Parametric Optimization of 4-Stroke Spark Ignition Engine Fuelled with Ethanol Blended Gasoline using Response Surface Methodology

[1] Mr. G. A. Kapadia, [2]Prof. P. D. Patel, [3] Prof. T. M. Patel

[1]Lecturer in Automobile Engineering, Automobile Engg. Department, Govt. Ploy., Ambawadi, Ahmedabad, India.
[2]Asst. Professor in Automobile Engineering, Automobile Engg. Department, L. D. C. E., Ahmedabad, India.
[3] Asst. Professor in Mechanical Engineering Department, L. D. R. P. College, Gandhinagar, India.

***Abstract*— This paper studies the use of RSM (Response Surface Methodology) to optimize the performance parameters of a 4-stroke spark ignition engine which operates with ethanol blended gasoline as fuel. The main objective was to optimize the engine parameters for minimum Brake Specific fuel Consumption (BSFC). The test were conducted on a Variable Compression Ratio engine test rig with different combinations of Compression Ratios (CR), Blend Ratio (BR) and Load. The experiments were designed with a statistical tool also known as DoE based on Response Surface Methodology (RSM). In Comparison with gasoline, the concentration of HC and CO in exhaust found decreased with ethanol blended gasoline as fuel, but CO2 and NOx in emission were found increased. The engine variable parameters were optimized using desirability approach of RSM. The value of 9.5 for compression ratio, 10% blend for ethanol and 6.5 Kg load were found to be optimal values. BSFC and BTE were found 0.432 Kg/kWhr and 19.45 % respectively at optimum value of the parameters.**

Keywords: Box-Behnken, Brake Specific Fuel Consumption, Optimization, Response Surface Methodology

I. INTRODUCTION

Using renewable energy resources has become an important feature of worldwide energy policy which aims to reduce greenhouse gas emissions caused by fossil fuel usage. India, is the fourth GHG emitter, the fifth largest energy consuming country and the second most populous country in the world. Naturally, there will be an increase in energy demand every year. India will need to import large amounts of energy from other countries in order to meet its energy demands. Although India's per capita emissions are very less than half the world's average, in 2010, its transport sector accounted for 13 percent of the country's energy-related GHG emissions. Hence, India needs to find good energy generation sources to meet its demands thereby providing a good market for biofuels.[1]

The main reason for blending ethanol with gasoline is to minimize fossil carbon dioxide emissions from vehicles by using bio-ethanol originating from renewable sources. Blending ethanol with gasoline has the two advantages that even with relatively small percentage additions will result in a substantial total volume of gasoline substitution, and the present infrastructure for distributing fuels can be used largely unchanged. The changes in fuel composition affects these vehicle performance qualities a purely dependent on the individual vehicle. It will depend on engine design, fuel and control system and also emissions control equipment.

Literally translated, the Latin term optimum means the best. Following this translation, optimization would refer to the search for the best solution to a problem. In the most simple case, parametric optimization means finding maxima or minima of a single evaluation criterion. So parametric optimization means determining the best value of variable parameters for best performance of the engine with reference to the title. Optimization is the act of obtaining the best result under given circumstances. optimization can be defined as the process of finding the conditions that give the maximum or minimum value of a function.

Due to continuously increase of fuel demand day by day which also increases the consumption of fossil fuels i.e. gasoline, diesel etc. To overcome the demand of fossil fuel and reduce their consumption, alternate biofuel or blended fuel should be used in IC engine which can be partially mixed with fossil fuel and gives the better performance on the engine. There are number performance parameters in internal combustion engine like Power, BSFC, Brake thermal efficiency and specific fuel consumption. The parameter SFC and BTE is normally used for to compare performance of different engines. SFC can be defined as the amount of fuel consumed for each unit of brake power per hour.

The brake specific fuel consumption found decreasing as the compression ratio increases on a light duty spark ignition engine [1,3]. The blend ratio (5-10-15) in case of blended fuel also affect SFC and BTE [1,2]. The blend ratio also affect the emission characteristics.[1,2] It is found as the blend ratio increases SFC & BTE increases. The BSFC generally increased with the increase in bioethanol percentage in the fuel blend.

