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# OPTIMIZATION STUDY OF FUEL BLENDS IN AN SI ENGINE RUNNING WITH GASOLINE/ISOPROPANOL/ISOAMYL ALCOHOL BLENDS

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## ABSTRACT

In this study, was focused on determining the optimum alcohol mixtures of gasoline iso-propanol and isoamyl alcohol mixtures according to minimum exhaust emission and BSFC (Brake Specific Fuel Consumption) and maximum CGP (Cylinder Gas Pressure) parameters. In the optimization study, 3 different iso-propanol (vol. 10, 20 and 30) and 3 different iso-amyl (vol. 5, 10 and 20) rate were used as input parameters at maximum power and torque speed. The experimental study, it was performed in a single-cylinder air-cooled, spark-ignition engine (SI), at full throttle position, maximum power speed (3600 $min^{-1}$) and maximum torque speed (2400 $min^{-1}$). In the optimization study, ANOVA supported RSM (Response Surface Methodology) and CCD (Central Composite Design) were used as the experimental design. In the results obtained, it was determined as an effective parameter for BSFC of engine speed, and for CGP were effective also alcohol types along with engine speed. As a result of the optimization, as the optimum operating parameters were determined as 3600 $min^{-1}$ engine speed, 27.7778% iso-propanol and 13.9394% iso-amyl alcohol. In the confirmation tests, the error rates were obtained as 3.36%, 3.45%, 9.81%, 4.76% and 4.67% for BSFC, CGP, HC, CO and $NO_X$, respectively.

# 1 INTRODUCTION

Exhaust emissions from road vehicles are one of the leading causes of air pollution in both developing and developed countries. Emissions from road vehicles account for approximately 50% of total pollution [1,2]. Incomplete combustion of gasoline in ICE (Internal Combustion Engine) increases CO and HC emission levels. However, at high operating temperatures, excess oxygen causes NOX emissions to increase [3]. The catalytic converter used in the exhaust system reduces the pollution rate. However, these systems used cause an increase in fuel consumption by about 15% [4]. For this reason, in many studies, it is seen that researchers are trying to exploration cleaner alternative fuels [5-7]. In these exploration efforts, biofuels have been a serious research topic. Alcohol-based fuels are accepted as one of the renewable solutions with almost zero $CO_2$ potential through efficiently conversion of biomass [8]. The higher-octane number, higher oxygen content and single boiling point of alcohols make it possible to use them in spark ignition engines. Besides, as an additive, alcohols can be a good solution to improve fuel properties. Due to the high research octane number (RON) and engine octane number (MON), the octane number increases rapidly when oxygenated fuels are mixed with gasoline [9-10]. Mourad and Mahmoud [11] investigated the performance and exhaust emissions of a spark ignition engine using gasoline-propanol fuel mixtures. In their results, they reported that fuel economy increased by approximately 2.84%, and there was an improvement over 10% in exhaust emissions, especially in HC and CO emissions. Similarly, Kaisan et al.,[12] stated in their study that as the alcohol percentage in gasoline-propanol-camphor mixtures increased, engine performance increased and exhaust emissions decreased. In addition, Uslu and Celik [13] investigated the effect on performance and exhaust emissions of engine of isoamyl alcohol addition at 3 different rates (10%, 20% and 30%) to gasoline. In their results, they stated that there were significant improvements in the exhaust emissions of the fuel mixture with 30% isoamyl alcohol added, compared to the use of gasoline at all compression ratios. In the engine performance, they stated that with the increase of the compression ratio, the engine torque and power increased with the fuel mixture added with 20% isoamyl alcohol.

In order to improve the performance and emission characteristics of internal combustion engines, different optimization methods have been used to optimize operating conditions such as ignition timing, injection timing, speed, load, compression ratio, air-fuel ratio, especially with alternative fuel [14-17]. In general, the technical approach of the studies done in the literature is to use the optimized mixture in a spark ignition engine without modification as well as increase performance and reduce emissions. Response Surface Methodology (RSM) is a good method for performing this experimental design. RSM is a widely used technique to solve many industrial problems. It is one of the practical and economical solutions to evaluate single and combined factors of experimental variables [18]. The main advantage of the method requires less testing, and less time is spent compared to a real experimental study. This approach is widely used and has been applied in much research. Uslu and Celik [17] experimentally investigated the effects engine performance and emissions of use isoamyl alcohol/gasoline fuel mixture in a spark ignition engine (SI). In addition, the obtained results were estimated with Artificial Neural Network (ANN) and optimized with Response Surface Methodology (RSM). In the RSM results, they stated that 15% isoamyl alcohol ratio at 8.31 CR (Compression Ratio) and 2957.58 rpm engine speed are the optimum engine operating parameters. In their results, they reported that the RSM supported ANN model is an effective method for estimating and optimizing engine outputs with minimum testing. In a study by Adebili et al., [20] were used RSM for the optimization of gasoline/fuseoil mixtures. In the optimization results, they founded that as 47.21% engine load and 25% fuse oil of the optimum operating parameters. They stated that the confirmation tests were performed successfully, and all the results were significant at the 5% level. However, a high desirability value of 0.63 for the regression model reported that RSM could be used efficiently for modelling and optimization of engine operating parameters. When the studies in the literature examined, it is seen that the effects of gasoline/propanol and gasoline/isoamyl alcohol mixtures on engine performance and exhaust emissions were examined. However, there are not many studies on triple fuel mixtures such as gasoline/propanol/isoamyl. Also, the ability to optimize the input-response factors of gasoline/isopropanol/isoamyl alcohol fuel blends in SI engines with a statistical approach (RSM) has not yet been investigated. This study is focused to the optimization of input parameters based on the response factors of fuel mixtures comprising gasoline, isopropanol, and isoamyl alcohol for use in a gasoline engine. The aim of this research is to address and contribute to the existing gap in the literature on this subject.

