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Improving the Running Conditions of Diesel Engine with Grape Seed Oil Additives by Response Surface Design

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Abstract

In this study, an optimization study was carried out by using Response Surface Methodology (RSM) to determine the optimum conditions by improving the working conditions in a single cylinder diesel engine using fuel blends created by mixing the biodiesel obtained from grape seed oil (GSO) to diesel in different proportions (5%, 10% and 15% by vol.). Experiments were carried out with three different fuel mixtures with three different injection pressures (200, 225 and 250 bar) at three different engine loads (400, 1000 and 1600-Watt). Since the minimum number of experiments proposed by the RSM application is 20 for optimization according to three different factors and three different levels of each factor, an RSM model was created from the experiment data obtained by performing 20 trials. While the GSO ratio, the injection pressure and engine load was determined as input factors, brake specific fuel consumption (BSFC), exhaust gas temperature (EGT), carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_x) and smoke were chosen as responses on the RSM model. Considering the findings taken from the RSM model, the working conditions in which the best output can be obtained from the engine; it has been determined as 13% GSO percentage, 245 bar injection pressure and 850-W engine load. The study to verify the results obtained from the optimization study reveals that the results were obtained with an error of less than 9%.

Keywords: Response surface, Optimization approach, Grape seed oil, Diesel engine

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1. Introduction

Diesel engines are widely used in large sectors of the global economy, such as industry, transportation, and agriculture, due to their high efficiency [1–3]. Despite the high efficiency of diesel engines, their emissions, especially NO_x and smoke emissions, have many negative effects on human health and the environment [4,5]. On the other hand, petroleum-based fuel reserves are running out rapidly due to the increase in world population and increasing energy demand in parallel with the development of the industry [6–9]. Studies on diesel engines are carried out for simultaneous reduction of fuel consumption and emissions due to both the depletion of fossil fuel reserves and high emission levels [10]. In this context, environmentally friendly renewable fuel research has accelerated in recent years and biofuels have emerged as an important alternative to fossil fuels [11–13]. Biodiesel is one step ahead in biofuels due to its advantage of being produced from many different substances [14–16]. There are various biodiesel raw materials such as fish oil, frying oil, and also oils of animal origin, as well as various vegetable origin substances, from soybeans to sunflower, canola to cotton seed oil [17–19]. In this study, GSO, which is in the category of biodiesel species of vegetable origin, was used. There are a limited number of studies in the literature about the use of GSO as fuel in diesel engines, and these studies are mostly done in marine engines or related to the production of GSO [20–22]. Azad and Rasul [23] examined the effects of using GSO and waste cooking oil as fuel in a four-cylinder, four-stroke diesel engine and compared two biodiesel results. According to their results, they stated that GSO gives better results in terms of both emission and performance. Vedagiri et al. [24] investigated the performance, combustion and emission parameters of a diesel engine powered by GSO biodiesel. In addition to GSO, they added nanocerium oxide and zinc oxide solids. They stated that by adding cerium oxide and zinc oxide emulsion mixtures, they achieved a significant decrease in NO_x emission and that GSO is an effective alternative fuel for diesel engines without any engine changes.

The search for alternative fuel brought an increase in the number of experiments accompanied. Experiment is needed to measure the suitability of a new type of fuel for use in internal combustion engines. For this reason, both the number of experiments, the time spent, and the costs of the experiment have increased considerably in recent years [25,26]. To prevent this, in other words, to reduce the number of experiments, computer applications have been developed that can simulate many more experiments using a certain number of experiment data. Among these applications, RSM stands out due to its ability to optimize in a shorter time as it creates the most suitable matrix for tests, unlike other applications [6,27]. There are many studies in recent years where diesel engines have been optimized with RSM using different alternative fuels [28–31].

Although there are a few studies evaluating the usability of GSO as a fuel in a diesel engine, an optimization study about diesel engine using GSO as a fuel has not been found in the literature. For this reason, in this study, an optimization study of a diesel engine was made using RSM, where GSO ratio, injection pressure and load were selected as the input variable.

