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Optimization of Performance and Exhaust Emissions of a PFI SI Engine Operated with Iso-stoichiometric GEM Blends Using Response Surface Methodology

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Abstract

The present work aimed at optimizing the performance and emission characteristics of a Port Fuel Injection (PFI) SI engine fueled with Gasoline-Ethanol-Methanol (GEM) blends using Response Surface Methodology (RSM). Test fuels used in the study are pure gasoline (E0), E10, E10 equivalent iso-stoichiometric GEM blend (E10_Eq), E20, E20 equivalent iso-stoichiometric GEM blend (E20_Eq). Formulated E10 and E20 equivalent blends have identical air-fuel ratios, lower heating values, density, and octane number as target binary blends (E10, E20). The test engine was operated with different fuel blends by varying the engine speed from 1700 to 3300 rpm at a constant engine load of 5 kg. For optimization of the engine, speed and fuel blends were considered as input parameters and brake thermal efficiency (B_The), brake specific fuel consumption (BSFC) and, nitrogen oxide (NOx) emissions as responses. Optimization was carried out using the desirability approach with a target of maximizing the B_The and minimizing the BSFC and NOx. From the results, it was observed that the E10_Eq GEM blend operation of the test engine has optimized values of B_The, BSFC, and NOx emissions with values of 33.17%, 251 g/kW-hr, and 1389.8 ppm respectively at an engine speed of 2416 rpm. A composite desirability value of 0.64 obtained from the regression model shows that RSM can be conveniently employed to determine the significant factors that could impact engine performance and emissions.

Keywords: GEM blends, Response surface methodology, Analysis of variance, Equivalent blends;

Nomenclature

Abbreviations

ANOVA	Analysis of Variance
A/F	Air Fuel ratio
BSFC	Brake specific fuel consumption
B_The	Brake thermal efficiency
CO	Carbon monoxide
DoE	Design of experiments
Eq	Equivalent
E0	Gasoline 100%
E10	Gasoline 90% + Ethanol 10%
E10_Eq	Gasoline 91.6% + Ethanol 5% + Methanol 3.35%
E20	Gasoline 80% + Ethanol 20%
E20_Eq	Gasoline 83% + Ethanol 10% + Methanol 7%
GEM	Gasoline-Ethanol-Methanol
HC	Hydrocarbons
NO_x	Nitrogen oxides
ppm	parts per million
RSM	Response surface methodology
RPM	Revolutions per minute

Symbols

p-value	Probability value
R^2	Coefficient of determination
R^2-(Adj)	Adjusted R^2 value
R^2-(Pred)	Predicted R^2 value

1. Introduction:

Fossil fuels are being consumed worldwide in enormous amounts especially in transportation sector, leading to increase in their demand every year. And also, fast depletion of conventional fossil fuel reserves along with the threat of global warming made research community to explore the alternative eco-friendly bio fuels. Alcohols are an important category of bio fuels which can be produced from variety of biomass in different ways. Also, alcohols are oxygenated fuels and have high latent heat of vaporization and octane number compared to gasoline. Among various alcohols, ethanol and methanol have the potential to be used in internal combustion engines due to fuel properties that are close to gasoline [1].Ethanol is generally produced from biomass feedstock such as sugarcane, potatoes, corn, sugar beets, etc. Although the high demand and utilization of

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ethanol in the present scenario, it is not regarded as a possible effective alternative to fossil fuels in the long run, due to the limitations in biomass of each country [2]. In contrast to this, methanol can be produced from a wide variety of renewable sources such as agricultural by-products, gasification of wood, coal gas, municipal waste, animal and human waste, etc, and at a cheaper price compared to ethanol.

A good amount of literature is available on the usage of alcohol fuels, especially on ethanol and methanol usage in internal combustion engines [3-7]. In almost all the cases, it was reported that the blending of alcohol fuels, at lower volume fractions, improved the efficiency of the test engine while also resulting in improved emission characteristics. Also, because of the expensive nature of the engine experimentation, design of experiments and optimization studies have become popular in the engine research community. There is also a significant amount of literature available on the optimization of various engine parameters. Some authors have reported various models developed in-house for the purpose, while others used different optimization software tools for the same purpose. While each optimization method has its own advantages depending upon the problem complexity, Response Surface Methodology (RSM) is gaining popularity because of its simplicity in modeling and analysis.RSM is a collection of statistical methods that can be used to solve many engineering problems based on modeling and optimization influenced by experimental variables. This method simultaneously analyzes the effects of different factors and the relationship between variables to find an optimum performance condition [8,9].Najafi et al. [10] experimentally studied the performance and emissions of the SI engine using gasoline ethanol blends of E5 to E20 (5%, 10% 15% and 20% (v/v)).Their test results using the blended fuels found to have increased brake thermal efficiency, volumetric efficiency and NOx emissions and, decreased CO and HC emissions.