# 2 MATERIALS AND METHOD

## 2.1 Test Fuel

In the study, iso-propanol was added to the gasoline at 3 different rates (10%, 20% and 30% vol.). Different fuel combinations were created by adding alcohol in 3 different ratios (5%, 10% and 20% vol.) to this prepared gasoline/iso-propanol fuel mixture. Fuel properties of gasoline and alcohols used in the study were given in Table 1.

***Table 1**. Properties of Fuels.*

| Properties | Gasoline | Iso-propanol | Iso-amyl |
|---|---|---|---|
| **Chemical Formula** | $C_8H_{18}$ | $C_3H_8O$ | $C_5H_{12}O$ |
| **Molecular weight (kg/kmol)** | 114.18 | 60.10 | 88.1 |
| **Lower Heating Value (Mj/kg)** | 44.0 | 32.940 | 35.370 |
| **Stoichiometric air/fuel ratio** | 14.6 | 10.28 | 11.76 |
| **Heat of evaporation (kj/kg)** | 225 | 761 | 621 |
| **Research octane number** | 95 | 112.5 | 113 |
| **Engine octane number** | 85 | --- | 84 |
| **Density** | 720-775 | 785 | 801.4 |

## 2.2 Experimental Procedure

In the experiments was used Single-cylinder, spark-ignition, air-cooled (ATIMAX AG 210 E) engine. Before starting the tests, the carburetor was adjusted using the exhaust emission data specified in the catalogue values. In all test conditions, the excess air coefficient was adjusted (HFK - $\lambda$=1) using a conical-tipped adjusting screw. The adjustment process was repeated for all fuel types used. Experiments were started when the engine reaches operating temperature. Measurements were made at maximum torque and power speeds in the experiments. In-cylinder pressure measurement was made with the help of Piezoresistive high pressure sensor and oscilloscope. The technical features of the engine used in the experiments are given in Table 2. The engine performance test stand is shown schematically in Figure 1. In the test system, an electric dynamometer is used with

26 kW power, 80 Nm torque and a speed of max 5000 rpm. In the test system, fuel consumption, engine torque and engine power data were instantly recorded digitally with the interface program used.

***Table 2***. *Features of the test engine.*

| Model | Atimax 210 E |
|---|---|
| **Engine Type** | Four Stroke, Single Cylinder |
| **Engine Volume ($cm^3$)** | 196 |
| **Compression Ratio** | 8.5/1 |
| **Maximum Speed (rpm)** | 4200 |
| **Ignition System Type** | Transistorized Coil |
| **Fuel System** | Carburetor |
| **Cooling System** | Air Cooled |

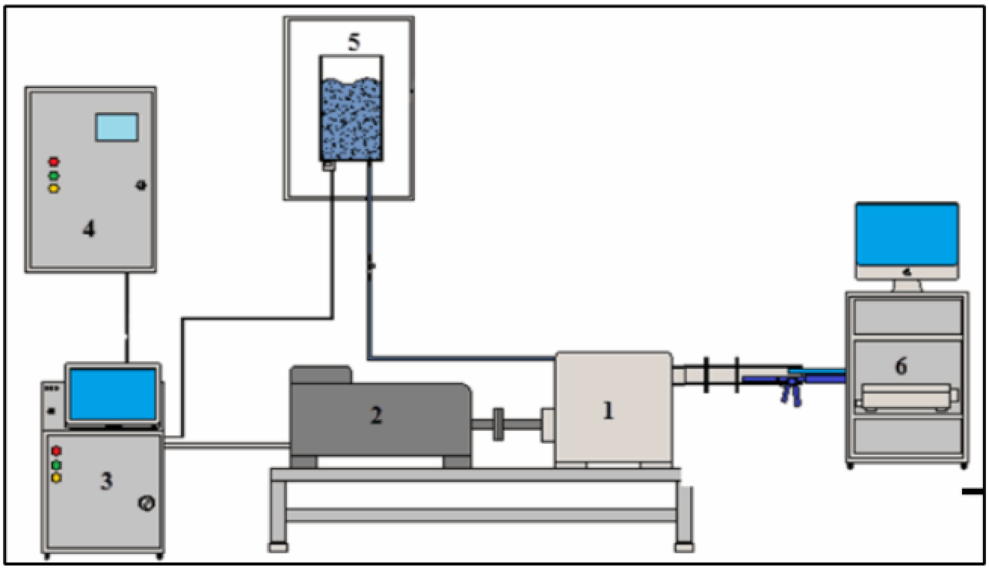


***Figure 1***. *Engine test setup.*

Emission measurements were measured at specified (max torque and max power) engine speeds. Mobydic-5000 gas analyzer was used for emission measurements. The technical features of the emission device used were given in Table 3.