2. Material and method

In this study, which is done to improve the engine conditions and determine the best conditions, the experimental data required for the creation of the RSM model was obtained using the experimental setup shown schematically in Fig. 1. In the tests, the exhaust gas temperature values were measured with the type J (Fe-Const), TMX-B12F08 brand thermocouple, which can measure between -200 °C and 800 °C. Fuel consumption was mass-measured with the Weightlab brand WH-2002 model, which can measure 0.01 g precision. The resistive load set with control panel used in the loading of the test engine and seen in Figure 1 is composed of General brand 200 W and 1000 W halogen bulbs and switches. The Bilsa brand MOD 2210 model exhaust gas emission device used for the measurement of exhaust emissions can perform CO, HC, NO_x, air fuel ratio, lambda and smoke darkness measurements according to the principles specified in the TS 11365 / T1 standard. Technical characteristics of the engine/generator and exhaust emission device used in the experiments are shown in Table 1 and Table 2, respectively.

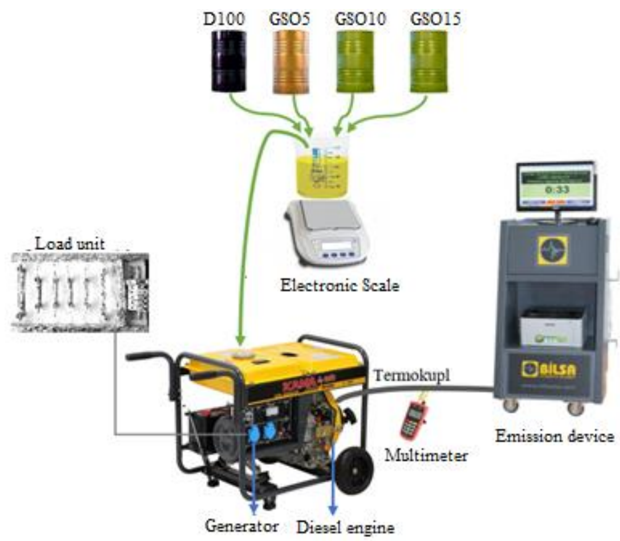

Fig. 1. Schematic view of experimental setup

Table 1. Factors and their levels.

Diesel engine	
Brand	Katana
Model	Km 178 F
Number of cycles	4
Number of cylinders	1
Stroke	62 mm
Bore	78 mm
Cylinder volume	296 cm^3
Maximum output power	6.7 hp
Continuous output power	6 hp
Compression ratio	18:1
Engine speed	3000 d/d
Fuel injection system	Direct injection
Injection timing	20° KMA
Injector nozzle number	4
Intake system	Naturally aspirated
Injection pressure	200 bar
Cooling system	Air-cooled
Generator	
Brand	Kama
Model	KDL3500CE
Power	2.7 kW
Maximum power	3 kW
Frequency	50 Hz
Current	11.6 A
Phase	1
Voltage	230 V

Table 2. Technical characteristics of the emission device

Parameter	Unit	Range	Accuracy
CO	%	0-10	0.001
CO_2	%	0-19.99	0.001
HC	ppm	0-10000	1
O_2	%	0-25	0.01
NO_X	ppm	0-5000	1
Lambda	-	0-5000	0.001
Air/fuel ratio	-	5-30	-
Smoke opacity	%	0-100	0.1
Operating temperature	°C	0-40	%0.01
Sensing time	s	<5	-
Feed voltage	V AC	220	-
Feed frequency	Hz	50	-

In the experiments, GSO5 (5% GSO + 95% diesel), GSO10 (10% GSO + 90% diesel) and GSO15 (15% GSO + 85% diesel) were used as fuel, which were obtained by adding GSO to the diesel in three different proportions. These three test fuels were tested at different injection pressure values (200, 225 and 250 bar) and at different engine loads (400, 1000 and 1600-W). Properties of test fuels are shown in Table 3.

Table 3. Properties of test fuels

Properties	Diesel	Grapeseed oil
Density at 15°C (kg/m^3)	835	910-922.17
Kinematic viscosity at 40°C (mm^2/s)	2.85	26.42-37.32
Cetane index (-)	46	48
Lower heating value (MJ/kg)	42.6	36.54
Flash point (°C)	53	250.7
Water content (ppm)	<10	390.8-1168
Acid value (mg KOH/g)	-	2.1
Iodine value (g I_2/100 g)	-	72-136
Free fatty acid content (%)	-	0.6
Cloud point (°C)	-10	-7
Pour point (°C)	-34	-4

RSM model was created with the data obtained from the experimental study. RSM is one of the primary optimization applications that can be used to minimize money and time spent in academic and commercial tests. It can both derive a basic equation for the parameters to be optimized using a minimum number of experimental data and present it with 3D graphics. In addition, it is an application that can determine the effect of working parameters on outputs with the analysis of variance (ANOVA) and Pareto charts. RSM optimization is based on the equations given below;

The basic model based on a first-degree polynomial available in RSM;

$$y = \beta_0 + \sum_{i}^{k} \beta_i x_i + \varepsilon \qquad (1)$$

If the model is second-order;

$$y = \beta_0 + \sum_{i}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j \geq i}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad (2)$$

Where Ɛ is random test error, k is the number of factors, y is the predicted response, x_i and x_j are independent factors [32] (Simsek and Uslu, 2020). β_0 is the constant, β_i is the linear coefficient and β_{ij} interactive coefficient, i and j are the linear and quadratic coefficient, respectively.