Elfasakhany [11] experimentally investigated the performance and emission characteristics on a single-cylinder SI engine using gasoline-ethanol, gasoline-methanol, and gasoline-ethanol-methanol blended fuels. The volume fraction of ethanol and methanol was varied from 3%, 7%, and 10% volume. It was reported that the ternary blend EM10 (Gasoline 80% +Ethanol 10%+Methanol10%) showed a significant reduction in CO and HC emissions, by about 46% and 23% respectively compared to other binary gasoline-ethanol and gasoline-methanol blends. Yusuf et al. [12] experimentally investigated the engine emissions, performance, and combustion characteristics of a four-stroke petrol engine using Mbwazirume bio-ethanol blends (5%, 10%, and 15%) with gasoline. The experiments were conducted at different engine speeds, from 1800 to 3000 rpm at 8.5:1 CR with wide-open throttle (WOT) and at a BMEP of 6.7 barat low ambient temperature. The results showed that B_The of the engine increases by 6.7% for E15 blend at an engine speed of 2700 rpm compared to gasoline and the rate of formation of NOx emissions was observed higher for E5 and E10 blends due to advance in combustion timing. Agarwal et al. [13] investigated the performance, combustion, emission characteristics, and particle size distribution of an SI engine using 10% and 20% methanol (M10, M20) blended with pure gasoline fuel. The engine was operated at different torques and speeds, and it was reported that the methanol blended fuels increased the thermal efficiency of the engine and also produced lower CO emissions compared to pure gasoline.

Yusri et al. [14] optimized the performance and emissions of a single-cylinder SI engine operated with gasoline-2 butanol blends of 5%, 10%, and 15% using RSM. The experiments were carried out at a constant torque, 50% wide open throttle, and at various engine speeds, from 2000 to 4000 rpm. It was concluded that the desirability approach of RSM was found to be an efficient optimization technique and the optimum condition was observed at 3205 rpm with a fuel blend of 15%. Abdalla et al. [15] applied RSM to optimize engine performance in terms of brake power, BSFC, NOx, and CO emissions using fuel blends of fusel oil, 10% and 20% with gasoline. The experiments were conducted at engine speeds of 1500-4500 rpm and at15%, 30% 45%, and 60% of wide-open throttle (WOT) positions. A desirability approach was used to determine the optimal multi-response parameters to maximize the brake power and minimize the BSFC, NO_x, and CO emissions. The optimization results were obtained for the engine operation using 20% fusel oil, at 60% WOT, and at an engine speed of 4500 rpm. Ardebili et al. [16] used RSM to optimize the performance and emission characteristics of a port fuel injected gasoline engine using gasoline-fusel oil blends (0%, 20%, 50% 75%, and 100%) at different engine loads at a constant engine speed of 2500 rpm. The engine load and fusel oil content (%) were considered as effective factors and engine performance and emissions as response parameters. Statistical analysis was performed using analysis of variance. It was reported that the optimal fusel oil ratio and the engine load were found at 25% and 47.21% respectively with a desirability value of 0.63. Najafi et al. [17] employed the RSM to optimize the engine performance for different gasoline-ethanol blends. Ethanol volume concentrations of 5%, 7.5%, 10%, and 15% were added to gasoline and engine speed was varied from 2000 to 4000 rpm. The engine speed and fuel blends were identified as input factors whereas the engine performance, emissions were taken as responses. The desirability approach was used to determine the optimum values of the input parameters. It was reported that the test condition with 10% ethanol at an engine speed of 3000 rpm resulted in the optimum performance and emission values with a desirability value of 0.74.

Extensive experimental investigations have been carried out by researchers using gasoline alcohol binary fuels, in which ethanol was widely used in low to moderate concentrations as a blend component in many parts of the world. Ethanol and methanol have high octane number, high latent heat of vaporization compared to gasoline. Because of this, a concept of ternary blends of Gasoline, Ethanol, and Methanol (GEM) was proposed by Turner et al. [18] in which each ternary blend has iso-stoichiometric air-fuel ratio, identical to that of a conventional equivalent binary gasoline-ethanol blend. The iso-stoichiometric air-fuel ratio property is essential for the formulated blends, to be used as drop-in fuels, not to cause engine operation to become stray outside the pre-determined limits of air to fuel ratio[19]. Sileghem et al. [20] experimentally investigated the E85 (Gasoline 15% + Ethanol 85%) equivalent three GEM blends on 1.8 L SI PFI 4-cylinder engine by varying the engine speed from 1500 to 3500 rpm at a fixed torque of 40 and 80 N-m. It was reported that all the three E85 equivalent GEM blends have nearly the same brake thermal efficiencies, volumetric efficiencies, and heat release rates when compared with binary E85 blend operation of the engine. Chaichan [21] reported the results of an experimental study using a ternary blend of gasoline, ethanol, and methanol (37% gasoline + 20% ethanol+ 43% methanol) on a multi cylinder Mercedes Benz engine. It was reported that the exhaust emissions of CO, HC, and $NO_x$are lower by 46.49%, 25.16%, and 1.75% respectively compared to pure gasoline operation.