***Table 3***. *Features of the exhaust gas analyser.*

| MOBYDIC 5000 GAS ANALYSIS DEVICE | |
|---|---|
| **CO % Vol.** | 0 - 10 |
| **$CO_2$ % Vol.** | 0 - 20 |
| **HC ppm** | 0 - 20000 |
| **$O_2$ % Vol.** | 0 - 21 |
| **$NO_X$ ppm** | 0 - 5000 |
| **Lambda** | - 5 |

## 2.3 Response Surface Methodology

Response Surface Methodology (RSM), which has achieved successful results in applications in many different fields, is a computer-based application. This application is widely used for modelling and optimization of the performance and emissions of internal combustion engines [21-23]. RSM establishes a relationship between input and output parameters. It optimizes the responses according to the input factors, according to the relationship between the input and output parameters. For this purpose, RSM uses the least squares technique. According to the RSM, each of the motor input parameters is assumed to be computable and can be expressed by the following equation: [23]

$$y = f(X_1, X_2, \ldots, X_n) \quad \textbf{(1)}$$

Here; $X_1$, $X_2 \ldots X_n$ the input parameters, respectively, and y is the output parameter. The first step in RSM consists of the field or independent variables of the process and empirical statistical modelling in order to develop empirical relationships for estimation and optimization, and to develop an appropriate approximation relationship between response and process variables. A quadratic equation model is applied for this relationship as shown below.

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

Here, i is the linear coefficient, j is the quadratic coefficient, ß is the regression coefficient, k is the number of parameters, and ε is the error discovered in the response. In this study, Central Composite Design (CCD), which gives relatively more precise results compared to other experimental designs, has been applied. Input variables were selected as engine speed (ES), Fuel type 1 (Iso-propanol) and Fuel type 2 (Iso-amyl alcohol). Input variables and levels were given in Table 4. As the output parameters of the model, Brake Specific Fuel Consumption (BSFC), Cylinder Gas Pressure (CGP), Hydrocarbon (HC), Carbon Monoxide (CO) and Nitrogen Oxide (NOX) were selected. The independent variables related to the experimental study were given in Table 5.

***Table 4**. Input parameters.*

| Input Factor | Code | Levels | | |
|---|---|---|---|---|
| **Engine Speed min$^{-1}$** | $X_1$ | 2400 | 3600 | - |
| **Iso-propanol (%)** | $X_2$ | 10 | 20 | 30 |
| **Iso-amyl (%)** | $X_3$ | 5 | 10 | 20 |

***Table 5**. The independent variables related to the experimental study.*

| Run Order | Engine Load | Iso-Propanol | Iso-amyl | BSFC (g/kWh) | CGP (bar) | HC (ppm) | CO (%) | $NO_X$ (ppm) |
|---|---|---|---|---|---|---|---|---|
| **1** | 2400 | 1 | 5 | 183.0341 | 29.80 | 38 | 2.75 | 1598 |
| **2** | 2400 | 10 | 10 | 180.0341 | 31.60 | 32 | 2.38 | 1756 |
| **3** | 2400 | 10 | 20 | 185.8102 | 28.70 | 35 | 2.12 | 1328 |
| **4** | 3600 | 10 | 5 | 146.5268 | 26.40 | 31 | 2.29 | 1892 |
| **5** | 3600 | 10 | 10 | 142.5685 | 28.60 | 25 | 1.84 | 2068 |
| **6** | 3600 | 10 | 20 | 144.0366 | 25.00 | 28 | 1.57 | 1696 |
| **7** | 2400 | 20 | 5 | 170.6845 | 30.70 | 36 | 1.91 | 1762 |
| **8** | 2400 | 20 | 10 | 167.2685 | 32.90 | 28 | 1.52 | 1863 |
| **9** | 2400 | 20 | 20 | 171.6385 | 29.10 | 33 | 1.32 | 1457 |
| **10** | 3600 | 20 | 5 | 132.6249 | 27.80 | 27 | 1.28 | 2035 |
| **11** | 3600 | 20 | 10 | 129.2836 | 29.30 | 20 | 1.08 | 2082 |
| **12** | 3600 | 20 | 20 | 143.9541 | 26.50 | 24 | 0.92 | 1949 |
| **13** | 2400 | 30 | 5 | 187.6215 | 30.40 | 31 | 2.29 | 1429 |
| **14** | 2400 | 30 | 10 | 184.0137 | 31.40 | 27 | 1.84 | 1598 |
| **15** | 2400 | 30 | 20 | 184.9688 | 29.20 | 32 | 1.57 | 1226 |
| **16** | 3600 | 30 | 5 | 149.3599 | 27.10 | 39 | 1.95 | 1321 |
| **17** | 3600 | 30 | 10 | 148.7166 | 29.10 | 32 | 1.53 | 1458 |
| **18** | 3600 | 30 | 20 | 150.0249 | 27.30 | 35 | 1.39 | 1272 |

# 3 RESULTS AND DISCUSSION

## 3.1 RSM Results

Analysis of variance (ANOVA) results for BSFC and CGP are given in Table 6, analysis of variance (ANOVA) results for HC CO and $NO_X$ were given in Table 7.

