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Mathematical Modeling of SFC Using RSM for CI Engine Fuled with Soybean Biodiesel and Diesel Blend

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Abstract: *Increasing demand of fossile fuel there is need to study a number of renewable sources. In present investigation influence of input parameter such as injection pressure, compression ratio and load on the performance of single cylinder diesel engine fueled with soybean biodiesel and its blend. The test are carried out with three different injection pressure (160, 200, 240 bar), compression ratio (18, 17, 16), load (1, 6, 11) and %of biodiesel (100%, 50%, 0%). This study investigated by Response Surface Methodology to optimize the performance parameter such as break specific fuel consumption (BSFC). A set of experimental runs was established by using a Central Composite Design (CCD) and the response surface method was employed to obtain the regression model for the break specific fuel consumption for different values of input parameter. The individual effects of these parameters and the combined effects of multiple parameters are examined. The experimental results reveal that the soybean biodiesel and its blend provide better engine performance and reduce break specific fuel consumption (BSFC) compared to diesel with little change in input parameter.*
Keywords: *Brake specific fuel consumption (BSFC), Parametric Optimization, RSM, Soybean biodiesel.*

I. Introduction

Developing renewable energy has become an important part of worldwide energy due to the depletion of fossil fuel. Alternative transport fuels such as hydrogen, natural gas and bio-fuels are seen as an option to help the transport sector in decreasing its dependency on oil [1]. Alternative fuels for the diesel engines are becoming important due to the diminishing petroleum reserves. Many countries around the world have passed legislations that diesel should contain a minimum percentage of bio-fuels. The best record available is that of the Czech Republic, which insists on 100% bio-fuel use for transportation (Paramathma 2004) [2]. Today many countries worldwide, including India, produce and use biodiesel. Bio-fuel sources, particularly Soybean oil have attracted much attention as an alternative energy source. It is renewable, available everywhere and has proved to be a cleaner fuel and more environment friendly than the fossil fuels. However engine test results showed durability problems with soybean oil because of higher viscosity of soybean oil. Blending and transesterification may overcome this problem. To achieve a better result with bio-fuel there is some modification made in input parameter.

II. Literature Review

The consumption of the crude oil increase day by day. There is also increases consumption of diesel fuel because diesel is a main source of transportation and passenger vehicle. For to reduce diesel fuel consumption there is alternate fuel or blended fuel used in IC engine which can be partially mixed with diesel and give good performance on IC engine. There are so many performance parameters in diesel engine like Power, Mechanical Efficiency and brake specific fuel consumption. The BSFC are normally used for to compare performance of different engines. It is defined as the amount of fuel consumed for each unit of brake power per hour.

The brake specific fuel consumption found decreasing as the injection pressure decrease (250-200-150 bar) on a light duty direct injection diesel engine [3]. The compression ratio 17 considered as optimum compression ratio for variable compression ratio (CR =15,16,17,18,19) diesel engine at rated speed of 1500 rev/min. which gives optimum value for fuel economy. The compression ratio 18 is also very close to optimum value for fuel economy [6]. With increase in Compression Ratio the specific fuel consumption decreases [8].

The BSFC generally increased with the increase in biodiesel percentage in the fuel blend [5]. So there is need to do engine modification for to achieve better performance. The minimum BSFC values were obtained with the increased injection pressure because of improved atomization and better mixing process. As compression ratio increases (14,16,18) there is BSFC decreases in B20 biodiesel [7]. It is also observed that the increased injection pressure & compression ratio gave the better results for BSFC and BTE compared to the original and decreased in DI diesel engine fueled with biodiesel-blended diesel fuel [5].