From the literature, it is evident that alcohols, as alternate fuels, have a significant potential to improve the performance and reducing the emissions from IC engines. The concept of iso-stoichiometric blends facilitates formulating the various volume fraction combinations of ethanol and methanol by blending with gasoline, based on the availability. Only a limited amount of literature is available on GEM blends potential use in SI engines and addition of experimental knowledge using this concept might result in widespread exploration of use of iso-stoichiometric multi-component alcohol blends in SI engines that could help reduce the fossil gasoline consumption. Therefore, the objective of the present work is to optimize the performance and emission characteristics of a PFI engine fueled with E10, E20 binary blends, and its equivalent GEM blends using response surface methodology (RSM). The fuel blends formulated for the present study are E10 and E20 binary blends along with their equivalent iso-stoichiometric GEM blends (E10_Eq, E20_Eq). The effect of input parameters (fuel blends (%) and engine speed (rpm)) was analyzed on the response parameters (B_The (%), BSFC (g/kW hr), NO_x (ppm)). Response surface methodology was employed to optimize fuel blend composition and engine speed to maximize the B_The and minimize the BSFC and NO_x.

2. Experimental setup and procedure:

The experiments were performed on a single-cylinder, Port fuel injection (PFI), four-stroke SI engine; model Honda GX 200, fitted with an eddy current type dynamometer for loading the engine. The advantage of using PFI is that the engine emits low particulate matter emissions into the environment than a direct injection engine [22]. The detailed schematic diagram of the engine is shown in Fig. 1 and the specification of the engine is shown in Table 1. The engine performance parameters were calculated by measuring the time taken by the engine to consume 20 cc of fuel for a given engine speed. Data acquisition system using ‘I.C.Engine soft 9.0’ software was used to acquire and analyze the performance data obtained from the engine at different test conditions. The operating parameters of the engine such as spark timing and fuel injection timing were controlled by an open Electronic control unit (ECU), developed by Performance Electronics Ltd, PE3 series system connected to windows based operating system through an Ethernet port. The PE software is installed on a computer for controlling the ignition timing for every engine cycle. The spark timing sweep tests were conducted to determine the maximum brake torque (MBT) at each engine speed for each fuel blend.

Table 1. Engine Specifications

Item Description	Specifications
No. of cylinders	01
No. of Strokes	04
Fuel	Gasoline
Rated Power	4.1 kW @3600 rpm
Cylinder Diameter	68mm
Stroke Length	54mm
Connecting rod length	105mm
Compression Ratio	8.5: 1
Cooling type	Air Cooled

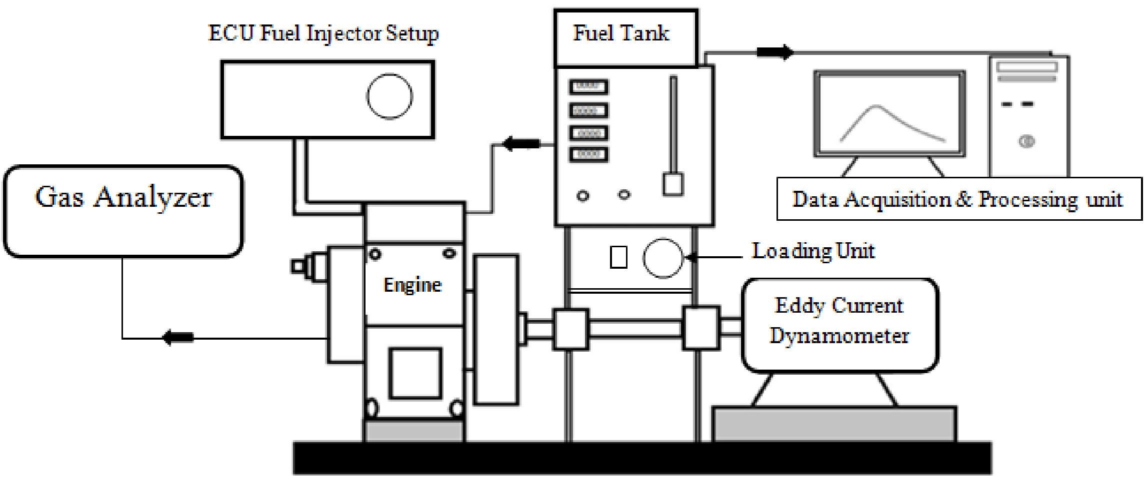


Figure 1. Schematic diagram of single cylinder SI engine

The exhaust emissions were measured using a 5-gas analyzer; model AVL Digas 444N which uses the techniques of Non-Dispersive Infrared (NDIR) absorption, Chemiluminescence and Flame Ionization to measure Carbon monoxide (CO), Nitrogen oxide (NO_x) and unburned Hydro carbons (HC) from the engine. Exhaust gases were purged completely from the stabilizing tank after each measurement.

