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Research Paper

Research of Effect on Gasoline-2-Propanol Blends on Exhaust Emission of Gasoline Engine with Direct Injection Using Taguchi Approach

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Abstract

One of the most important causes of global warming is the greenhouse gas effect caused by the increased CO_2 emission due to the use of petroleum-based fuels in internal combustion engines. O_2, H_2O, NO_X emissions released as a result of the combustion reaction and released into the atmosphere from the exhaust turn into nitric acid (HNO_3) as a result of some reactions taking place in nature. In addition, the OH radicals released as a result of these reactions that can not turn into nitric acid react with the ozone layer (O_3) and support the formation of hydroperoxyl (HO_2), which causes a harmful emission cycle. CO emissions, on the other hand, react with O_2 and NO_X and pollute the water vapor in the air, causing the O_2 level to drop. Despite quite a lot of work done to date, it is known that due to the increase in the number of gasoline engines, their environmental damage is excessive. In this study, the effect of 2-Propanol / Gasoline fuel mixtures on exhaust emission values has been experimentally investigated using Taguchi Approach. The input factors for Taguchi Approach are 2-Propanol ratio and Engine speed and output values are determined as carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), Nitrogen Oxide (NO_X), and Oxygen (O_2) emissions. In the created Taguchi design, experiments were planned by using an L9 orthogonal array. The engine speed was determined as 1500, 2500, and 3500 (rpm), and 2-propanol ratio was determined as 5%, 10%, and 15% (% by volume). Tests were conducted under partial load conditions. In tests conducted at 1500 rpm, CO emissions decreased by 41.99% compared to gasoline, while CO_2, HC, NO_x, and O_2 emissions decreased by 7,09%, 20,91%, 8.64%, and 20.34%, respectively. 2500 rpm test, CO, CO_2, HC, O_2, and NO_x reductions in emissions, respectively 16.60%, 2.09%, 17.39%, 10.64%, and 27.14% 3500 rpm, while the rate of decrease of the emission test values, respectively 25.30%, 4.88%, 29.09%, 9.72%, and 37.09% has been found in.

Keywords: Direct Injection, 2-Propanol, Exhaust Emissions, Taguchi Approach

1. INTRODUCTION

One of the most critical problems of today is environmental pollution. One of the primary sources of environmental pollution is the use of fossil fuels [1]. Fossil fuels are primarily used in internal combustion engines. Using biomass fuels instead of fossil fuels in these engines may reduce environmental pollution [2].

For engines that use gasoline as fuel, alcohol is considered a good biomass fuel. Alcohols obtained by biochemical processes have an alternative fuel potential with an excess oxygen content, renewable, and cleaner-burning [3]. Alcohols with a lower molecular weight than gasoline can significantly improve engine emissions when mixed with gasoline. Alcohols contain specific amounts of oxygen in their structures [4,5]. Alcohols have a smaller molecular structure than engine fuels, have oxygen in their structure, do not contain sulfur, carcinogenic substances, and heavy metals found in engine fuels, causing positive effects on exhaust emissions [6]. In this way, brighter and faster combustion is provided. Increasing the combustion speed improves combustion efficiency and ensures a more stable operation of the engine. In addition, by achieving high compression rates with fast combustion, efficiency can be increased without engine knock [7]. One of the alcohols that can be used as fuel in engines is 2-Propanol. It contains three carbons in the structure of 2-Propanol, defined by the formula C_3H_7OH. In addition, due to the presence of OH in its structure, it increases

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the oxygen content of gasoline when added to gasoline [8]. 2-Propanol is a colorless, flammable, organic compound. 2-Propanol is well mixed with many solvents, including water. It is a volatile chemical 2-Propanol fuel, also known as isopropanol [9].

In a study conducted by Keskin and Guru [9], gasoline fuel in a four-stroke spark plug ignition engine 4%, 8%, 12%, 16%, 20% added ethanol in its proportions. Additionally, 4%, 8%, 12%, 16%, and %20 2-Propanol was added to gasoline fuel. By experimenting with the resulting fuels, they investigated the effect of the engine on exhaust and noise emissions. As a result of the experiments, they stated that HC and CO emissions decreased and NOx and CO_2 emissions increased using fuels added 2-Propanol.