***Table 6***. *Analysis of Variance for BSFC and CGP.*

| | | BSFC | | | CGP | | |
|---|---|---|---|---|---|---|---|
| | DF | Sum of Sequare | F-valuare | p-valuare | Sum of Sequare | F-valuare | p-valuare |
| **Model** | 8 | 6774.69 | 82.66 | 0.000 | 69.0281 | 52.66 | 0.000 |
| **Linear** | 3 | 5869.79 | 190.98 | 0.000 | 43.4818 | 88.46 | 0.000 |
| **($X_1$) Engine Speed** | 1 | 5820.14 | 568.10 | 0.000 | 38.2571 | 233.49 | 0.000 |
| **($X_2$) Iso-Propanol** | 1 | 40.32 | 3.94 | 0.079 | 1.8113 | 11.05 | 0.009 |
| **($X_3$) Iso-amyl** | 1 | 9.33 | 0.91 | 0.365 | 3.4133 | 20.83 | 0.001 |
| **Square** | 2 | 723.83 | 35.33 | 0.000 | 19.4236 | 59.27 | 0.000 |
| **$X_2^2$** | 1 | 674.33 | 65.82 | 0.000 | 1.7778 | 10.85 | 0.009 |
| **$X_3^2$** | 1 | 49.50 | 4.83 | 0.056 | 17.6458 | 107.69 | 0.000 |
| **2-Way Interaction** | 3 | 11.92 | 0.39 | 0.765 | 1.1509 | 2.34 | 0.141 |
| **$X_1 x X_2$** | 1 | 4.37 | 0.43 | 0.530 | 0.5633 | 3.44 | 0.097 |
| **$X_1 x X_3$** | 1 | 6.37 | 0.62 | 0.451 | 0.1575 | 0.96 | 0.352 |
| **$X_2 x X_3$** | 1 | 1.18 | 0.12 | 0.742 | 0.4301 | 2.62 | 0.140 |
| **Error** | 9 | 92.20 | | | 1.4747 | | |
| **Total** | 17 | 6866.89 | | | 70.5028 | | |

***Table 7***. *Analysis of Variance for HC CO and NOX.*

| | | HC | | | CO | | | $NO_X$ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | DF | Sum of Sequare | F-valuare | p-valuare | Sum of Sequare | F-valuare | p-valuare | Sum of Sequare | F-valuare | p-valuare |
| **Model** | 8 | 363.627 | 6.02 | 0.007 | 3.98756 | 89.05 | 0.000 | 1333169 | 25.80 | 0.000 |
| **Linear** | 3 | 78.624 | 3.47 | 0.064 | 2.31498 | 137.87 | 0.000 | 612708 | 31.62 | 0.000 |
| **($X_1$) Engine speed** | 1 | 55.269 | 7.32 | 0.024 | 0.78874 | 140.92 | 0.000 | 184438 | 28.56 | 0.000 |
| **($X_2$) Iso-Prop.** | 1 | 4.605 | 0.61 | 0.455 | 0.4582 | 81.86 | 0.000 | 325780 | 50.44 | 0.000 |
| **($X_3$) Iso-amyl** | 1 | 18.750 | 2.48 | 0.150 | 1.06803 | 190.82 | 0.000 | 102490 | 15.87 | 0.003 |
| **Square** | 2 | 183.373 | 12.14 | 0.003 | 1.67240 | 149.40 | 0.000 | 514473 | 39.83 | 0.000 |
| **$X_2^2$** | 1 | 66.694 | 8.83 | 0.016 | 1.54588 | 276.19 | 0.000 | 370881 | 57.42 | 0.000 |
| **$X_2^2$** | 1 | 116.679 | 15.15 | 0.003 | 0.12652 | 22.60 | 0.001 | 143592 | 22.23 | 0.001 |
| **2-Way Interaction** | 3 | 117.349 | 5.18 | 0.024 | 0.05149 | 3.07 | 0.084 | 143471 | 7.40 | 0.008 |
| **$X_1 x X_2$** | 1 | 114.083 | 15.10 | 0.004 | 0.04320 | 7.72 | 0.021 | 115248 | 17.84 | 0.002 |
| **$X_1 x X_3$** | 1 | 2.099 | 0.28 | 0.611 | 0.00734 | 1.31 | 0.282 | 21047 | 3.26 | 0.105 |
| **$X_2 x X_3$** | 1 | 1.167 | 0.15 | 0.703 | 0.00095 | 0.17 | 0.690 | 7176 | 1.11 | 0.319 |
| **Error** | 9 | 67.984 | | | 0.05037 | | | 58131 | | |
| **Total** | 17 | 431.611 | | | 4.03796 | | | 1391300 | | |