The tested ethanol and methanol were industrial grade with 99.9% purity. The ethanol and methanol fuels were splash blended with gasoline before filling in the fuel tank. Different properties of gasoline, ethanol, and methanol are presented in Table 2. The basic formulation of iso-stoichiometric blends was carried out using the mathematical formulation given by Pearson et al. [19] in Appendix 2. And also for the determination of binary and ternary blend fuel properties such as iso-stoichiometric air to fuel ratios, lower heating values, and octane number same reference has been followed. The experiments were performed at dry ambient conditions. Five fuel samples were used for the tests namely, pure gasoline, binary E10, and E20, and their equivalent iso-stoichiometric GEM blends on a volume % basis (E10_Eq, E20_Eq).In equivalent GEM blends, the volume of ethanol was reduced to half of its volume than in binary blend. The reduced quantity of ethanol is taken care of by adding gasoline and methanol in suitable proportions to maintain the identical air to fuel ratio as the target binary blend. It can be observed from Table 3 that two formulated equivalent GEM (E10_Eq, E20_Eq) blends have an identical air-fuel ratio, lower heating value, and octane numbers as conventional binary E10 and E20 blends. The experiments were conducted at a constant engine load of 5 kg while varying the engine speed from 1700 to 3300 rpm. During the experiment at each speed, the engine was kept running till it attained a steady state condition. The engine performance and emissions data were recorded for each speed after attaining engine stable operating conditions. The performance tests and emission measurement were repeated 3 times per test and the averaged data value was considered for the investigation.

2.1. Response Surface Methodology (RSM)

RSM can be used to establish the relationship between output responses of the engine to its input parameters using statistical methods and mathematical equations. The input variables can be indicated as X1, X2, X3 ………Xk and response of interest (output) as y as in Eq. (a)

$$Y = f'(X)\,\beta + \varepsilon \quad \text{(a)}$$

Where X = (X1, X2, X3 ………Xk)', f(x) is a vector function of p elements that consists of powers and cross-products of powers of X1, X2, X3 ………Xkup to a certain degree denoted by d (>1), β is a vector of p unknown constant coefficients referred to as parameters, and ε is a random experimental error assumed to have a zero mean. For a first order polynomial (d = 1), the equation can be described as in

$$y = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \varepsilon \quad \text{(b)}$$

And if the model predicted a curvature, then a polynomial of higher degree is necessary to be used, such the second order model (d=2) can be described as in

$$y = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \sum \sum_{i<j} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \varepsilon \quad \text{(c)}$$

Where'y' is the predicted response, 'i' is the linear coefficient, 'j' is thequadratic coefficient, 'β' is the regression coefficient, 'k' is the number of factors [16].

In the present work, the engine speed and fuel blend composition were taken as input parameters and the output responses were performance and emission values, B_The, BSFC, and NO_x respectively as shown in Tables 4 and 5. Design of Experiments (DoE) with the multilevel factorial design was used in this study and the modeling and analysis were carried out using Minitab software (Version 17). Engine tests were carried out as per the run order given in Table 6 and the obtained experimental results were analyzed using ANOVA. Regression analysis was carried out to determine the coefficients of the equations which can be used to predict the engine output responses. The optimum combination of engine speed and blend composition was obtained using the desirability approach of RSM. To validate the optimized response parameters, experimental tests were conducted at identified optimum input parameters.

Table 2. Fuel Properties [17]

	Gasoline	Ethanol	Methanol
Molecular Formula	C_4-C_{12}	C_2H_5OH	CH_3OH
Molecular Weight	95-120	46	32
Oxygen content (%)	0	34.73	49.9
Density (kg/m^3)	731	789	791
Lower Heating Value, LHV (MJ/kg)	45.2	26.9	20.09
Research Octane number	95.3	109	109
Motor Octane number	85	92	88.6
Stoichiometric A/F ratio	14.8	9.0	6.5
Latent heat of vaporization (kJ/kg)	305	840	1100
Boiling point, °C	38-204	79	65

Table 3. Properties of Blended fuels

Fuel Component	E0 (G 100)	E10 (G90 E10)	E10_Eq (G 91.65 E 5 M 3.35)	E20 (G 80 E20)	E20_Eq (G 83 E 10 M7)
Stoichiometric A/F ratio	14.8	14.3	14.35	13.8	13.9
Density (kg/m^3)	731	736.3	736	742	741.6
Lower Heating Value (MJ/kg)	45.2	43.3	43.25	41.55	41.6
Research Octane Number, RON	95.3	98.3	98.2	100.5	100.38
Motor Octane Number, MON	85	86.58	86.41	87.7	87.3
Octane Number, ON	90.15	92.44	92.305	93.78	93.705

Table 4

S.No	Input Parameters	Parameters Type	Code	Level				
				1	2	3	4	5
1	Engine Speed (RPM)	Numerical	Speed	1700	2100	2500	2900	3300
2	Fuel Blends (%)	Numerical	Blend	E0	E10	E10_Eq	E20	E20_Eq

Table 5

S.No	Response Factors	Type	Code	Target
1	Brake Thermal Efficiency (%)	Numeric	B_The	Maximization
2	Brake Specific Consumption (g/kW hr)	Numeric	BSFC	Minimization
3	Nitrogen Oxide (ppm)	Numeric	NO_x	Minimization