Altun et al. [10] 5% and 10% 2-Propanol were added to gasoline fuel in a spark plug engine. They investigated the effect of fuel blends on exhaust emissions. As a result of the study, CO and HC observed decreased emission values while CO_2 emissions increased.

In a study conducted by Mourad and Mahmoud [8], propanol was added to gasoline fuel in 5%, 10%, 15%, and 20% by volume. They evaluated the performance of a spark plug engine using fuel blends. Their results stated that particular fuel consumption decreased by about 2.84%, exhaust emissions decreased by 4.18% in HC values, and 10.87% in CO values.

Simsek et al. [6] their study first added 20% n-Propanol and 2-Propanol to gasoline fuel in a spark plug engine. In the second stage, they examined 1-3% hexane addition to previous fuels on engine performance and emissions. The emission results obtained stated a significant decrease in HC and CO emissions compared to gasoline fuel, there was no significant change in NO_X emissions, and there was an increase in CO_2 emissions.

In this study, changes in the exhaust emission values of a direct injection engine were examined by adding 2-Propanol by 5%, 10%, and 15% volumetric to gasoline fuel. In this study, researches were taken into consideration while determining the fuel blends. But there is no such study on direct injection engines. For this reason, it was increased up to 15% while preparing fuel blends.

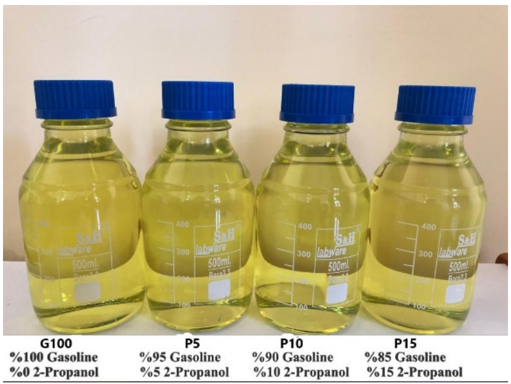

Figure 1. Test fuels

In addition, with this study, unlike other studies in the literature, the number of tests was reduced by using the Taguchi method, and the effects of 2-Propanol and engine speed values on each emission parameter were obtained as mathematical functions. Apart from this, the test intervals were visualized with contour graphics and it was determined at which ratios of 2-Propanol use was more appropriate according to the engine speed. This study comprehensively covers the effects of 2-Propanol and engine speed on emissions and forms a reference for future research.

2. MATERIAL AND METHOD

2.1. Fuel blends and Test Setup

Fuel blends were obtained by blend 2-Propanol supplied by Sigma Aldrich with 5% (P5), 10% (P10), and 15% (P15) gasoline by volume. In addition, 95 octane gasoline was used as a fuel for comparison. Fuel properties are given in Table 1 [3,9]. Test fuels are shown in Figure 1. During the experiment, the fuels were mixed continuously with a mechanical mixer. As a result, phase separation is prevented.

Table 1. Fuel properties [3,9]

Property	Gasoline	2-Propanol
Density (g/ml)	0.775	0.786
Flash Point (°C)	<-40	12
Autoignition Temperature (°C)	>250	425
Boiling Point	>32	82.6
Octane Number	95	95
Lower Heating Value (kJ/kg)	43430	31000

The tests were carried out under partial load using a 1.2 TSI direct injection, 4-stroke, and 4-cylinder gasoline engine, using the BT-190 FR hydraulic dynamometer at 1500, 2500, and 3500 rpm. Dynamometer properties are given in Table 2. The properties of the test engine are given in Table 3, and the experimental setup is given in Figure 2.

Table 2. Hydraulic dynamometer specifications

Feature	Capacity
Maximum Braking Power	100 kW
Maximum Speed	6000 rpm
Maximum Torque	750 Nm
Brake Water Working Pressure	0-2 kg/cm^2
Water Requirement for Maximum Power	2.3 m^3/h
Maximum Brake Water Outlet Temperature	80 °C
Torque Measurement	Electronic Load-Cell
Rotation Direction	Right and Left

Table 3. Test engine technical specifications

Feature	Property
Volume	1197 cm^3
Number of Cylinders	4
Compression Rate	10:1
Cylinder Diameter	71 mm
Stroke	75.6 mm
Maximum Power Output	77 kW (@5000 rpm)
Maximum Torque	175 Nm (@1500-3500)
Emission Standard	Euro 5
Control Unit	Continental Simos 10.1

For the measurement of exhaust emissions, the Bosch BEA350 model emission meter was used in the experiments. The specification values of the emission meter are given in Table 4.