II. RESPONSE SURFACE METHODOLOGY (RSM)

Response surface methodology, or RSM, is a collection of mathematical and statistical techniques useful for the modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response.

In statistics, response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables. RSM designs are useful for investigating the nature of relationship between the response and factors. These designs models the quadratic effect of factors and so they are well suited for optimization and modelling. The method was introduced by G. E. P. Box and K. B. Wilson in 1951. The main idea of RSM is to use a sequence of designed experiments to obtain an optimal response. Response surface methodology uses statistical models, and therefore practitioners need to be aware that even the best statistical model is an approximation to reality. In practice, both the models and the parameter values are unknown, and subject to uncertainty on top of ignorance. Of course, an estimated optimum point need not be optimum in reality, because of the errors of the estimates and of the inadequacies of the model. Nonetheless, response surface methodology has an effective track-record of helping researchers improve products and services.

For example, suppose that a chemical engineer wishes to find the levels of temperature (x1) and pressure (x2) that maximize the yield (y) of a process. The process yield is a function of the levels of temperature and pressure, say

$$y = f(x1, x2) + \epsilon$$

where ϵ represents the noise or error observed in the response y. If we denote the expected response by $E(y) = f(x1, x2) = \eta$, then the surface represented by, $E(y) = f(x1, x2) = \eta$ is called a response surface.

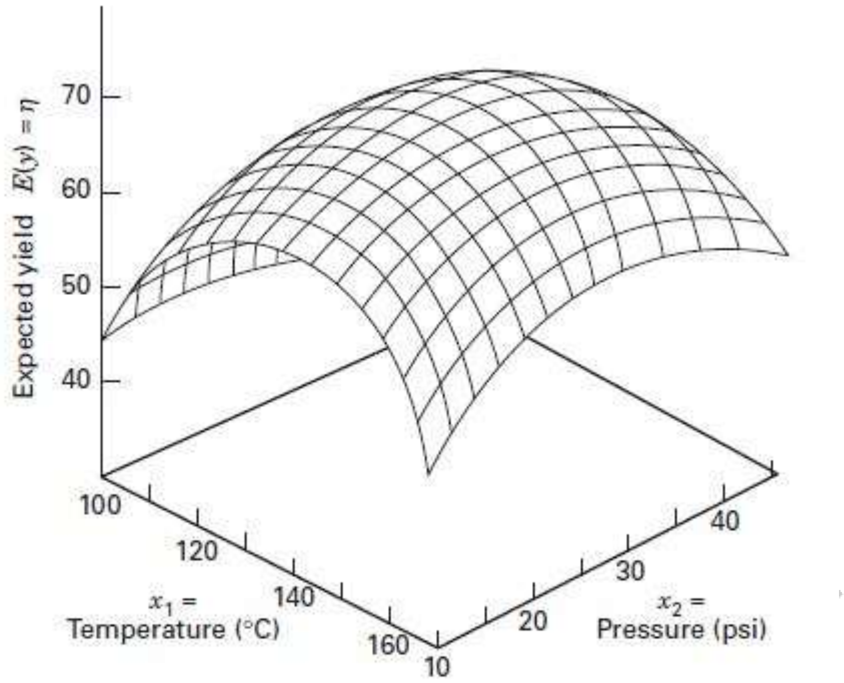


Figure 1: A 3-D response surface showing expected yield as a function of temp. & press.
(Ref. Design and analysis of experiments By: Douglas C. Montgomery)

III. Objectives of the Present Investigation:

The objective of the present investigation is to carry out research work in the field in which bio-ethanol or its blend is used as fuel in I. C. engine so that experimental data can be collected which can be used to improve fuel economy in automobile. Also its objective is to optimize the value of various parameters such as compression ratio, blend ratio etc for best performance of the engine and to improve its emission characteristics & to find the best alternate option of fossil fuels.