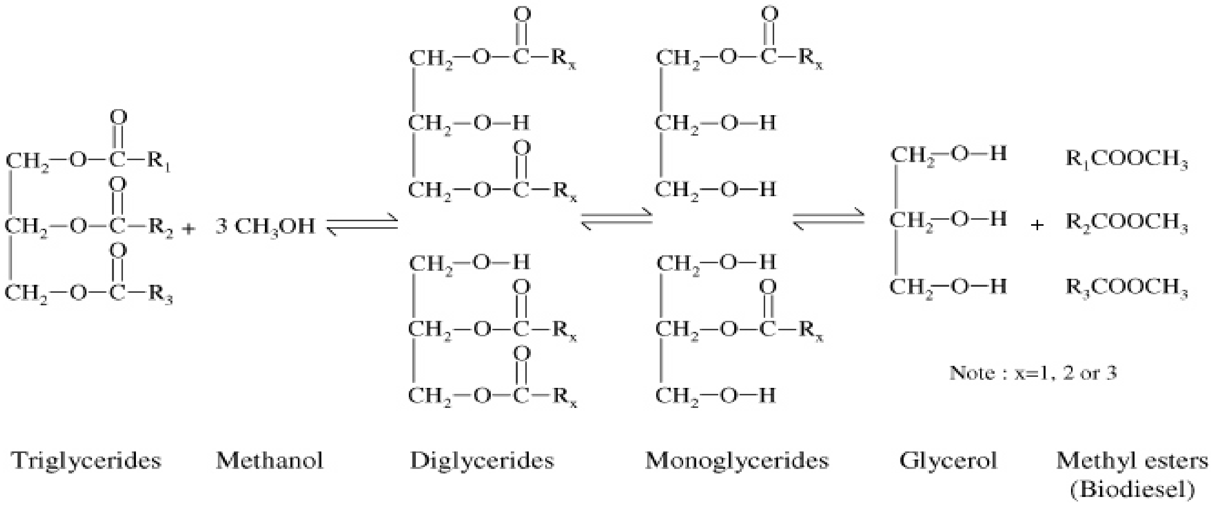
2.1 Soybean oil

Soybean oil is produced from the seeds of soybean which are green or yellow in color and smaller in size. For to extract oil from soybean there is need to cleaned, dried and dehulled soybean. The soybean hulls needs to be removed because they absorb oil and give a lower yield. Magnets are used to separate any iron from the soybeans. The soybeans are cut in flakes which are put in percolation extractors and immerged with a hexane. The hexane is separated from the soybean oil in evaporators. The oil-insoluble material are removed with filtration and the soluble materials is removed with different processes including degumming (removing of phosphatides), alkali refining (washing with alkaline solution to remove free fatty acids, colorants, insoluble matter and gums) and bleaching (with activated earth or activated carbon to remove color and other impurities. The Table 1 shows the various physico-chemical properties of soybean biodiesel and diesel.

Table 1. Physico-Chemical Properties of Soybean biodiesel and Diesel[2].

Property	Soybean	Diesel
Calorific value (MJ/kg)	39.76	42–45.9
Relative density	0.885	0.82–0.867
Kinematic viscosity at 40◦C (cSt)	4.08	2.5–5.7
Cetane number	40–53	45–55
Flash point (◦C)	69	50–86
Fire point (◦C)	−	60–92
Cloud point(◦C)	−2	(−15 to 5)
Pour point (◦C)	−3.8	(−35 to −15)
Sulphur content (%wt)	0.01	1.2–2

Transesterification process used for converting this soybean oil into a soybean biodiesel. It is the displacement of alcohol from an ester by another alcohol in a similar process to hydrolysis [4].



Transesterification process

Note: Methanol is inflammable and potassium hydroxide is caustic, hence proper and safe handling of these chemicals is required.

III. Experimental Setup

The setup consists of single cylinder, four stroke, multi-fuel, research engine connected to eddy type dynamometer for loading as shown in Fig.1. The operation mode of the engine can be changed from diesel to Petrol of from Petrol to Diesel with some necessary changes. In both modes the compression ration 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 flow measurements, process indicator and hardware interface. Rota meters are provided for cooling water and calorimeter water flow measurement. A battery, starter and battery charger is provided for engine electric start arrangement [1].