Table 4. Emission meter specifications

Emission	Measure Range	Precision
CO	0 – 10 (%) volumetric	0.001%
CO_2	0 – 18 (%) volumetric	0.01%
HC	0 – 9999 ppm volumetric	1 ppm
NO_X	0 – 5000 ppm volumetric	1 ppm
O_2	0 – 22 (%) volumetric	0.01%

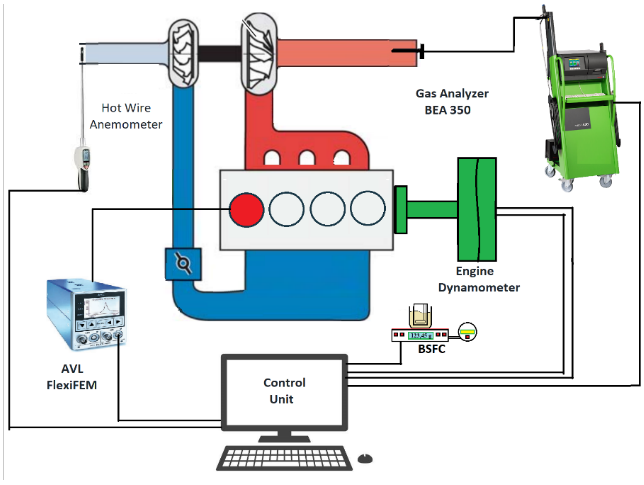

Figure 2. Experimental setup

2.2. Taguchi Experimental Design

Experimental design techniques (DoE), reducing costs by reducing the number of tests, determining input values at different levels (small, medium, most prominent, etc.) instead of performing tests in the whole range, only to investigate the effect of these values on the response values and to analyze the results mathematically depending on the estimation functions and used to express. Taguchi's experimental design technique is one of the DoE methods developed by Dr. Genichi Taguchi. In this study, 2-Propanol and engine speed were determined as input parameters, while CO, CO_2, HC, NO_X, and O_2 values were determined as output parameters. In table 4, the levels of input parameters are given.

Table 4. Taguchi method factors and level

Factors	Level 1	Level 2	Level 3
A-Engine Speed (rpm)	1500	2500	3500
B-2PR (% volume)	5	10	15

Unlike other statistical designs, the Signal/Noise (S/N) ratio is used in the Taguchi design. This parameter is calculated depending on the effect of the output values on the design (lowest best, highest best, nominal best). Since all output values were wanted to be the lowest in this study, the S/N ratio was calculated as given in Equation 1, with the Y output value, the I level, and n is the number of combinations at the O Level. In addition, the L9 orthogonal sequence was used depending on the levels of parameters and parameters, and a total of 9 measurements were made consisting of 3 levels of each input parameter and combinations of these levels. The measurement values were compared with the gasoline fuel values.

$$\frac{S}{N} = -10 log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

Different from traditional statistical mathematical approaches to obtain mathematical function of a test procedure as the test procedure to predict output values for input values that are not included in the prediction function y, β constant-coefficient, k the number of input factors, X to represent the input value and the standard error is given by equation 2, it is stated that[11]. Functions that cannot be explained linearly are expressed as I linear; J is given in equation 3 to represent the polynomial coefficient [12].

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_k X_k + \in \tag{2}$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \Sigma \sum_{i<j}^{k} \beta_{ij} X_i X_j + \in \tag{3}$$

3. RESEARCH RESULTS AND DISCUSSION

Analysis of variance (ANOVA) ensures that non-repetitive combinations of output variables are associated with input parameters due to regression. ANOVA analysis includes factors such as R_2, R_{adj}^2, Test value F (F-value), probability value (P-value), as well as statistical factors such as exponential values of factors (A^2, B^2, A*B). In cases where the P-value is less than 0.05, the result is statistically significant. In addition, the fact that the F-value is significant increases statistical significance. R^2 values, a measure of the explainability of response values with input values, are above %97 for all emissions. In addition, in cases where there are two or more input parameters, R_{adj}^2 is used for benchmarking, and Anova results are given in Table 5 for all output values.