Analysis of variance (ANOVA) provides numerical information for the probability value [24]. In this study, ANOVA was used to verify the stability of the models [25]. The “p” value is an important parameter in ANOVA results. For the “p” value, 0.05 is accepted as the reference limit. "p" value greater than 0.05 indicates that the model is unimportant. If the “p” value is less than 0.05, it means that the factor has a high effect on the model being developed [8]. When the linear coefficients obtained for BSFC in Table 6 are examined, the “p” value of the engine speed is less than 0.05 and it is greater than 0.05 for alcohol types. In terms of second order coefficients, the “p” value for the percent iso-propanol is less than 0.05, and the “p” value for the engine speed and percent isoamyl alcohol is greater than 0.05. This indicates that engine speed has a greater influence on BSFC optimization. Considering the linear and second order coefficients obtained for CGP, the “p” value of the percentage of motor speed and alcohol species in linear coefficients is less than 0.05. Additionally, all “p” values for second order coefficients are greater than 0.05. The alcohol types used together with the engine speed are also effective parameters for CGP. Similarly, in Table 7, in the ANOVA results for HC CO and $NO_X$ emission results, the “p” value for linear and square coefficients is less than 0.05, except for HC emission. However, in all emission results, p values for the parameters are greater than 0.05 except for the factor $X_1xX_2$ for the second order coefficients. It is understood that the model is important for the CO and $NO_X$ results. Regression statistical fit (evaluation of the model) is given in Table 8. When the values obtained in the 5% and 95.82%, respectively. It is understood from the obtained results that the developed model is compatible table are examined, BSFC, CGP, HC, CO and $NO_X$ were obtained as 98.66%, 97.91%, 84.25%, 98.7. The $R^2$ value is an indicator of how well the statistical model developed with the experimental data is matched. If the $R^2$ value was '0', the obtained correlation line does not fit, and the $R^2$ value was '1' means perfect fit [26]. The adjusted version of $R^2$ indicates the fit of the predictors to the conventional estimate. The Predictors $R^2$ indicates how well a regression model predicts responses from new observations. The Adj. $R^2$ and Pred. $R^2$ values given in Table 8, it is shows that the values for BSFC, CGP, CO and NOX are in acceptable agreement. The highest difference between these values is about 9%. In a study by Shameer and Ramesh [27], Adj. $R^2$ and Pred. $R^2$ values difference are less than 20% and therefore these values are in reasonable agreement. However, in all these results, it cannot be said that the values for HC are compatible. In HC result Adj. $R^2$ and Pred. $R^2$ between difference is about 45%.

***Table 8***. *Assessment of Model.*

| Model | BSFC | CGP | HC | CO | $NO_X$ |
|---|---|---|---|---|---|
| **$R^2$ (%)** | 98.66 | 97.91 | 84.25 | 98.75 | 95.82 |
| **Adj. $R^2$ (%)** | 97.46 | 96.05 | 70.25 | 97.64 | 92.11 |
| **Pred. $R^2$ (%)** | 93.45 | 90.13 | 38.84 | 94.49 | 84.02 |

The second-order regression equations generated by RSM to estimate the output parameters based on the input parameters are given in Equations 3-7 respectively.

$$BSFC = 309.2 - 0.03423\,ES - 5.248\,IPA - 2.05\,IAA + 0.1298\,IPA*IPA + 0.0716\,IAA*IAA + 0.000101\,ES*IPA + 0.000159\,ES*IAA - 0.0050\,IPA*IAA \quad (3)$$

$$CGP = 32.99 - 0.003486\,ES + 0.160\,IPA + 0.863\,IAA - 0.00667\,IPA*IPA - 0.04278\,IAA*IAA + 0.000036\,ES*IPA + 0.000025\,ES*IAA + 0.00304\,IPA*IAA \quad (4)$$

$$HC = 95.4 - 0.01208\,ES - 3.175\,IPA - 2.743\,IAA + 0.0408\,IPA*IPA + 0.1100\,IAA*IAA + 0.000514\,ES*IPA - 0.000091\,ES*IAA + 0.0050\,IP*IAA \quad (5)$$

$$CO = 7.000 - 0.000619\,ES - 0.3002\,IPA - 0.1494\,IAA + 0.006217\,IPA*IPA + 0.003622\,IAA*IAA + 0.000010\,ES*IP + 0.000005\,ES*IA + 0.000143\,IP*IA \quad (6)$$

$$NO_X = -384 + 0.383\,ES + 149.3\,IPA + 48.9\,IAA - 3.045\,IPA*IPA - 3.859\,IAA*IAA - 0.01633\,ES*IPA + 0.00914\,ES*IAA + 0.392\,IPA*IAA \quad (7)$$

Here, ES, IPA and IAA are engine speed, Iso-propanol and Iso-amyl alcohol, respectively.

### 3.2 Brake Specific Fuel Consumption

In the Figure 2 given common impact of engine speed, Iso-propanol ratio and Iso-amyl ratio on BSFC.