Figure 1 Experimental setup

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. Lab view based Engine Performance Analysis software package "Engine soft" is provided for on line performance evaluation. Table 2 shows Technical specification of C.I Engine [1].

Table 2. Technical Specifications[1]

Item	Specification
Model	TV1
Make	Kirlosker Oil Engines
Type	Four stroke, Water cooled, Diesel
No. of cylinder	One
Bore	87.5 mm
Stroke	110 mm
Compression ratio	12 to 18
Power rating	7.5 HP
Injection timing	$\leq 25^{\circ}$ BTDC

IV. Methodology

Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize response [2]. In practice the requirement of RSM for to chose the sample point such that the sufficient accurate model can be generated with the minimum number of experiments. Response Surface Method is used to examine the relationship between a response and a set of quantitative experimental variables or factors.

4.1 Following step are carried out for RSM

4.1.1 Determination of independent variables and their levels :- select the parameters (variable) that have major effects on output. The levels of the parameters are determined. All variable will be tested over the same range. Range of the variable are forced between the range of coded variable -1 to 1. Equation of coding is given below [10]:

$$X = \frac{x-[x_{max} + x_{min}]/2}{[x_{max} - x_{min}]/2} \quad (1)$$

Where,
X = coded variable
x = natural variable
x_{max} ,x_{min} = maximum and minimum values of the natural variable

4.1.2 Selection of the experimental design, and prediction and verification of model equation :- Experimental design are generated as per selection of experimental points, number of runs and blocks. Then the model equation is defined and coefficients of the model equation are predicted. For to understand the whether the model is making a good prediction, the test data and the predicted data are compared with each other. For to compare these data the statical method of root mean square error (RMSE) and coefficient of multiple determination (R^2) values are used. These values are determined by following equation [1]:

$$\text{RMSE} = \left[\frac{1}{n}\sum_{j=1}^{n}\left|a_j - p_j\right|^2\right]^{1/2} \quad (2)$$

$$R^2 = 1 - \left[\frac{\sum_{j=1}^{n}(a_j - p_j)^2}{\sum_{j=1}^{n}(p_j)^2}\right] \quad (3)$$

Where,
a_j = Experimental Specific consumption
p_j = Predicted Specific consumption

4.1.3 Graphical presentation of the model equation and determination of optimal operating conditions:- The prediction of model equation is done by the surface and contour plot. The surface plot is the 3 dimensional plot which showing the relationship between response and the variable.

4.2 Experimental Method

The selected process variables were varied up to three levels and central composite rotatable design was adopted to design the experiments. Response Surface Methodology was used to develop second order regression equation relating response characteristics and process variables. The process variables and their ranges are given in Table 3.

Table 3. Actual and Coded Levels of Independent Variables in Experimental Design

Independent Variable	Symbol		Level	
	Actual	Coded	Actual	Coded
% of Biodiesel	A	x_1	0	-1
			50	0
			100	1
Compression Ratio	B	x_2	16	-1
			17	0
			18	1
Injection Pressure	C	x_3	160	-1
			200	0
			240	1
Load	A	x_4	1	-1
			6	0
			11	1

Series of analysis is conducted to obtain the optimum parameter for performance of engine. Central composite design is applied to select the control factors levels (percentage of biodiesel, compression ratio, Injection pressure, Load) to come up with optimal response value (SFC).

V. Result And Discussion

5.1 Fitting the model and analysis of variance (ANOVA)

The analysis experiments were conducted, with the process parameter levels set as given in Table 3, to study the effect of process parameters over the output parameters. Experiments were conducted according to the test conditions specified by the second order central composite design. Experimental results for Specific fuel consumption are given in Table 4. Altogether 31 experiments were conducted using response surface methodology.