Table 5. ANOVA Table (A: Engine Speed (rpm) B:2-Propanol Rate (% Vol))

Parameter	CO		CO_2		HC		O_2		NO_X	
	P-Value	F- Value	P- Value	F- Value	P- Value	F- Value	P- Value	F- Value	P- Value	F- Value
A	0.0056	51.10	0.0033	73.40	0.0005	273.78	0.0146	26.02	0.0030	78.25
B	0.0506	10.03	0.0098	34.69	0.0000	1160.18	0.0000	1352.46	0.0079	40.20
A^2	0.9796	0.00	0.3213	1.40	0.0741	7.26	0.4388	0.79	0.9214	0.01
A*B	0.1283	4.35	0.5588	0.43	0.3751	1.08	0.1174	4.75	0.8892	0.02
B^2	0.0004	289.26	0.2881	1.66	0.0187	21.66	0.0006	227.05	0.5971	0.35
R^2	0.9916		0.9738		0.9997		0.9981		0.9753	
R_{adj}^2	0.9776		0.9301		0.9993		0.9950		0.9343	

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In this study, the 2nd order functions obtained depending on the input parameters for CO, CO_2, HC, O_2, and NO_X are respectively (4), (5), (6), (7), and (8) are given in equations.

$$CO = -0.533639 - 0.019075*2PR + 0.000965833*ES + 0.0000133333*2PR^2 + 0.00000355*2PR*ES - 2.04667E-7*ES^2 \quad (4)$$

$$CO_2 = 13.0219 - 0.0176667*2PR - 0.000256667*ES - 0.00306667*2PR^2 + 0.000006*2PR*ES + 8.33333E-8*ES^2 \quad (5)$$

$$HC = 216.597 - 0.0833333*2PR - 0.0583333*ES - 0.0733333*2PR^2 + 0.0001*2PR*ES + 0.00000316667*ES^2 \quad (6)$$

$$O_2 = 4.56306 - 0.0504167*2PR - 0.002425*ES + 0.000866667*2PR^2 + 0.0000075*2PR*ES + 3.66667E-7*ES^2 \quad (7)$$

$$NOx = 1456.71 - 9.83333*2PR - 0.00466667*ES + 0.04*2PR^2 - 0.0002*2PR*ES - 0.0000055*ES^2 \quad (8)$$

Test studies show a decrease in all emission values in proportion to the increased amount of 2-Propanol. In tests conducted at 1500 rpm, CO emissions decreased by 41.99% compared to gasoline, while CO_2, HC, NO_x, and O_2 emissions decreased by 7,09%, 20,91%, 8.64%, and 20.34%, respectively. 2500 rpm test, CO, CO_2, HC, O_2, and NO_x reductions in emissions, respectively 16.60%, 2.09%, 17.39%, 10.64%, and 27.14% 3500 rpm, while the rate of decrease of the emission test values, respectively 25.30%, 4.88%, 29.09%, 9.72%, and 37.09% has been found in. Test results are given in Table 6.

In Figure 3, contour graphs obtained for all emission values are given. Contour charts are essential for determining the most suitable conditions of use for output values. CO emission is an important parameter that shows the chemical energy formed in incomplete combustion and cannot be converted into heat energy. In cases where there is not enough air-fuel mixture in the combustion zone, the efficiency of the combustion event decreases, and CO is formed as a combustion product. When the CO graph is examined, it is seen that as the 2-Propanol ratio in the fuel blend increases, the CO values decrease. Due to the presence of oxygen in the structure of 2-propanol, the amount of oxygen taken into the cylinder increases. Therefore, combustion is considered to be more efficient. The results reported by Keskin and Guru, Mourad et al. [8,9] are similar to the results of the studies.

CO_2 gas is a colorless, harmless, and scentless gas. CO_2 emission is a parameter that's revealed during combustion and shows complete combustion. If there is enough O_2 in the combustion chamber, the fuel oxidizes, and the C atom in the fuel combines with O_2 to form CO_2 gas. When the CO_2 graph is investigated, it is seen that there is a decrease in CO_2 emission values due to the increase in the 2-Propanol ratio in the blend. Since 2-Propanol has fewer C atoms in its structure than gasoline, it is thought that CO_2 emissions are lower than gasoline [13].