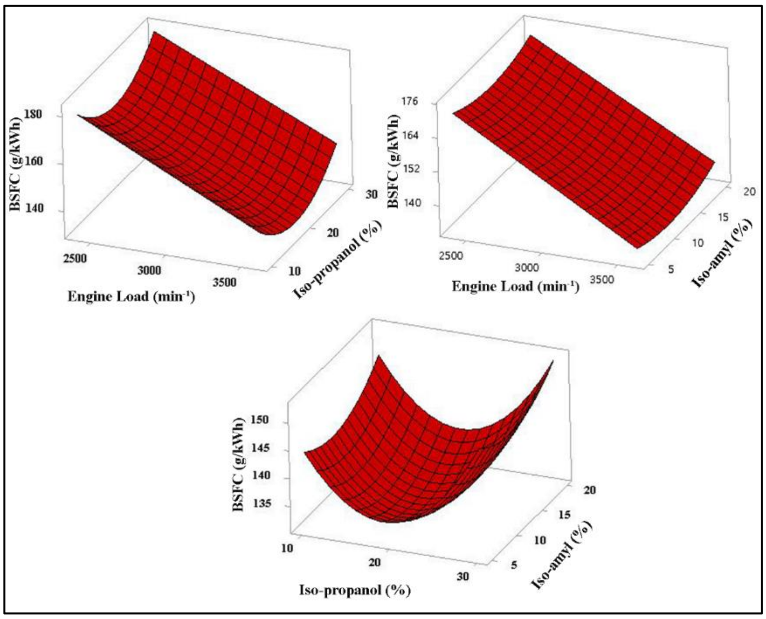


***Figure 2***. *Common impact of engine speed, Iso-propanol ratio and Iso-amyl ratio on BSFC.*

When the graph of the joint effect of engine speed, iso-propanol ratio and iso-amyl ratio on BSFC given in Figure 2 is examined, it is understood that BSFC is lower at maximum power speed compared to maximum torque speed. The results obtained were expected. BSFC is the ratio of the fuel consumption rate to the effective power generated from the engine. In other words, it is an indicator of how much of the fuel consumed by the engine is converted into useful work [6]. Similarly, in the same graphs, it is seen that BSFC decreases to a certain extent at all engine speeds with increasing alcohol content in the fuel and increases again with increasing alcohol content. The decrease in BSFC with a certain percentage of alcohol in the fuel can be explained by the combustion efficiency. The oxygen content in the structure of alcohols supports combustion in the cylinder. Both the oxygen content and the high flame speed of alcohols allow unburned hydrocarbons that cannot enter the combustion reaction to react. This improves the combustion efficiency [28]. An increase in combustion efficiency leads to a decrease in BSFC. The BSFC increases again with increasing alcohol content, which can be attributed both to a further decrease in the lower heating value of the blend fuel and to the lower stoichiometric air-fuel ratio of the alcohols. In order to maintain the same engine power, it is necessary to achieve the required stoichiometric value. To achieve this, more fuel must be injected into the cylinder. This leads to an increase in BSFC [29].

### 3.3 Cylinder Gas Pressure

In the Figure 3 given common impact of engine speed, iso-propanol ratio and iso-amyl ratio on CGP.

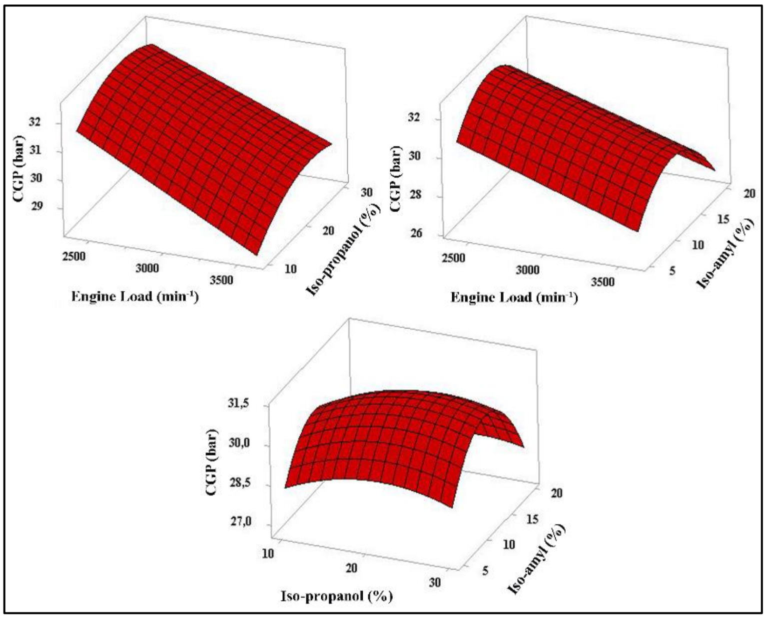


***Figure 3***. *Common impact of engine speed, Isopropanol ratio and Isoamyl ratio on CGP.*

When the joint effect of engine speed, iso-propanol ratio and iso-amyl ratio on CGP given in Figure 3 is analyzed, it is seen that CGP decreases with increasing engine speed for both alcohol types. However, CGP increase are show with increasing iso-propanol alcohol in gasoline. Similarly, with the use of iso-amyl alcohol, CGP increases up to a certain rate, while CGP decreases after a certain rate. Increasing alcohol content in the fuel increases the combustion efficiency (due to oxygen content), which leads to an increase in in-cylinder pressure [30]. Masum et al., [31] reported in similarly a study that the peak in-cylinder pressure was higher with P20 (Gasoline + 20% propanol) fuel because P20 has a higher RON and therefore P20 starts heat release earlier than other fuels. However, it is seen that the increased alcohol content in gasoline causes the CGP to decrease again. The high latent heat of vaporization of alcohols increases the charge cooling effect resulting in lower in-cylinder temperature [5]. Due to the charge cooling effect, the end of combustion temperature and pressure are also reduced.

### 3.4 Exhaust Emissions

In the Figure 4 given common impact of engine speed, iso-propanol ratio and iso-amyl ratio on HC emission.