The objectives of this investigation can be summarized as:

(1) Experimental determination of the effects of the various parameters like compression ratio, blend ratio, load on the performance measures like BSFC, BTE.

(2) Implement an optimization technique that could give global optimum parameters to minimize BSFC and to achieve required performance and emission characteristics.

(3) Modelling of the performance measures using response surface methodology (RSM).

IV. Selection of parameters:

There are various parameters available for maximizing performance of I. C. engine like as, compression ratio, blend ratio, load, speed, AFR, Injection pressure, spark timing etc. For present work three parameters from above listed are selected as compression ratio, blend ratio and load based on their importance and availability of experimental facility.

Based on literature available, test rig specification and past experiments conducted, value of parameters for experiments are selected as following.

Table 1: Selection of Parameters:

Parameters	Compression Ratio	Blend Ratio (% Ethanol)	Load (Kg)
1	8	5	1
2	9	10	4
3	10	15	7

V. SELECTION OF RESPONSE PARAMETERS:

The performance of engine can be evaluated by various performance measures such as, Brake specific fuel consumption, Brake thermal efficiency, Power, Torque, Specific fuel consumption etc. Among them BSFC is very important because for comparing the performances of various engines generally it is used. Also BTE is very useful for competetive stategy, but for present work response parameters selected is as follow.

- BSFC (Brake Specific Fuel Consumption)

VI. EXPERIMENTAL SET UP:

The setup consists of single cylinder, four stroke, Multi-fuel, research engine connected to eddy current type dynamometer for loading. The operation mode of the engine can be changed from diesel to Petrol or from Petrol to Diesel with some necessary changes. In both modes the compression ratio can be varied without stopping the engine and without altering the combustion chamber geometry by specially designed tilting cylinder block arrangement. The injection point and spark point can be changed for research tests. Setup is provided with necessary instruments for combustion pressure, Diesel line pressure and crank-angle measurements. These signals are interfaced with computer for pressure crank-angle diagrams. Instruments are provided to interface airflow, fuel flow, temperatures and load measurements. The set up has stand-alone panel box consisting of air box, two fuel tanks for duel fuel test, manometer, fuel measuring unit, transmitters for air and fuel flow measurements, process indicator and hardware interface. Rotameters are provided for cooling water and calorimeter water flow measurement. A battery, starter and battery charger is provided for engine electric start arrangement. The setup enables study of VCR engine performance for brake power, indicated power, frictional power, BMEP, IMEP, brake thermal efficiency, indicated thermal efficiency, Mechanical efficiency, volumetric efficiency, specific fuel consumption, A/F ratio, heat balance and combustion analysis. Labview based Engine Performance Analysis software package “Enginesoft” is provided for on line Performance evaluation.

VII. TABLE 2: TECHNICAL SPECIFICATION OF THE ENGINE:

Equipment	Research Engine test setup 1 cylinder, 4 stroke, Multifuel (Computerized)
Engine Type	1 cylinder, 4 stroke, water cooled, stroke 110 mm, bore 87.5 mm. Capacity 661 cc.
Diesel mode	Power 3.5 KW, Speed 1500 rpm, CR range 12:1-18:1. Injection variation:0- 25 Deg BTDC
Petrol mode	Power 4.5 KW @ 1800 rpm, Speed range 1200-1800 rpm, CR range 6:1-10:1, Spark variation: 0-70 deg BTDC
Dynamometer Type	eddy current, water cooled, with loading unit
Propeller shaft	With universal joints
Air box	M S fabricated with orifice meter and manometer
Fuel tank Capacity	15 lit, Type: Duel compartment, with fuel metering pipe of glass
Software	“Enginesoft” Engine performance analysis software
Rotameter	Engine cooling 40-400 LPH; Calorimeter 25-250 LPH
Pump Type	Monoblock

VIII. TEST PROCEDURE:

- The experiment has been performed as per guidelines given in IS:10000.
- Correction factor for power and fuel consumption has been calculated as per guidelines given in IS:10000 Part-IV. Section II. Clause 7 & 8.
- The blend was prepared just before the start of experiment, So no emulsifier was used.
- Measurement of fuel consumption was done on volumetric basis. Also the engine RPM was recorded.
- The experiment was performed for 13 runs as explained in design of experiment.