Table 6. Experimental Design Matrix

Run	Speed (RPM)	Blend (%)	B_The (%)	BSFC (g/kW hr)	NO_x (ppm)
1	3300	E10_Eq	34.30	238.00	1550
2	2900	E10_Eq	34.90	243.00	1680
3	2900	E0	32.50	245.00	1892
4	3300	E20_Eq	35.34	245.10	1990
5	1700	E10_Eq	24.70	325.00	254
6	2500	E10	32.87	265.00	1325
7	3300	E0	33.20	239.90	1700
8	1700	E20	26.29	329.60	350
9	2900	E20	36.10	240.00	1985
10	2500	E0	30.30	261.13	1525
11	2100	E20	32.25	268.70	955
12	2500	E20_Eq	33.17	261.19	1770
13	2100	E20_Eq	32.18	269.23	1050
14	3300	E10	34.10	241.50	1590
15	2500	E20	34.04	254.50	1698
16	2100	E0	28.13	274.64	850
17	2100	E10	30.40	263.50	780
18	2900	E20_Eq	35.26	245.73	2110
19	3300	E20	35.74	244.00	1855
20	1700	E0	23.10	334.65	320
21	2900	E10	34.51	240.00	1700
22	2500	E10_Eq	31.29	262.00	1385
23	1700	E20_Eq	25.16	344.37	360
24	1700	E10	24.90	320.00	245
25	2100	E10_Eq	29.55	265.00	750

3. Results and Discussion:

3.1. Model analysis and evaluation:

The analysis of the developed model was carried out using ANOVA to give the numerical interpretation of the p-value. Table 7 indicates that the model is stable with the p-value being less than 0.0001 and the regression performance indicators like R^2 and R^2 –Adj being in agreement with each other. A high R^2 value, near 100, is desirable and a reasonable agreement with R^2 (Adj) is necessary. ANOVA results of the test data in Table 7 revealed that the values of R^2, R^2 (Adj), and R^2 (Pred) are in the range of 88.34% to 97.1% which indicates that the generated models are accurate. Fig. 2 shows the normal probability plots of residuals for engine response parameters (B_The, BSFC, NO_x). It can be observed from the figure that the majority of the data points form a straight line, signifying the correlation accuracy of regression equations with that of experimental data. The regression equations developed for different response parameters with different input parameters like speed and blend are expressed as below:

B_The = 15.05 + 7.172 Speed + 1.969 Blend - 0.792 Speed*Speed - 0.200 Blend*Blend - 0.0202 Speed*Blend (1)

BSFC = 393.1 - 67.75 Speed - 8.08 Blend + 8.03 Speed*Speed + 1.56 Blend*Blend - 0.250 Speed*Blend (2)

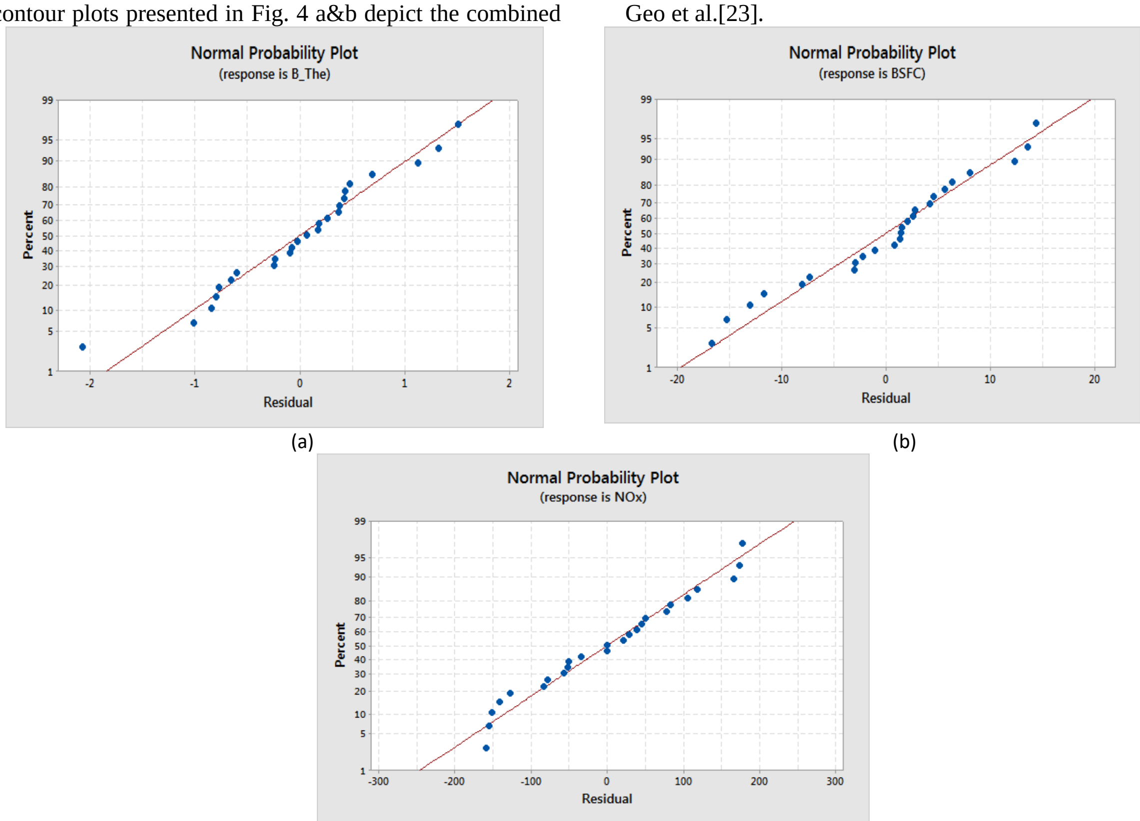
NO_x = -482 + 1090.2 Speed - 272.7 Blend - 124.7 Speed*Speed + 48.8 Blend*Blend + 14.7 Speed*Blend (3)