Table 4. Experimental Layout of Central Composite Design and Its Corresponding Observed Values of Specific Fuel Consumption

RUN	Variable properties				SFC
	% of Biodiesel	Compression Ratio	Injection Pressure	Load	
1	50	17	200	6	0.39
2	100	16	240	1	1.65
3	50	17	200	1	1.61
4	0	16	240	11	0.29
5	100	18	240	1	1.62
6	50	17	200	6	0.39
7	100	18	160	11	0.3
8	0	16	160	11	0.3
9	50	17	200	11	0.28
10	0	18	240	11	0.27
11	50	17	240	6	0.33
12	50	17	200	6	0.39
13	50	17	200	6	0.36
14	0	18	160	11	0.24
15	0	17	200	6	0.34
16	50	16	200	6	0.34
17	100	16	160	1	1.35
18	100	17	200	6	0.36
19	50	17	200	6	0.36
20	50	17	200	6	0.36
21	0	18	160	1	1.27
22	100	16	240	11	0.27
23	0	18	240	1	1.22
24	0	16	240	1	1.45
25	50	18	200	6	0.36
26	50	17	200	6	0.36
27	100	16	160	11	0.29
28	100	18	160	1	1.14
29	0	16	160	1	1.6
30	50	17	160	6	0.38
31	100	18	240	11	0.13

The ANOVA Table for specific fuel consumption are shown below in which Coefficient and p-values of parameters are shown.

Table 5. ANOVA for Response Surface Model

Source of variation	Coefficient	p-Value probability
Constant	-6.37523	0.706
BR (A)	- 0.0085	0.343
CR (B)	1.028	0.613
IP (C)	0.00374	0.836
Load (D)	- 0.46018	0.000
A^2	- 0.00001	0.556
B^2	- 0.03521	0.556
C^2	-0.00002	0.613
D^2	0.02239	0.000
AB	0.00034	0.484
AC	0.00002	0.058
AD	-0.00008	0.395
BC	0.00027	0.658
BD	0.00738	0.137
CD	-0.00023	0.064
R^2	98.28	
Adj. R^2	96.78	

Statistical inferences:

- The “Adj R-Squared” of 96.78 % is in reasonable agreement with the “Pred R-Squared” of 86.93%.
- Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case load D is significant model term.
- The coefficient of determination (R^2) and adjusted coefficient of determination (R^2 adj) were 98.28% and 96.78%, respectively which indicated that the estimated model fits the experimental data satisfactorily. Lee et al. (2010) suggested that for a good fit of a model, R^2 should be at least 80 %. The R^2 for these response variables was higher than 80 %, indicating that the regression models explained the mechanism well [9].

The second-order polynomial models used to express the SFC as a function of independent variables (Eq. (4)) is shown below in terms of coded level:

$$SFC(Coded) = -6.37523 - 0.0085x_1 + 1.028x_2 + 0.00374x_3 - 0.46018x_4 - 0.00001x_1^2 - 0.03521x_2^2 - 0.00002x_3^2 + 0.02239x_4^2 + 0.00034x_1x_2 + 0.00002x_1x_3 - 0.00008x_1x_4 + 0.00027x_2x_3 + 0.00738x_2x_4 - 0.00023x_3x_4 \quad (4)$$

From Equation (4) the predicted result of SFC for different set of parameters can be calculated. The complete set of 81 combination of SFC can also be predicted from equation (4). For to evaluate the generated model are good predicted or not the value of the R^2 and RMSE are computed. For good predicted model the value of R^2 are come closer to 1 and value of RMSE are come close to 0(zero) [10].