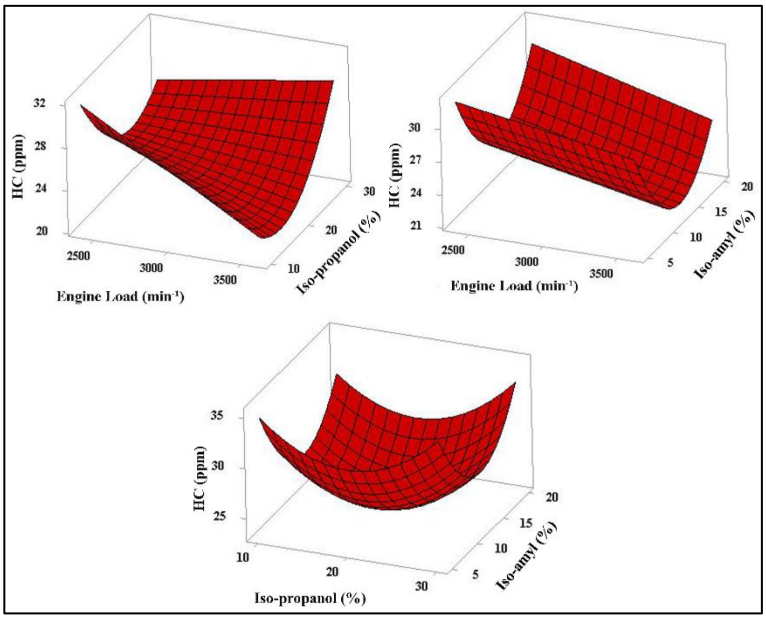


***Figure 4**. Common impact of engine speed, iso-propanol ratio and iso-amyl ratio on HC emission.*

When the joint effects of engine speed, iso-propanol and iso-amyl ratios on HC emissions given in Figure 4 are analyzed, it is seen that HC emissions decrease with increasing engine speed. It is understood that HC emissions decrease with increasing iso-propanol ratio in gasoline fuel and increase again after a certain ratio. HC emissions are seen as at lower levels with decreasing iso-propanol ratio at max power speed compared to max torque speed. The fact that iso-propanol alcohol has a high heat of vaporization negatively affects the combustion efficiency at high engine speeds. In addition, the turbulence of the air taken into the cylinder at high engine speeds has a cooling effect on the cylinder walls and therefore causes an increase in unburned HC emissions [32]. In the Figure 5 given common impact of engine speed, iso-propanol ratio and iso-amyl ratio on CO emission.

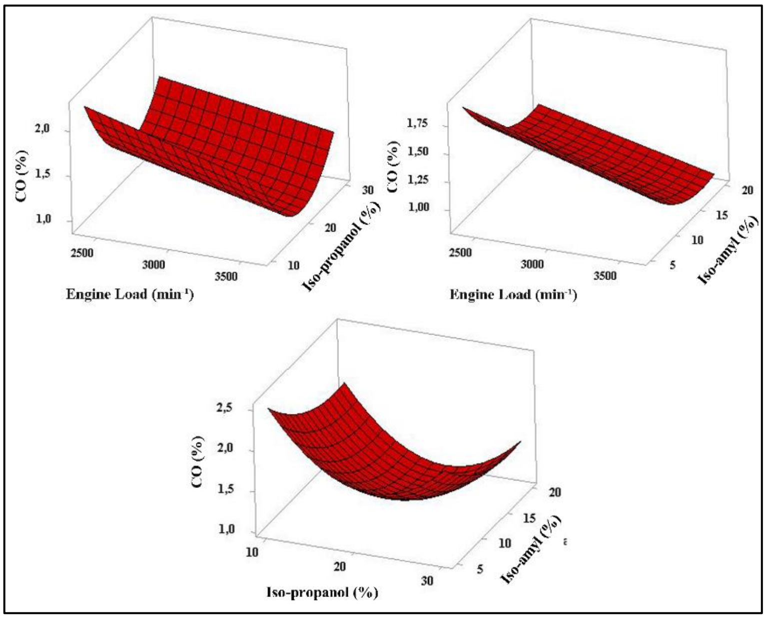


***Figure 5**. Common impact of engine speed, iso-propanol ratio and iso-amyl ratio on CO emission.*

When the joint effects of engine speed, iso-propanol and iso-amyl ratios on CO emissions given in Figure 5 are analyzed, it is seen that CO emissions decrease with increasing engine speed. However, it is seen that CO emissions decrease with the increase of iso-propanol and iso-amyl alcohol ratios up to a certain level at all engine speeds. With further increase in the alcohol ratio, CO emissions increase again. CO emission is a toxic gas resulting from incomplete combustion. The oxygen contained in the structure of alcohols improves the combustion efficiency of the fuel. Therefore, CO emission decreases [33]. In the Figure 6 given common impact of engine speed, iso-propanol ratio and iso-amyl ratio on $NO_X$ emission.