The correlation coefficient (R^2) is assigned as per Eq. (3), the adjusted correlation coefficient (Adj. R^2) is assigned using Eq. (4), the predicted correlation coefficient (Pred. R^2) is assigned using Eqs. (5) with Eqs. (6) and (7) [6] (Uslu, 2020);

$$R^2 = 1 - \left[\frac{SS_{residual}}{SS_{residual} + SS_{model}}\right] \qquad (3)$$

$$Adj.\ R^2 = 1 - \left[\left(\frac{SS_{residual}}{df_{residual}}\right) \Big/ \left(\frac{SS_{residual} + SS_{model}}{df_{residual} + df_{model}}\right)\right] \qquad (4)$$

$$Pred.\ R^2 = 1 - \left[\frac{PRESS}{SS_{residual} + SS_{model}}\right] \qquad (5)$$

$$PRESS = \sum_{i=1}^{n} (e-1)^2 \qquad (6)$$

$$e - 1 = \frac{e_i}{1 - h_{ii}} \qquad (7)$$

In this optimization study, the input factors to be optimized are selected as the GSO ratio, the injection pressure and the engine load, while the outputs to achieve the best values are selected as BSFC, EGT, CO, HC, NO_x and smoke. Factors selected for input are shown in Table 4, along with their levels.

Table 4. Input variables with levels.

Variables	Levels		
GSO ratio (% vol.)	5	10	15
Injection pressure (bar)	200	225	250
Engine load (watt)	400	1000	1600

3. Results and Discussion

The R^2 is an evidence of how the test data fit with the models. The R^2 of BSFC, EGT, HC, CO, NO_x, and smoke are 99.67%, 90.17%, 94.93%, 94.88%, 91.22% and 90.07%, respectively which are supplying high-level accurate results of the model compared the experimental outcomes. Each response has R^2 bigger than 90%.

Second order equations duplicate by regards to the operating variables to estimate the responses of BSFC, EGT, HC, CO, NO_x and smoke are performed by equations (8), (9), (10), (11), (12) and (13), respectively.

$$\mathbf{BSFC} = 338 + 13.8\,\mathbf{GSO} + 10.83\,\mathbf{IP} - 1.556\,\mathbf{L} + 0.057\,\mathbf{GSO * GSO} - 0.0227\,\mathbf{IP * IP} + 0.000546\,\mathbf{L * L} - 0.0391\,\mathbf{GSO * IP} - 0.00467\,\mathbf{GSO * L} - 0.000188\,\mathbf{IP * L} \tag{8}$$

$$\mathbf{EGT} = 2114 + 0.24\,\mathbf{GSO} - 18.21\,\mathbf{IP} + 0.0584\,\mathbf{L} + 0.142\,\mathbf{GSO * GSO} + 0.04091\,\mathbf{IP * IP} - 0.000006\,\mathbf{L * L} - 0.0117\,\mathbf{GSO * IP} - 0.00087\,\mathbf{GSO * L} - 0.000022\,\mathbf{IP * L} \tag{9}$$

$$\mathbf{HC} = -167 + 3.78\,\mathbf{GSO} + 1.518\,\mathbf{IP} + 0.0059\,\mathbf{L} + 0.0163\,\mathbf{GSO * GSO} - 0.00319\,\mathbf{IP * IP} - 0.000004\,\mathbf{L * L} - 0.01873\,\mathbf{GSO * IP} + 0.000050\,\mathbf{GSO * L} - 0.000011\,\mathbf{IP * L} \tag{10}$$

$$\mathbf{CO} = -2.171 + 0.0407\,\mathbf{GSO} + 0.01827\,\mathbf{IP} + 0.000189\,\mathbf{L} + 0.000018\,\mathbf{GSO * GSO} - 0.000037\,\mathbf{IP * IP} - 0.000179\,\mathbf{GSO * IP} - 0.000002\,\mathbf{GSO * L} - 0.000001\,\mathbf{IP * L} \tag{11}$$