Table 7. ANOVA outcome for engine responses factors

Responses	B_The	BSFC	NO_x
p	0.00	0.00	0.00
R^2	95.91%	93.72%	97.10%
R^2 (Adj)	94.83%	92.07%	96.34%
R^2 (Pred)	93.24%	88.34%	95.21%

3.2. Effect of input parameters on Brake thermal efficiency (B_The)

Brake thermal efficiency variation with engine speed for different fuel blends is shown in Fig. 3. As it can be observed from the figure, the B_The is lower at lower engine speed and subsequently increases with engine speed. And also, it can be observed that the obtained B_The values of E10_Eq and E20_Eq equivalent ternary blends are identical to the binary E10 and E20 blends test data satisfying the hypothesis proposed by Turner et al. [11] that iso-stoichiometric blends have similar B_The as target binary blends at all engine speeds. Similarly, surface and contour plots presented in Fig. 4 a&b depict the combined effects of fuel blend composition and engine speed on B_The. The B_The of the engine is observed higher for E20 blends at all engine speeds compared to other fuels. This is because the higher alcohol content increases the oxidizing nature of blended fuel and its high latent heat of vaporization causes an increase in brake power and volumetric efficiency of the engine. And also, high laminar burning velocities of alcohols contribute to quick and near complete combustion of the air-fuel mixture by decreasing heat loss from cylinder walls [1]. The average increase in B_The for E10, E10_Eq, E20, and E20_Eq is 6.4%, 5.98%, 11.6%, and 10.8% compared to E0 for a given range of speeds and are in agreement with the results reported by Geo et al.[23].



(c)

Figure 2. Normal probability plots of residual for (a) B_The, (b) BSFC, (c) NO_x

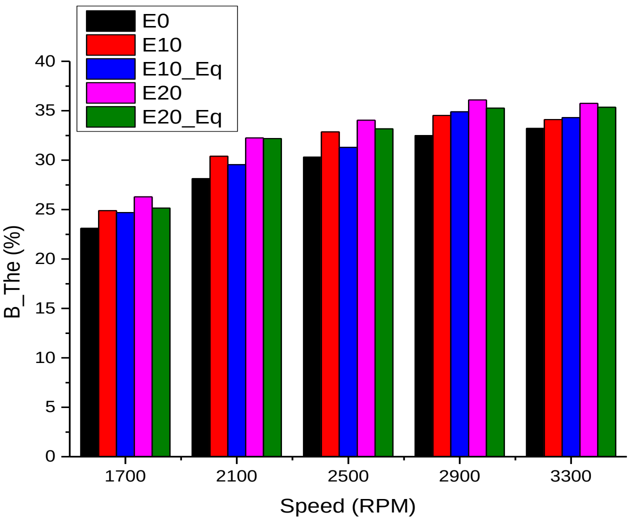


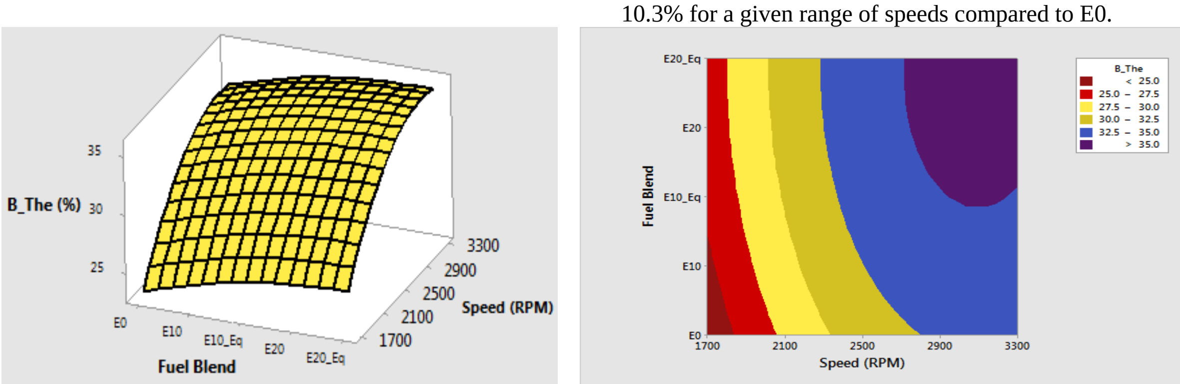
Figure 3. Comparison of B_The of engine for different speeds and blends