IX. TABLE 3: LEVELS AND CODE OF VARIABLE FOR BOX-BEHNKEN DESIGN:

Variables	Symbol		Code Levels		
	Uncoded	Coded	Low (-1)	Intermediate (0)	High (+1)
Compression Ratio	X_1	A_1	8	9	10
Blend Ratio (% Ethanol)	X_2	A_2	5	10	15
Load	X_3	A_3	1	4	7

X. TABLE 4: BOX BEHNKEN DESIGN METRIX FOR 17 RUNS:

RUN	DESIGN PARAMETERS			RUN	DESIGN PARAMETERS			RUN	DESIGN PARAMETERS		
	A1	A2	A3		A1	A2	A3		A1	A2	A3
1	0	0	0	7	0	0	0	13	0	1	-1
2	-1	1	0	8	0	-1	1	14	1	1	0
3	0	1	1	9	-1	-1	0	15	0	-1	-1
4	0	0	0	10	1	0	1	16	1	-1	0
5	-1	0	-1	11	0	0	0	17	0	0	0
6	-1	0	1	12	1	0	-1				

XI. REGRESSION MODELLING:

For predicting the optimum point, a second order polynomial model is developed to establish relationship between the engine parameters and the response (BSFC). The result achieved through the 13 experimental runs- designed based on Box-Behnken design with three engine parameters (CR, BR & LOAD) and three levels (-1, 0 & +1), indicating three replicate at the centre point is used for fitting a second order polynomial equation. The model is cross checked with an F-test and the determination coefficient R2. The ANOVA (analysis of variance) (for brake specific fuel consumption as response) has been shown in table 5.2 indicates that the model is highly significant ($p < 0.0001$) with F value of 246.30. In this case the term C, C2 are significant model terms. For three variable factors, the equation obtained is,

$$Y = BSFC = \beta 0 + \beta 1A + \beta 2B + \beta 3C + \beta 12AB + \beta 13AC + \beta 23BC + \beta 11A^2 + \beta 22B^2 + \beta 33C^2$$

Where, Y = Predicted Response (BSFC)

β0 = Model Constant

A, B, C = Engine parameters (CR, BR and LOAD)

β1, β2, β3 = Linear Coefficient

β12, β13, β23 = cross product coefficient

β11, β22, β33 = quadratic coefficient

The coefficient of the quadratic model are described in the following table.

Table 5: Coefficient of the polynomial equation: (BSFC)

Sr. No.	Constant	Value
1	β0	+5.90598
2	β1	-0.28541
3	β2	-0.065004
4	β3	-1.26658
5	β12	+4.851E-003
6	β13	+0.024736
7	β23	+5.23333E-005
8	β11	+2.71875E-003
9	β22	+1.30245E-003
10	β33	+0.088029

XII. TABLE 6: SIGNIFICANT TEST (ANOVA) OF THE SECOND ORDER POLYNOMIAL EQUATION: (BSFC)

Source	Sum of Squares	df	Mean Square	F value	p-value prob>F	Remark
Model	11.05	9	1.23	246.30	<0.0001	Significant
A-CR	0.063	1	0.063	12.72	0.0091	Significant
B-BR	4.828E-003	1	4.828E-003	0.97	0.3579	
C-LOAD	8.28	1	8.28	1661.39	<0.0001	Significant
AB	2.353E-003	1	2.353E-003	0.47	0.5142	
AC	0.022	1	0.022	4.42	0.0737	
BC	2.465E-006	1	2.465E-006	4.943E-004	0.9829	
A^2	3.112E-005	1	3.112E-005	6.242E-003	0.9392	Significant
B^2	4.464E-003	1	4.464E-003	0.90	0.3756	
C^2	2.64	1	2.64	530.04	<0.0001	Significant
Residual	0.035	7	4.986E-003			
Lack of Fit	0.035	3	0.012			
Pure Error	0.000	4	0.000			
Cor Total	11.09	16				