HC emissions occur in combustion products because the fuel cannot oxide or the ignition temperature is unavailable [10]. HC emission exhibited behavior similar to the CO_2 emission value at lower engine speeds. The lowest HC emission values were obtained in P15 fuel at an engine speed of 3500 rpm.

O_2 emission exhibited behavior similar to CO_2 emission value at lower engine speeds. The lowest values for O_2 emission value were obtained in P15 fuel at 3500 rpm engine speed. O_2 emission is a vital parameter to see the oxygen consumed during combustion. In affluent mixing areas, O_2 further improves combustion. The measurement of O_2 emission shows at what rate the amount of oxygen is used during combustion [13]. An increase in the turbulence in the combustion chamber with the increase in engine speed, providing an ideal fuel-air blend, and thus better combustion, is seen as the reason for this decrease in O_2 emissions. In addition, it is seen that the O_2 emissions of the blends with 2-Propanol fuel are lower than the use of gasoline. Using these fuels is normal for the O_2 values to decrease due to the increase in

Table 6. Test results

Engine Speed (rpm)	Fuel	CO (% Vol)	CO_2 (% Vol)	HC (ppm)	NO_x (ppm)	O_2 (% Vol)
1500	Gasoline	0.412	12.97	153	1422	1.72
	P5	0.382	12.72	135	1396	1.6
	P10	0.335	12.37	129	1327	1.41
	P15	0.239	12.05	121	1299	1.37
2500	Gasoline	0.554	12.42	92	1419	0.70
	P5	0.545	12.86	89	1356	0.63
	P10	0.497	12.53	86	1312	0.59
	P15	0.462	12.16	76	1268	0.51
3500	Gasoline	0.328	13.11	55	1347	0.62
	P5	0.317	13.02	51	1317	0.47
	P10	0.262	12.97	46	1284	0.42
	P15	0.245	12.47	39	1216	0.39

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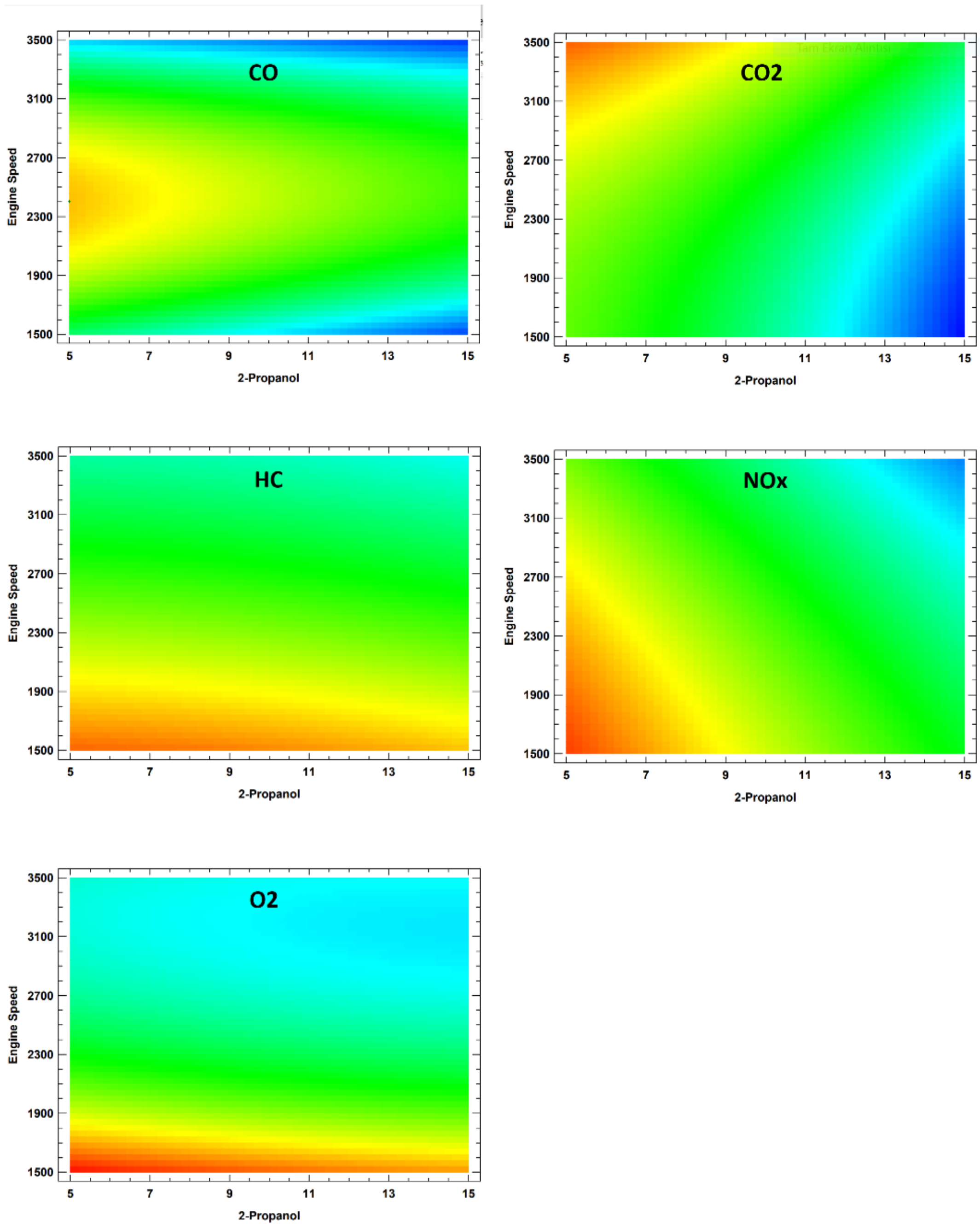