Table 6. Target vs Predicted Specific Fuel Consumption

RUN	Target SFC	Predicted SFC	Error	R^2	RMSE
1	0.39	0.3278	0.0622		
2	1.65	1.5325	0.1175		
3	1.61	1.4678	0.1422		
4	0.29	0.1803	0.1097		
5	1.62	1.4066	0.2134		
6	0.39	0.3278	0.0622		
7	0.3	0.1824	0.1176		
8	0.3	0.3779	-0.0779		
9	0.28	0.3074	-0.0273		
10	0.27	0.1339	0.1360		
11	0.33	0.2938	0.0362		
12	0.39	0.3278	0.0622		
13	0.36	0.3278	0.0322		
14	0.24	0.2884	-0.0484		
15	0.34	0.3128	0.0272		
16	0.34	0.3465	-0.0065	0.98833	0.08497
17	1.35	1.3861	-0.0361		
18	0.36	0.2928	0.0672		
19	0.36	0.3278	0.0322		
20	0.36	0.3278	0.0322		
21	1.27	1.2429	0.0270		
22	0.27	0.1663	0.1037		
23	1.22	1.2725	-0.0526		
24	1.45	1.4665	-0.0165		
25	0.36	0.2387	0.1213		
26	0.36	0.3278	0.0322		
27	0.29	0.2039	0.0861		
28	1.14	1.2169	-0.0769		
29	1.6	1.4801	0.1199		
30	0.38	0.2978	0.0822		
31	0.13	0.1879	-0.0579		

Here error is show the difference between the targeted and predicted value of SFC. The value of R^2 and RMSE are calculated by equation (2) and (3). The value of R^2 is 0.99, which are close to the 1 and the value of RMSE is 0.08 which is close to 0. So, the model is making a good prediction.

5.2 Comparison of Results

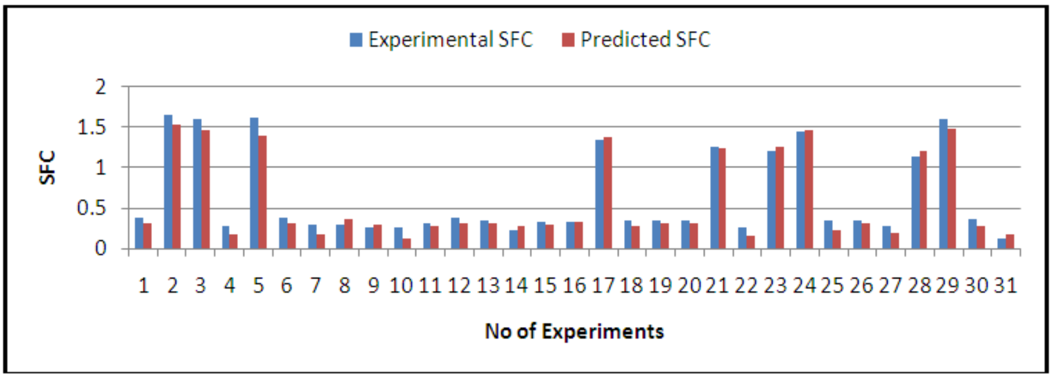


Figure 2. Experimental & Predicted SFC

The predicted value of Specific fuel consumption of model is compared with the actual target value of experiment is shown in graph by different colors. It is clear from graph that predicted results are very close to actual targets. It also concludes that model has good prediction capability.

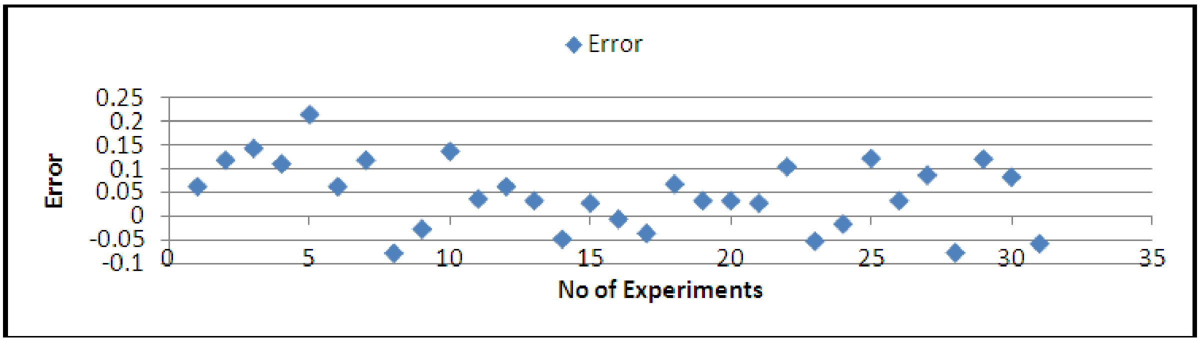


Figure 3. Experiment vs Error

The errors of the experiments are shown in Fig.2 which are above and below the 0(zero) value.

