative study of biodiesel production from different waste oil sources for optimum operation conditions and better engine performance. J Therm Engineer 2022;8:457−465. [CrossRef]

[6] Antony AG, Rajaguru K, Dinesh S, Radhakrishnan K, Parameswaran P, Saravanan K. Analysis of compression ignition engine characteristics with addition of MTBE with diesel. Mater Today Proc 2020;37:1154−1157. [CrossRef]

[7] Yang Q, Shao S, Zhang Y, Hou H, Qin C, Sun D, et al. Comparative study on life cycle assessment of gasoline with methyl tertiary-butyl ether and ethanol as additives. Sci Total Environ 2020;724:138130. [CrossRef]

[8] Jeevanantham AK, Nanthagopal K, Ashok B, Al-Muhtaseb AH, Thiyagarajan S, Geo VE, et al. Impact of addition of two ether additives with high speed diesel-Calophyllum Inophyllum biodiesel blends on NOx reduction in CI engine. Energy 2019;185:39−54. [CrossRef]

[9] Johnson R, Pankow J, Bender D, Price CZ. Peer reviewed: MTBE-to what extent will past releases contaminate community water supply wells. Environ Sci Technol 2000;34:210A−217A. [CrossRef]

[10] Achten C, Kolb APW. Methyl tert-butyl ether (MTBE) in urban and rural precipitation in Germany. Atmos Environ 2001;35:6337−6345. [CrossRef]

[11] Da Silva R, Cataluña R, Menezes EWD, Samios D, Piatnicki CMS. Effect of additives on the antiknock properties and Reid vapor pressure of gasoline. Fuel 2005;84:951−959. [CrossRef]

[12] Sezer I, Bilgin A. Effects of methyl tert-butyl ether addition to base gasoline on the performance and CO emissions of a spark ignition engine. Energy Fuels 2008;22:1341−1348. [CrossRef]

[13] Douihit WH, Davis BC, Steinke EDL, Doherty HM. Performance features of 15% MTBE/gasoline blends. SAE Tech Pap 1988;881667. [CrossRef]

[14] Balki MK, Temur M, Erdoğan S, Sarıkaya M, Sayin C. The determination of the best operating parameters for a small SI engine fueled with methanol gasoline blends. Sustain Mater Technol 2021;30:e00340. [CrossRef]

[15] Hsieh WD, Chen RH, Wu TL, Lin TH. Engine performance and pollutant emission of an SI engine using ethanol-gasoline blended fuels. Atmos Environ 2002;36:403−410. [CrossRef]

[16] Porpatham E, Ramesh A, Nagalingam B. Investigation on the effect of concentration of methane in biogas when used as a fuel for a spark ignition engine. Fuel 2008;87:1651−1659. [CrossRef]

[17] Sheet EAE. Relative change in SI engine's emission and performance parameters using new locally made octane enhancer. Pet Res Stud 2017:1−24. [CrossRef]

[18] Alptekin E, Canakci M. Performance and emission characteristics of solketal-gasoline fuel blend in a vehicle with spark ignition engine. Appl Therm Engineer 2017;124:504−509. [CrossRef]

[19] Kolakoti A, Mosa PR, Kotaru TG, Mahapatro M. Optimization of biodiesel production from waste cooking sunflower oil by Taguchi and ANN techniques. J Therm Engineer 2020;6:712−723. [CrossRef]

[20] Joshi T, Parkash O, Krishan G. Estimation of energy consumption and transportation characteristics for slurry flow through a horizontal straight pipe using computational fluid dynamics. Phys Fluids 2023;35:53303. [CrossRef]

[21] Joshi T, Parkash O, Krishan G. CFD modeling for slurry flow through a horizontal pipe bend at different Prandtl number. Int J Hydrogen Energy 2022;47:23731−23750. [CrossRef]

[22] Joshi T, Parkash O, Krishan G, Murthy AA. Numerical investigation of bi-model slurry transportation through horizontal pipe bend. Powder Technol 2023;418:118284. [CrossRef]

[23] Abdalla AN, Tao H, Bagaber SA, Ali OM, Kamil M, Ma X, et al. Prediction of emissions and performance of a gasoline engine running with fusel oil-gasoline blends using response surface methodology. Fuel 2019;253:1−14. [CrossRef]