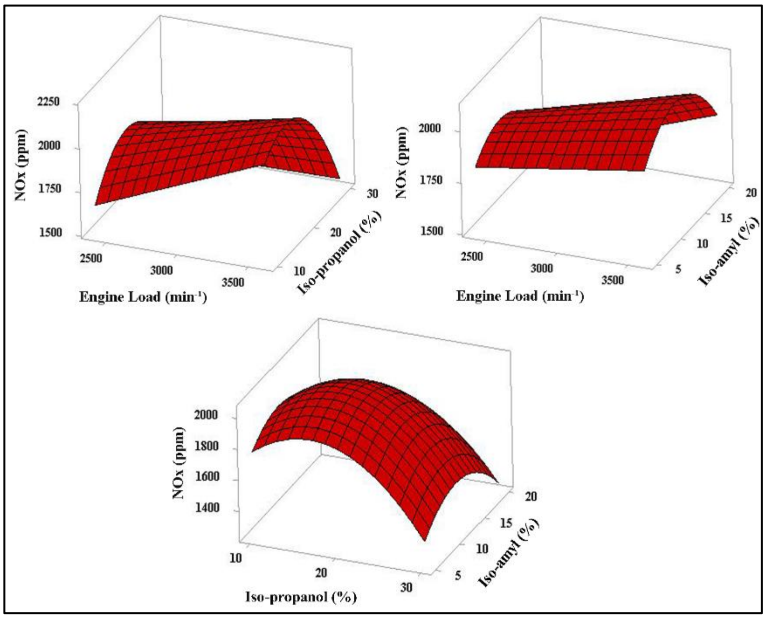


***Figure 6**. Common impact of engine speed, iso-propanol ratio and iso-amyl ratio on NOX emission.*

When the joint effects of engine speed, iso-propanol and iso-amyl alcohol ratios on $NO_X$ emissions given in Figure 6 are analyzed, it is seen that $NO_X$ emissions increase with increasing engine speed. This increase in $NO_X$ emissions can be explained by the increase in combustion efficiency in the cylinder. It is known that $NO_X$ emission formation depends on in-cylinder temperature and pressure. The use of alcohols with high oxygen content causes higher $NO_X$ emissions due to higher in-cylinder pressure and temperature [34,35]. It is seen that $NO_X$ emissions decrease after a certain ratio in both alcohol ratios increasing in gasoline. This decrease in $NO_X$ emissions is due to the high evaporation temperature of alcohols. The high evaporation temperature of the alcohols used causes a cooling effect in the cylinder. This cooling effect causes $NO_X$ emissions to decrease [36].

## 3.5 Optimization Results

The optimization results of different alcohol and gasoline blended fuels are given in Figure 7.

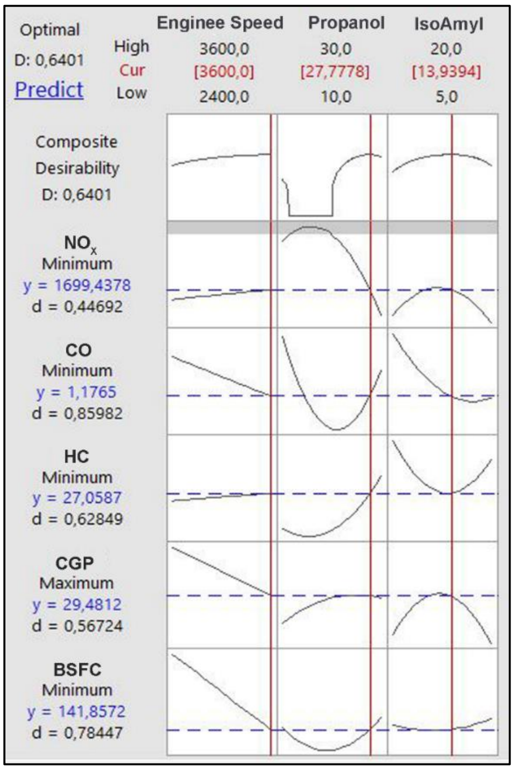


***Figure 7**. Optimization results of alcohol ratios of different alcohol-gasoline blends.*

In this study, an RSM optimization was performed to determine the ratios of iso-propanol and iso-amyl alcohol added to gasoline in a way to maximize CGP while minimizing BSFC and all emissions. The results obtained in the optimization with a desirability value of 0.6401 were 27.7778% iso-propanol, 13.9394% iso-amyl and 3600 min-1 engine speed as shown in Figure 6. In addition, while 29.4812 bar CGP was obtained at optimum engine speed and alcohol ratios, BSFC, HC, CO and NOX results were obtained as 141.857 g/kWh, 27.0587 ppm, 1.1765% and 1699.4378 ppm, respectively. In order to evaluate the optimization results, a verification study was carried out and the results obtained are given in Table 9 comparatively.

***Table 9**. Validation test for predicted and actual values.*

| Engine Speed | Iso-propanol | Iso-amyl | Value | BSFC | CGP | HC | CO | $NO_X$ |
|---|---|---|---|---|---|---|---|---|
| **3600** | 27 | 14 | Predicted | 141.8572 | 29.4812 | 25.0587 | 1.176 | 1699.4371 |
| | | | Experimental | 146.635 | 30.50 | 22.6 | 1.12 | 1620 |
| | | | Error (%) | 3.36 | 3.45 | 9.81 | 4.76 | 4.67 |

The validation test was based on the optimization results. When the results given in Table 9 are examined, it is seen that BSFC, CGP, CO, NOX results can be evaluated with less than 5% error rate. For HC emissions, this error rate is approximately 10%.

## 4 CONCLUSIONS

In the present presented study, RSM with ANOVA was applied to determine the optimum iso-propanol and iso-amyl alcohol ratios and engine speed in an SI engine operating with a gasoline alcohol blend to simultaneously find maximum CGP, minimum BSFC, HC, CO and $NO_X$. The results obtained in the study are given below.

As a result of optimization, engine speed was obtained as 3600 min-1, iso-propanol ratio was 27.7778% and iso-amyl ratio was 13.9394%.

CGP 29.4812 bar, BSFC 141.8572 g/kWh, HC 25.0587 ppm, CO 1.176% and $NO_X$ 1699.4371 ppm were obtained corresponding to the optimum engine speed and alcohol ratios.

$R^2$ values for BSFC, CGP, HC, CO, $NO_X$ were obtained as 98.66, 97.91, 84.25, 98.75 and 95.82, respectively. The $R^2$ values were found to be at acceptable levels for BSFC, CGP, CO, $NO_X$ responses.

The validation test showed good agreement between the optimization results and the experimental results for BSFC, CGP, CO and $NO_X$ with less than 5% error rate. For the HC emission result, it showed that there is less than 10% error rate between the optimization and experimental results. It is thought that the high error rate in HC emissions is due to factors such as measurement error and measurement accuracy.

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