3.3. Effect of input parameters on Brake Specific Fuel Consumption (BSFC)

BSFC is defined as the ratio of the rate of fuel consumption to brake power of the engine. Fig. 5 depicts the effect of engine speed and fuel blend on BSFC. From the surface plot, it can be observed that BSFC decreases with an increase in engine speed, whereas the addition of alcohol has a varying effect on it. For E10 and its E10_Eq blends, BSFC decreases by 1.8% and 2.1% when compared to pure gasoline (E0). This is due to the high latent heat of vaporization of alcohols, which increases the density of the air-fuel mixture in an engine cylinder. This causes an increase in the brake power of the engine compared to pure gasoline [5]. But with an increase in ethanol content to 20%, the lower heating value of the blended fuel decreases further compared to pure gasoline, this dominates the increase in brake power of engine for alcohol blended fuels. Thus, to maintain the same speed, the engine consumes more fuel for higher alcohol blended fuels (i.e; E20 and E20_Eq). The average increase in BSFC for E20 and E20_Eq are 1.3% and 1.24% for a given range of speeds compared to E0.

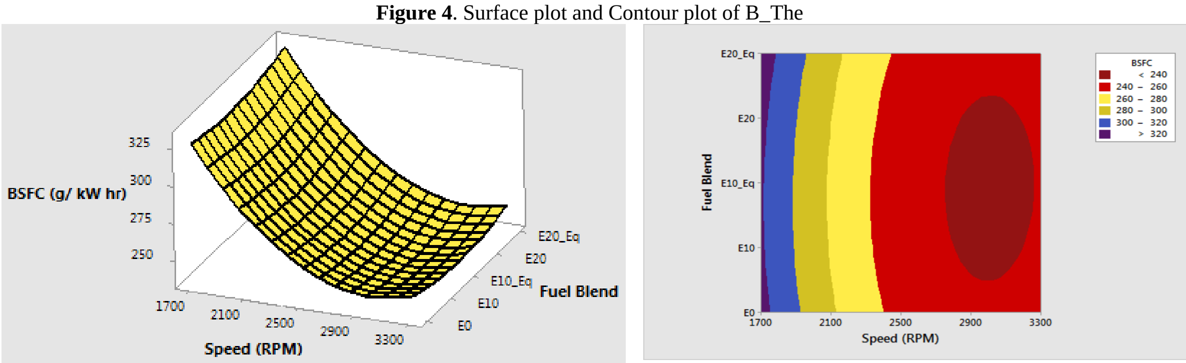
3.4. Effect of input parameters on Nitrogen Oxides (NOx)

Nitrogen oxides (NO_x) formation in the engine cylinder mainly depends on the availability of excess oxygen, in-cylinder temperatures, and engine operating conditions. During the combustion process, nitrogen molecule dissociates at high in-cylinder temperatures and reacts with oxygen molecules, and results in the formation of NO_x emissions [24]. Fig. 6 shows the effect of engine speed and fuel blend composition on the variation of NO_x by using surface and contour plots. It can be observed from the figure that, NO_x emissions decrease by 10.29% and 11.21% for E10 and its equivalent blends compared to pure gasoline. This is due to the high latent heat of vaporization of alcohol blended fuel, which results in lower in-cylinder temperatures inside the engine combustion chamber [23]. But with the further addition of ethanol to 20% by volume and for its equivalent blend, NO_x formation increases compared to pure gasoline. This is due to the increase in excess oxygen concentration inside the cylinder, because of the oxygenated nature of alcohol blended fuels [9]. The average increase in NO_x for E20 and E20_Eq is 9.2% and 10.3% for a given range of speeds compared to E0.



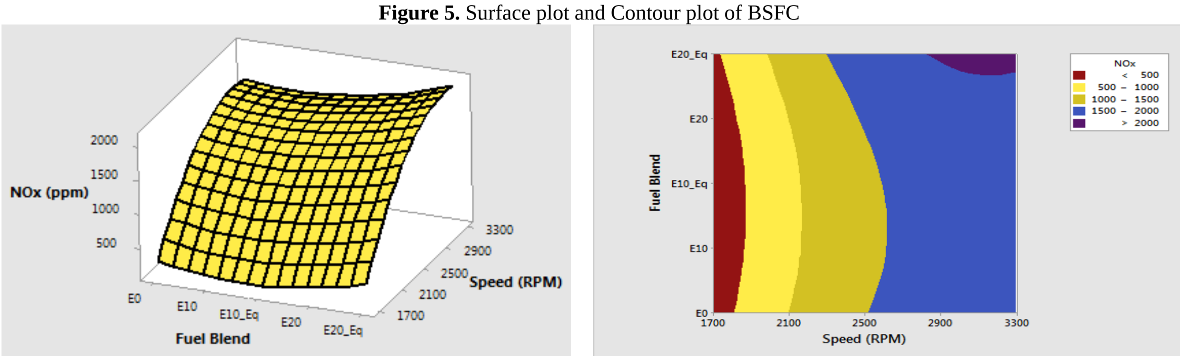
(a) (b)