$$\mathbf{NO_x} = -1759 + 17.9\,\mathbf{GSO} + 16.4\,\mathbf{IP} - 0.102\,\mathbf{L} - 0.240\,\mathbf{GSO * GSO} - 0.0367\,\mathbf{IP * IP} + 0.000011\,\mathbf{L * L} - 0.0697\,\mathbf{GSO * IP} - 0.00048\,\mathbf{GSO * L} + 0.000352\,\mathbf{IP * L} \tag{12}$$

$$\mathbf{Smoke} = 693 - 13.96\,\mathbf{GSO} - 4.98\,\mathbf{IP} - 0.0407\,\mathbf{L} - 0.017\,\mathbf{GSO * GSO} + 0.00887\,\mathbf{IP * IP} - 0.000004\,\mathbf{L * L} + 0.0559\,\mathbf{GSO * IP} + 0.000971\,\mathbf{GSO * L} + 0.000155\,\mathbf{IP * L} \tag{13}$$

Where GSO, IP and L characterize GSO percentage, injection pressure and engine load, respectively.

Fig. 2 shows the effects of the selected variables on BSFC and EGT simultaneously. It is desirable that BSFC and EGT are at low levels. Looking at 3D graphics, the increase in GSO rate caused BSFC to increase. Considering

Table 3, where the fuel properties are shown, the lower heating value of the diesel is 42.6 MJ / kg, while the GSO is 36.54 MJ / kg. Therefore, as the amount of GSO increases in the fuel mixture, the lower thermal value of the mixture will decrease. In order to obtain the equal outlet power from the engine, it is essential to utilize more fuel with low thermal value. Therefore, BSFC increased with the use of GSO. On the other hand, if the BSFC change is examined according to the load variation, it is clearly understood from the graph that BSFC decreases as the load increases. It is a known fact that as the load increases, the temperature inside the cylinder increases. Along with the increased in-cylinder temperature, the combustion temperature also rises, and as a result, the exact combustion rate increases. This situation reduces BSFC. The injection pressure changes increased BSFC up to 225 bar and after 225 bar, BSFC tended to decrease again. Since the viscosity of GSO is very high, incomplete combustion occurred at low pressures and BSFC increased. BSFC is thought to decrease as the rate of incomplete combustion decreases with increasing pressure.

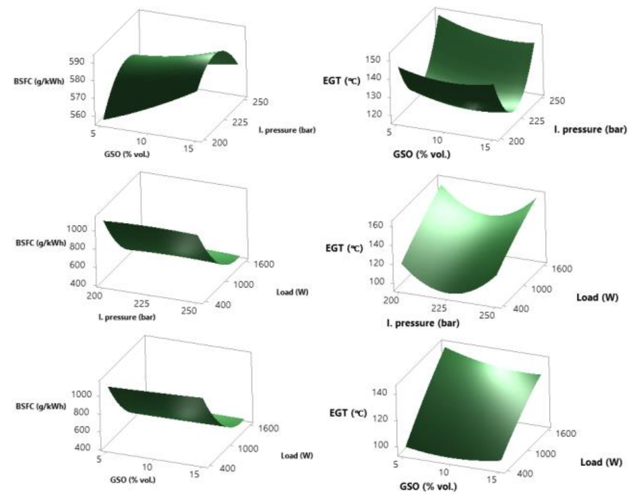

Fig. 2. Simultaneous effects of engine variables on BSFC and EGT

Simultaneous effects of engine variables on CO and HC emissions are demonstrated in Fig. 3. The main factor triggering both CO emission and HC emission formation is incomplete combustion. All factors that increase incomplete combustion also cause CO and HC to increase. It was mentioned in the explanation of an upper graph that the rate of complete burning increases with increasing engine load. Consequently, as the engine load increases, CO and HC emissions must decrease, and the graph has given supporting results. On the other hand, CO and HC emissions have increased as the incomplete combustion has increased with the increase of GSO, whose kinematic viscosity is quite high compared to diesel. Since the spraying difficulty caused by the effect of high viscosity is relatively resolved at high injection pressure values, CO and HC emissions decrease as the pressure increases.

Changes in smoke and NO_x depending on engine variables are shown in Fig. 4. NO_x is a type of emission that occurs mostly due to high temperatures and oxygen excess. Consequently, it increased with the increasing load of the engine, which increased the temperature inside the cylinder, and decreased with increasing GSO due to the cooling effect of GSO. Similarly, smoke emission increased with increasing engine load and decreasing with increasing GSO rate. The injection pressure value with the highest smoke and NO_x emission was determined as 225 bar. Emissions decreased as the rate of complete combustion reaction increased at higher pressures.