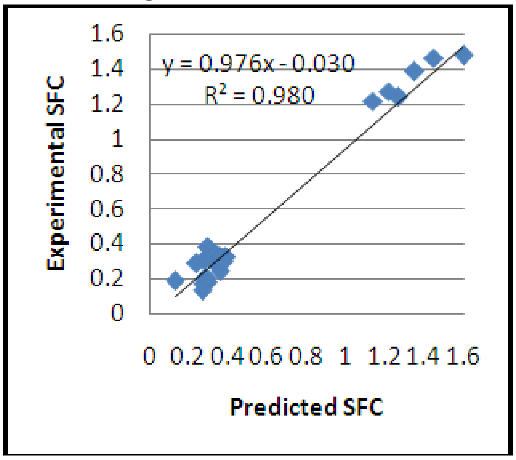


Figure 4. Experimental vs Predicted specific fuel consumption.

Fig. 4 shows the experimental versus predicted Specific fuel consumption obtained from Eq. (4). A linear distribution is observed which is indicative of a well-fitting model. The values predicted from Eq. (4) were close to the observed values of Specific fuel consumption.

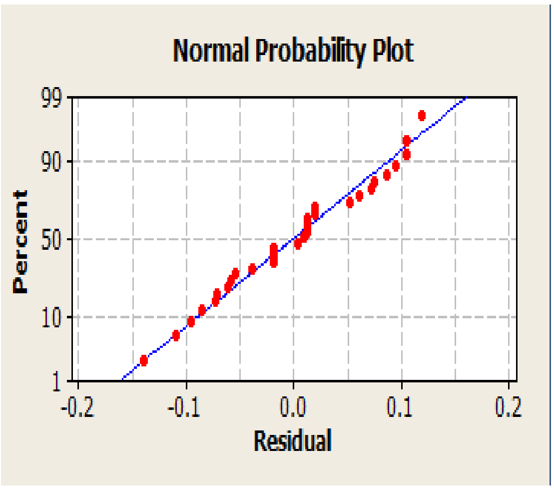


Figure 5. Normal probability of residuals

The normal probability plot is also presented in Fig.5.The plot indicates that the residuals (difference between actual and predicted values) follow a normal distribution and form an approximately straight line.

5.3 Effect of independent processing parameters

The effect of the four independent variables on the specific fuel consumption is shown in Fig. 6.