Figure 4. Surface plot and Contour plot of B_The



(a) (b)

Figure 5. Surface plot and Contour plot of BSFC



(a) (b)

Figure 6. Surface plot and Contour plot of NO_x

3.5. Response optimization:

In the present work, an RSM optimizer was used to determine the optimum combination of B_The, BSFC, and NO_x, with an objective of maximizing the B_The and minimizing BSFC and NO_x. Fig. 7 shows the results of RSM and as it can be seen, optimum values of B_The, BSFC, and NO_x emissions are 33.17%, 251 g/kW-hr, 1389.8 ppm respectively. These optimum values are obtained with a composite desirability value of 0.6401, at input parameters, 2416 rpm of engine speed with E10_Eq blended fuel. The obtained value of composite desirability is similar to the composite desirability value reported by [15, 25].

3.6. Experimental Validation:

To validate the RSM optimum results, engine experiments were carried out at 2416 rpm for E10_Eq blended fuel. The details of the engine experimental responses are shown in Table. 8. The obtained results were compared with the optimized values and it is noticed that the optimized values are in good agreement with the experimental data with an error less than 1.5 %.

Table 8. Validation experiments

Speed (rpm)	Blend	Value	B_The (%)	BSFC (g/kW hr)	NO_x(ppm)
2416	E10_Eq	Predicted	33.17	251	1389.8
		Actual	32.68	248	1361.5
		Error (%)	1.47	1.19	1.01

4. Conclusion:

The present work aimed to find out the optimum engine operating state as to maximize its performance and minimize emission by using RSM. Different gasoline-ethanol-methanol binary and ternary fuel blends and engine speed were considered as input parameters while considering B_The, BSFC, and NO_x as response parameters. The engine tests were performed at constant load and varied speeds from 1700 to 3300 rpm. The obtained results of the gasoline alcohol blend were compared with pure gasoline. The following conclusions have been drawn from the obtained results:

1. Formulated E10 and E20equivalent iso-stoichiometric blends, namely E10_Eq, E20_Eq have identical air to fuel ratio, lower heating values, RON, MON, and Octane number as target E10 and E20 blends.
2. B_The of the engine is similar for equivalent blends at different engine speeds due to the same air to fuel ratios and lower heating values as target binary blends.
3. Adding ethanol and methanol to gasoline increased the brake thermal efficiency of the engine to a maximum of 11.6% for the E20 binary blend.
4. BSFC and NO_x were observed to be decreasing for E10 and its equivalent blends, whereas it was found to be increasing for E20 and its equivalent ternary blends.
5. ANOVA study revealed that the values of R^2, R^2 (Adj), and R^2 (Pred) are in the range of 88.34% to 97.1% for the response factors.
6. The optimized values of B_The, BSFC, and NO_x emissions are 33.17%, 251 g/kW-hr, 1389.8 ppm respectively, when the input parameters are at an engine speed of 2416 rpm using E10_Eq blended fuel with composite desirability of 0.6401.
7. RSM optimum results were confirmed by conducting validation experiments at optimized input conditions namely, at an engine speed of 2416 using E10_Eq fuel blend. The difference between the experimental results and optimized values are in good agreement with other with an error of less than 1.5%.

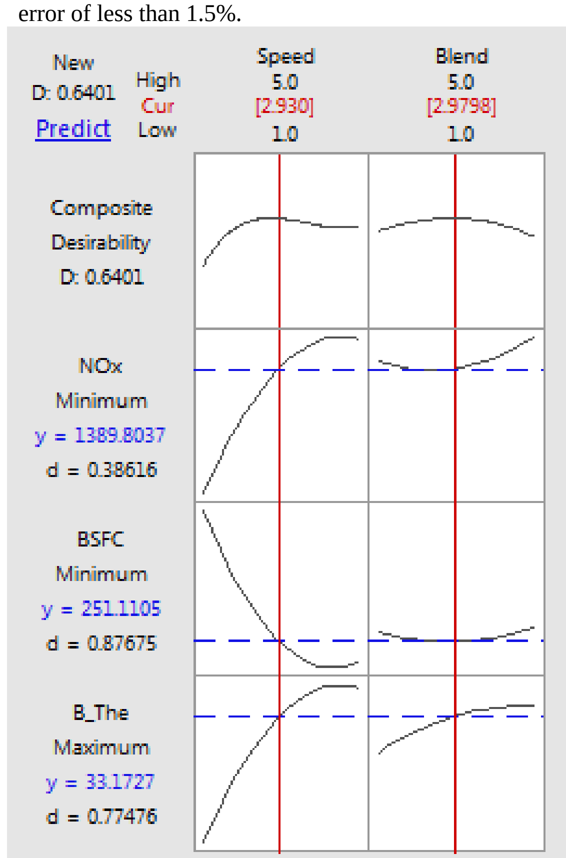


Figure 7. RSM optimizer

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