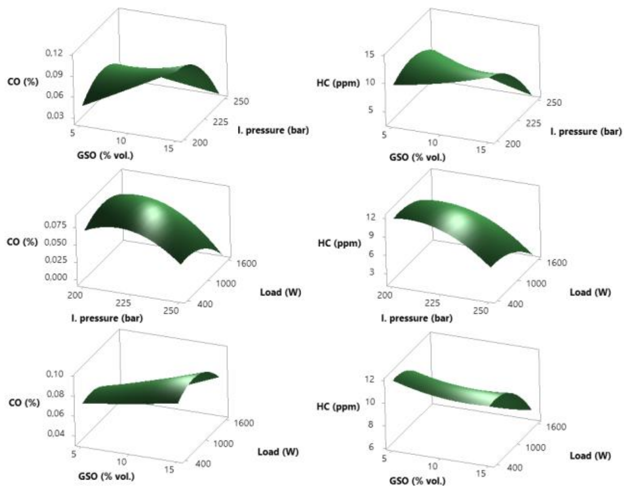

Fig. 3. Simultaneous effects of engine variables on CO and HC

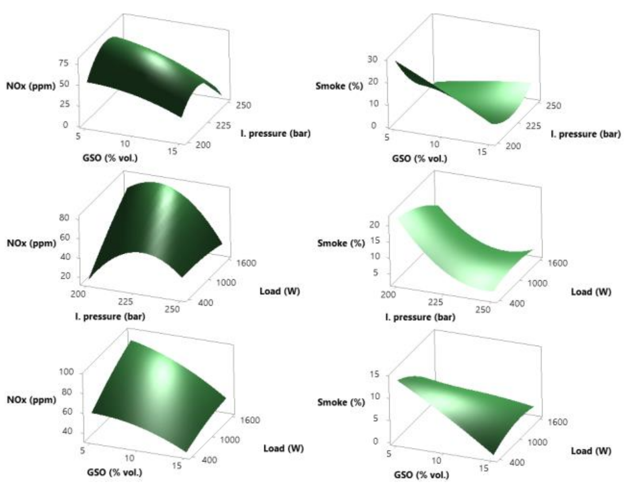

Fig. 4. Simultaneous effects of engine variables on Smoke and NO_x emissions

3.1. Optimization and Validation

The main purpose of this study is to optimize the selected input variables and the responses arising from these variables. Accordingly, the criteria of the optimization study are shown in Table 5. All the responses that are required to be minimum in internal combustion engine processes. Therefore, it was chosen to minimize all responses as optimization criteria.

Results obtained from the optimization study based on the selected criteria are shown in Fig. 5. Considering the findings taken from the RSM model, the working conditions in which the best responses can be obtained from the engine; it has been determined as 13% GSO percentage, 245 bar injection pressure and 850-W load. According to the optimum working conditions obtained, the responses are 675.82 g/kWh, 130.32 ℃, 25.732 ppm, 5.245%, 3.542 ppm and 0.023% for BSFC, EGT, NO_x, smoke, HC, and CO, respectively.

Table 5. Optimization principles

Name	Goal	Lower	Upper	Importance
GSO ratio	In range	5	15	1
Injection pressure	In range	200	250	1
Load	In range	400	1600	1
BSFC (g/kWh)	Minimize			1
EGT (°C)	Minimize			1
CO (%)	Minimize			1
HC (ppm)	Minimize			1
NO_x (ppm)	Minimize			1
Smoke (%)	Minimize			1