Figure 3. Contour charts for all emission values

the CO_2 value.

NO_X emissions occur when the nitrogen in the air is ionized and combined with oxygen as the temperature in the combustion chamber increases. Temperature, oxygen ratio, and combustion time are important parameters affecting NO_X emissions [2]. When the NO_X graph is examined, it is seen that NO_X values decrease as the engine speed increases. As the engine speed increases, the combustion event accelerates and the intake time shortens, and sufficient oxygen cannot be taken into the cylinders. Therefore, it can be expressed as the reason that NO_X formation decreases. In addition, the amount of NO_X emission decreases with the increase of the 2-Propanol ratio in the blended fuels. As seen in Table 1, the lower heating value of 2-Propanol is lower than that of gasoline. As a result, it leads to a lower combustion end temperature in the cylinder [2,14]. As a result of this situation, it is thought that there is a decrease in the number of NO_X emissions. While NO_X emission is at its highest value up to 2700 rpm engine speed and approximately 9% 2-Propanol, it decreases with increasing engine speed and 2-Propanol ratio. NO_X emission reaches its lowest value at 3500 rpm engine speed and P15 fuel.

4. CONCLUSION

In this study, the effect of gasoline fuel mixtures containing 5%, 10%, and 15% 2-Propanol on exhaust emissions at 1500, 2500 and 3500 rpm engine speeds using 1197 cc, 1.2 TSI engine was investigated experimentally and statistically. Taguchi method was used for experimental designs. Engine speed (rpm) and 2-Propanol (%) ratios were determined as input parameters and emission values as output parameters. Nine tests were performed for every three levels of input parameters, and these tests were compared with 100% gasoline. As a result of the study, emission values in 2-Propanol-gasoline fuel blends decreased at all engine speeds. 2-Propanol has a lower heating value compared to gasoline, lowers the combustion temperature, and reduces emission. In addition, the OH group in its chemical structure is connected to water molecules in the fuel by hydrogen bonding, and the methyl groups are connected to gasoline by dipole bonds, forming an excellent blend and contributing to the reduction of CO_2, CO, and HC emissions. With increasing engine speed, the amount of O_2 per unit fuel decreases proportionally. This study obtained mathematical functions depending on the input parameters for all emission values and shown with contour graphs. The Taguchi approach in internal combustion engine tests is of great economic benefit by reducing the number of experiments, time, and material used. In addition, as a result of the study using the Taguchi approach, an approximate estimation of unknown input parameters is possible by obtaining prediction functions.

Symbols and Abbreviations

G	Gasoline	**HC**	Hydrocarbon (ppm)
P5	95% Gasoline + 5% 2-Propanol	**CO**	Carbon monoxide (% by volume)
P10	90% Gasoline + 10% 2-Propanol	**CO_2**	Carbon dioxide (% by volume)
P15	85% Gasoline + 15% 2-Propanol	**NO_x**	Nitrous oxide (ppm)
2PR	2-Propanol	**O_2**	Oxygen (% by volume)

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