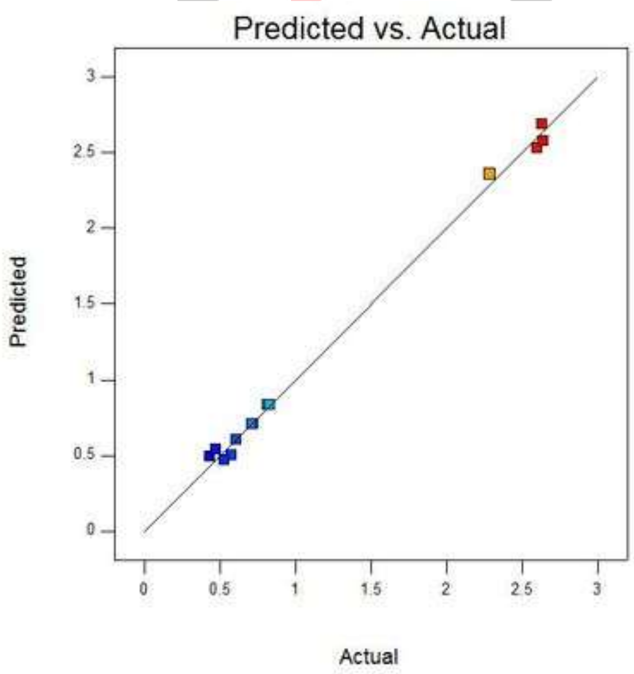
The model F value is 246.30 implies that the model is highly significant.

XIII. Validation of the Model:

The validation of the model is done by comparing the experimental value with the predicted values, which is shown in the following table. The following table 5.3 shows the difference between the experimental value and predicted value is very less. The results shows that the developed model is quite accurate

Table 7: Comparison of actual BSFC v/s Predicted BSFC as per above equation:

RUN	Engine Parameters			BSFC (Kg/kWh)		
	A	B	C	Experimental	Predicted	Difference
1	0	0	0	0.709	0.710	0.001
2	-1	1	0	0.830	0.830	0.000
3	0	1	1	0.470	0.540	0.07
4	0	0	0	0.709	0.710	0.001
5	-1	0	-1	2.63	2.68	0.05
6	-1	0	1	0.576	0.500	0.076
7	0	0	0	0.709	0.710	0.001
8	0	-1	1	0.432	0.490	0.058
9	-1	-1	0	0.817	0.830	0.013
10	1	0	1	0.467	0.470	0.003
11	0	0	0	0.709	0.710	0.001
12	1	0	-1	2.284	2.360	0.076
13	0	1	-1	2.63	2.58	0.05
14	1	1	0	0.720	0.700	0.020
15	0	-1	-1	2.599	2.530	0.069
16	1	-1	0	0.610	0.610	0.00
17	0	0	0	0.709	0.710	0.001



XIV. RESULTS AND DISCUSSIONS:

(1) Interactive effect of Compression ratio (CR) and Blend ratio (BR) on response function (BSFC):

The simultaneous effect of compression ratio and blend ratio on BSFC has been shown in following figure. The BSFC is found decreasing significantly as the compression ratio is increased. Also the blend ratio has some effect on BSFC. On varying compression ratio, the effect on BSFC can be visualized from the figure. The minimum value of BSFC can be found at compression ratio of around 9. The minimum value of BSFC can be found for blend ratio of around 10 as seen on the graph.