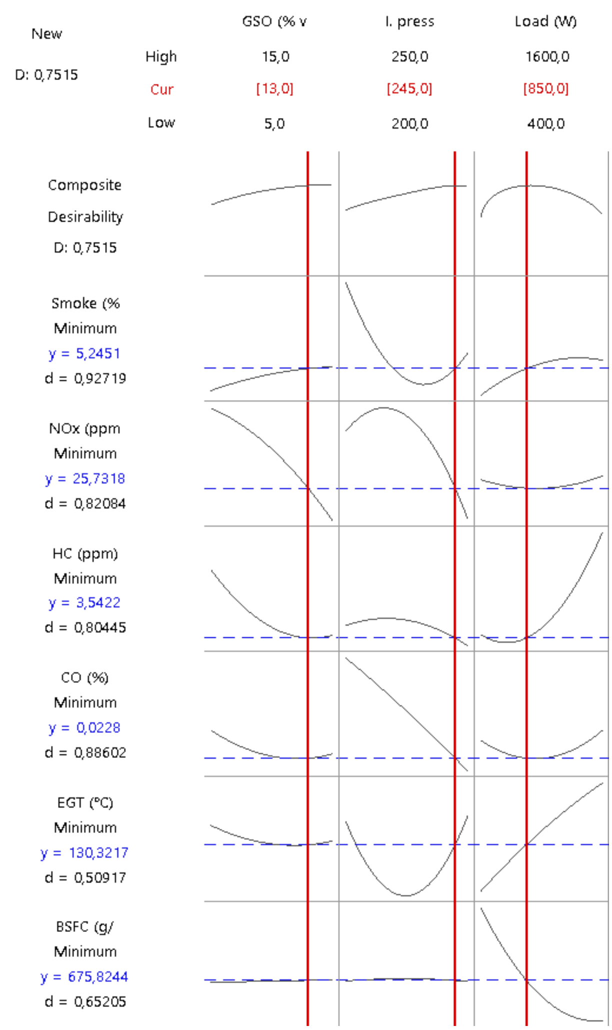

Fig. 5. Optimized results

It is extremely important to determine how closely the optimized results and the experimental results converge. Because one of the leading goals in the optimization study is to reduce the number of tests. While reducing the number of tests, it is an important criterion not to get away from the experimental results.

A verification study was carried out to compare the optimization results and the test results. For the verification study, an experimental study was performed with the optimum working conditions obtained from RSM optimizer. The results were compared as shown in Table 6. The scale in comparison is the magnitude of the error rate. Looking at the error rates, they are all lower than 9%. The lowest error rate was obtained in EGT with 3.44%, while the highest error occurred in HC with 8.71%. When the literature information is examined, it is understood that error rates less than 9% are at acceptable levels.

Table 6. Verification evaluations for optimized and experimental results with % error.

GSO Ratio (%)	I. Pressure (bar)	Load (watt)	
13	245	850	
	Optimized	**Test**	**Error (%)**
BSFC (g/kWh)	675.82	705.4	4.37
EGT (°C)	130.32	134.8	3.44
CO (%)	0.023	0.037	7.83
HC (ppm)	3.542	4.94	8.71
NO_x (ppm)	25.732	22.51	8.63
Smoke (%)	5.245	4.365	7.25

4. Conclusions

In this study, RSM model has been developed for the improvement of a GSO doped diesel engine operating at different injection pressures and different loads. The following conclusions have been obtained;

- ✓ Optimum engine variables were determined as 13% GSO percentage, 245 bar injection pressure and 850-W load with RSM optimization.
- ✓ Responses obtained based on optimum working conditions for BSFC, EGT, NO_x, smoke, HC, and CO are 675.82 g/kWh, 130.32 ℃, 25.732 ppm, 5.245%, 3.542 ppm and 0.023%, respectively.
- ✓ The error rates between the optimum responses and experimental responses are less than 9%. The lowest error rate was obtained in EGT with 3.44%, while the highest error occurred in HC with 8.71%.
- ✓ The magnitude of R^2 values, which is an indicator of the significance of the results in statistical studies, was found as 99.67%, 90.17%, 94.93%, 94.88%, 91.22% and 90.07% for BSFC, EGT, HC, CO, NO_x, and smoke, respectively. Each response has R^2 values bigger than 90%.

According to the results of the study, it is understood that a diesel engine with a GSO contribution will be successfully optimized with RSM according to the level change of different variables.

Nomenclature

ANOVA	Analysis of variance
β_i	linear coefficient
β_{ij}	interactive coefficient
β_0	constant
BSFC	Brake specific fuel consumption
CO	Carbon monoxide
ε	random test error
EGT	Exhaust gas temperature
GSO	Grape seed oil
GSO5	5% grape seed oil + 95% diesel
GSO10	10% grape seed oil + 90% diesel
GSO15	15% grape seed oil + 85% diesel
HC	Hydrocarbon
i	Linear coefficient
j	Quadratic coefficient
k	Number of factors
NO_x	Nitrogen oxides
R^2	Correlation coefficient
Adj. R^2	Adjusted correlation coefficient
Pred. R^2	Predicted correlation coefficient
RSM	Response surface methodology
x_i, x_j	Independent factors
y	Predicted response

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