[24] Safieddin Ardebili SM, Solmaz H, Mostafaei M. Optimization of fusel oil-gasoline blend ratio to enhance the performance and reduce emissions. Appl Therm Engineer 2019;148:1334−1345. [CrossRef]

[25] Abdalla AN, Ali OM, Awad OI, Tao H. Wavelet analysis of an SI engine cycle-to-cycle variations fuelled with the blending of gasoline-fusel oil at a various water content. Energy Conver Manage 2019;183:746−752. [CrossRef]

[26] Awad OI, Ali OM, Hammid AT, Mamat R. Impact of fusel oil moisture reduction on the fuel properties and combustion characteristics of SI engine fueled with gasoline-fusel oil blends. Renew Energy 2018;123:79−91. [CrossRef]

[27] Saxena V, Kumar N, Saxena VK. Multi-objective optimization of modified nanofluid fuel blends at different TiO2 nanoparticle concentration in diesel engine: Experimental assessment and modeling. Appl Energy 2019;248:330−353. [CrossRef]

[28] Awad OI, Mamat R, Ali OM, Sidik NAC, Yusaf T, Kadirgama K, et al. Alcohol and ether as alternative fuels in spark ignition engine: A review. Renew Sustain Energy Rev 2018;82:2586−2605. [CrossRef]

[29] Safieddin Ardebili SM, Solmaz H, İpci D, Calam A, Mostafaei M. A review on higher alcohol of fusel oil as a renewable fuel for internal combustion engines: Applications, challenges, and global potential. Fuel 2020;279:118516. [CrossRef]

[30] Yusri IM, Abdul Majeed APP, Mamat R, Ghazali MF, Awad OI, Azmi WH. A review on the application of response surface method and artificial neural network in engine performance and exhaust emissions characteristics in alternative fuel. Renew Sustain Energy Rev 2018;90:665−686. [CrossRef]

[31] Mehmood T, Ahmed A, Ahmad A, Ahmad MS, Sandhu MA. Optimization of mixed surfactants-based β-carotene nanoemulsions using response surface methodology: An ultrasonic homogenization approach. Food Chem 2018;253:179−184. [CrossRef]

[32] Kunduru SR, Venkata HRY, Vallapudi D, Deenadayalan N, Kumaravel AR. Prediction of recital characteristics of a CI diesel engine operated by bio-fuel extracts from cotton seed oil, linseed oil and mahua seed oil using ANN method. J Therm Engineer 2023;9:366−376. [CrossRef]

[33] Safieddin Ardebili SM, Solmaz H, Calam A, İpci D. Modelling of performance, emission, and combustion of an HCCI engine fueled with fusel oil-diethylether fuel blends as a renewable fuel. Fuel 2021;290:120017. [CrossRef]

[34] Solmaz H, Ardebili SMS, Calam A, Yılmaz E, İpci D. Prediction of performance and exhaust emissions of a CI engine fueled with multi-wall carbon nanotube doped biodiesel-diesel blends using response surface method. Energy 2021;227:120518. [CrossRef]

[35] Yaman H, Yesilyurt MK. The influence of n-pentanol blending with gasoline on performance, combustion, and emission behaviors of an SI engine. Engineer Sci Technol Int J 2021;24:1329−1346. [CrossRef]

[36] Monroe E, Shinde S, Carlson JS, Eckles TP, Liu F, Varman AM, et al. Superior performance biodiesel from biomass-derived fusel alcohols and low grade oils: Fatty acid fusel esters (FAFE). Fuel 2020;268:117408. [CrossRef]

[37] Ağbulut Ü, Yeşilyurt MK, Sarıdemir S. Wastes to energy: Improving the poor properties of waste tire pyrolysis oil with waste cooking oil methyl ester and waste fusel alcohol-A detailed assessment on the combustion, emission, and performance characteristics of a CI engine. Energy 2021;222:119942. [CrossRef]

[38] Simsek S, Uslu S. Experimental study of the performance and emissions characteristics of fusel oil/gasoline blends in spark ignited engine using response surface methodology. Fuel 2020;277:118182. [CrossRef]

[39] Awad OI, Mamat R, Ali OM, Azmi WH, Kadirgama K, Yusri IM, et al. Response surface methodology (RSM) based multi-objective optimization of fusel oil-gasoline blends at different water content in SI engine. Energy Conver Manage 2017;150:222−241. [CrossRef]