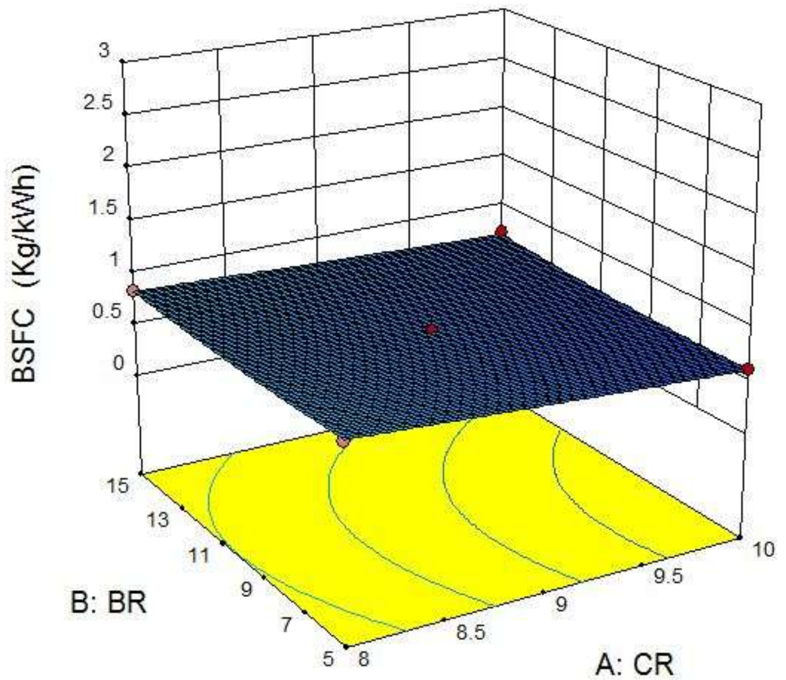


Figure 2: Interactive effect of CR & BR on BSFC

(2) Interactive effect of Compression ratio (CR) and Load on response function (BSFC):

The simultaneous effect of CR and Load on BSFC is shown in the following graph. As seen in the graph, as the load is increased, the BSFC is found decreasing significantly. Also the BSFC is found decreased as the compression ratio is increased. As seen from the graph the minimum value of BSFC is found around 6.5 Kg load and compression ratio of 9. From the figure it is clear that the load has significant effect on the BSFC.

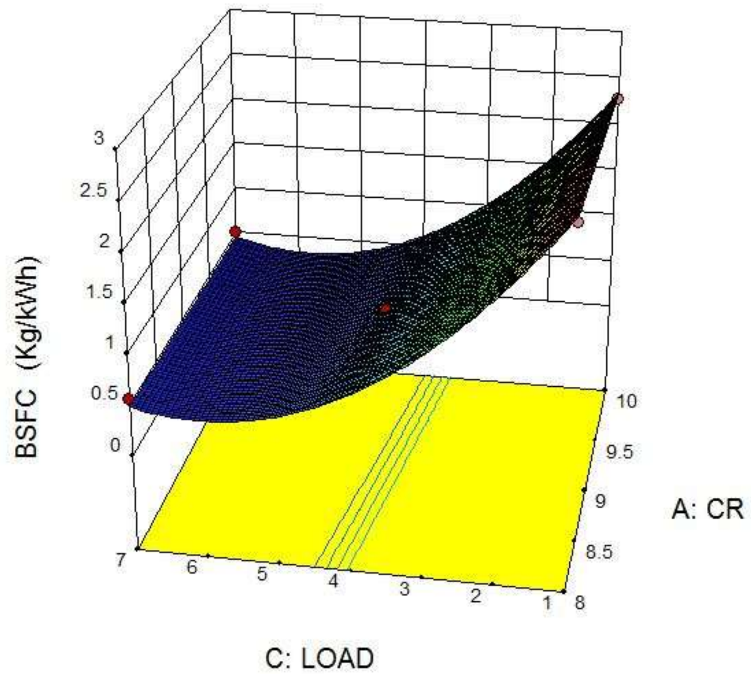


Figure 3: Interactive effect of CR & Load on BSFC

(3) Interactive effect of Load and Blend ratio (BR) on response function (BSFC):

The simultaneous effect of blend ratio and load on BSFC is shown in following figure. As seen in the figure the effect is quite significant. As the load is increased, the BSFC is found decreased. For blend ratio, as the value is increased first the BSFC is found decreased then for further increase in blend ratio it is found decreased slightly. The minimum BSFC can be found for value of around 6.5 Kg load and around blend ratio of 10% ethanol.