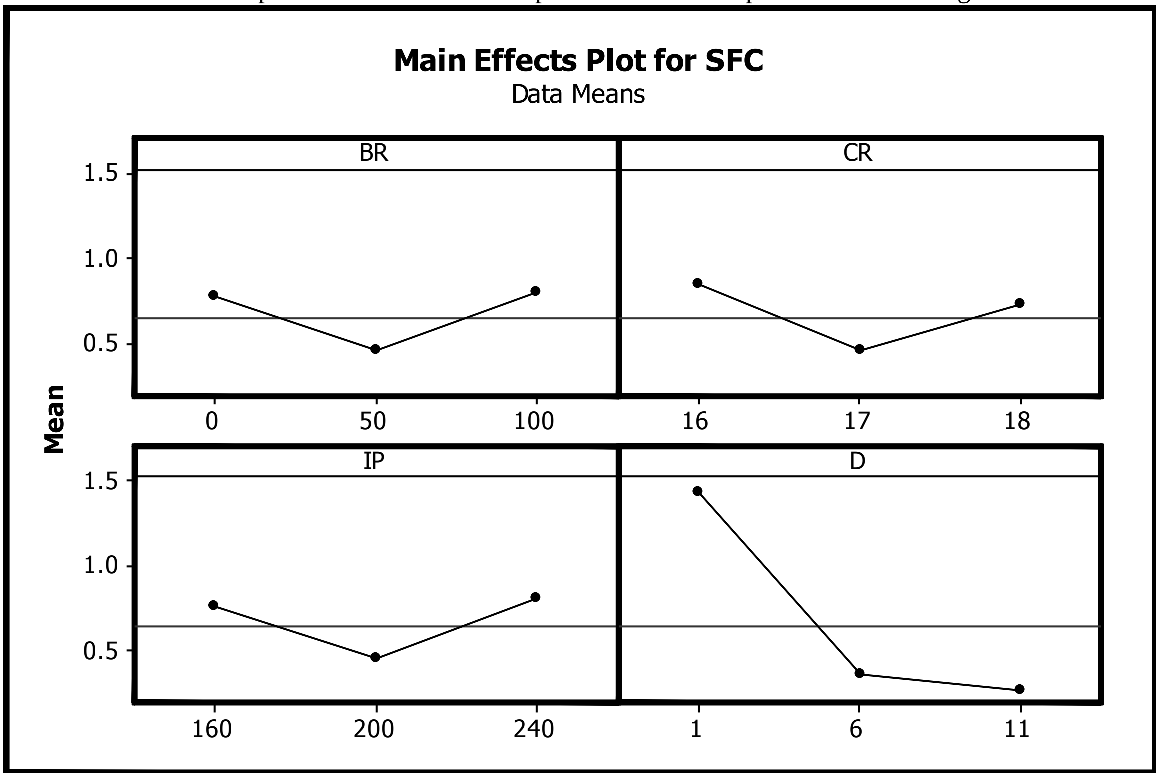


Figure 6. Main effect plot for SFC

- SFC improved with increasing percentage of biodiesel(A) from 0 to 50% in diesel as shown in Fig. 6. However, after that the increase in percentage of biodiesel increase the specific fuel consumption. So 50 % biodiesel portion in diesel is optimum for SFC.
- SFC decreasing with increase in compression ratio(B) from 16 to 17, then after there is increase in SFC from 17 to 18. So 17 chosen as a optimum compression ratio.
- SFC improve with increasing injection pressure(C) from 160 to 200 bar then after increasing injection pressure increasing SFC.
- As shown in Fig.6 increasing load improve specific fuel consumption. As load increase from 1 to 11 kg the specific fuel consumption decrease from 1.43 to 0.26 kg/kwh. This can also confirmed by ANOVA table indicating p-value of 0.00 indicating the load is significant value for specific fuel consumption.

VI. Conclusion

The present investigation aimed at optimization of SFC for CI engine. This analysis is carried out by developing SFC models based on L31 CCD array in Response surface optimization technique. Model for SFC prediction draws the following conclusions.

- It has been proved that predicted SFC values are closer to the experimental results.
- It has been also conclude that the RSM may be used as a good alternative for the analysis of the effects of engine parameters on the SFC.
- Optimum set of SFC for pure diesel is 0.13398 kg/kwh when compression ratio, injection pressure and load are at 18, 240 bar and 11 kg.
- Optimum set of SFC for pure soybean biodiesel is 0.13993 kg/kwh when compression ratio, injection pressure and load are at 18, 160 bar and 6 kg.

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Appendix

Nomenclatures:

SFC	Specific fuel consumption
RSM	Response Surface Methodology
CI Engine	Compression Ignition Engine
IC Engine	Internal Combustion Engine
BR	Blend Ratio, percentage of soybean biodiesel in blend of diesel and soybean biodeisel
BSFC	Break specific fuel consumption
CCD	Central Composite Design
CR	Compression Ratio
IP	Injection Pressure
BTE	Brake thermal efficiency
DI	Direct injection
RMSE	Root mean square error
Adj R-square	Adjusted R-square
Pre R-square	predicted R-square