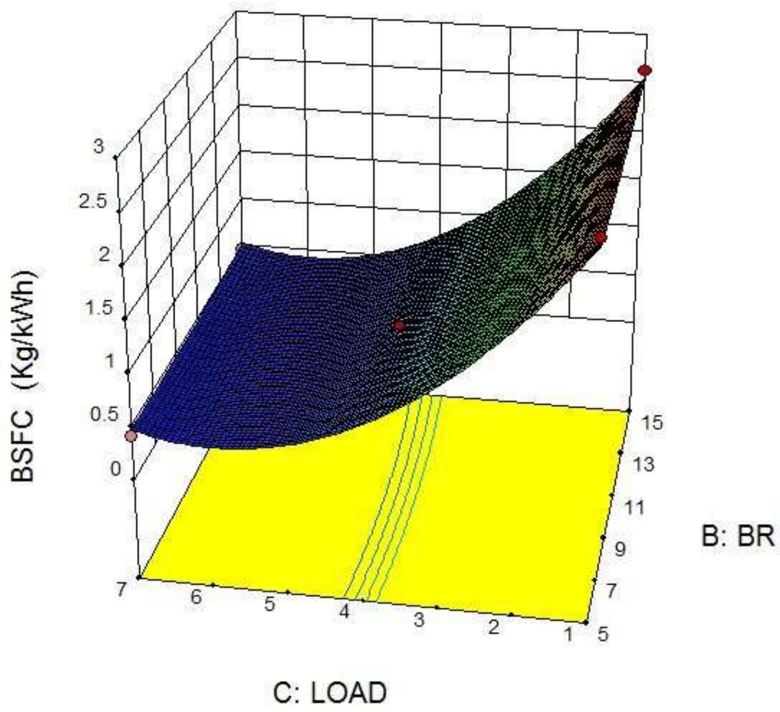


Figure 4: Interactive effect of Load & BR on BSFC

XV. **SUMMARY OF THE RESULT & CONCLUSIONS:**

From above analysis which is based on Box-Behnken Response surface analysis, it is suggested that the optimum combination of engine parameters for minimum BSFC is: Compression Ratio 9.5, Blend Ratio 10 and load 6.5 kg.

Table 5.5 Summary of Results: (BSFC)

Parameters	**Value**			**BSFC (Kg/kWh)**	
	Optimized Value	Low Level	High Level	Predicted	Experimental
Compression Ratio CR	**9.5**	8	10	**0.400**	**0.432**
Blend Ratio BR	**10**	5	15		
Load Kg	**6.5**	1	7		

Also, it can be shown from the experiment that, with minimum number of experiments, Box-Behnken design based Response surface methodology is powerful and useful tool to understand the interactive effects of various engine parameters on the response (BSFC). A quadratic model is developed, which establishes the relation between response (BSFC) and the parameters. Verification of the model is done with ANOVA. Also validation of the model is done by comparing the experimental data and the data predicted from the model.

From the experiment conducted and result obtained, it can be concluded that:

1. RSM can be used to optimize the engine performance and exhaust emissions.
2. Adding ethanol in gasoline fuel can improve engine performance and reduce CO and HC emissions. But it can also cause increase in emission of CO_2 and NO_x.
3. The RSM was highly helpful in designing the experiment. Also it was helpful in statistical analysis and to identify significant parameters which are most influencing on engine performance and emission characteristics. The design of experiment considerably reduced the time required by minimizing the number of experiment to be performed.
4. The performance parameters for different ethanol-gasoline blends were found close to gasoline and emission characteristics of the engine improved significantly. The results of this study revealed that at optimal input parameters, the values of BSFC and BTE were found 0.432 and 19.45 respectively.

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