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Mathematical Modeling of Mechanical Efficiency Using RSM for CI Engine Fueled With Soybean Biodiesel and Diesel Blend

KEYWORDS: Mechanical efficiency, Parametric optimization, RSM, Soybean biodiesel

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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 percentage of biodiesel (100%, 50%, 0%). This study investigated by Response Surface Methodology to optimize the performance parameter such as Mechanical efficiency. A set of experimental runs was established by using a Central Composite Design and the RSM was employed to obtain the regression model for the Mechanical efficiency for different values of input parameter. The experimental results reveal that the soybean biodiesel and its blend provide better engine performance compared to diesel with little change in input parameter.*

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.

LITERATURE REVIEW

The fuel 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 Mechanical Efficiency is normally used for to compare performance of different engines. It is defined as ratio of brake power to the indicated power.

Mechanical efficiency = (B.P)/(I.P) (1)

Where,

B.P =Brake Power

I.P = Indicated Power

SOYBEAN OIL

Soybean oil is produced from the seeds of soybean which are green or yellow in color and small in size.

TABLE – 1
PHYSICO-CHEMICAL PROPERTIES OF SOYBEAN BIODIESELS 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

For to extract oil from soybean there is need to cleaned, dried and dehulled of 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.

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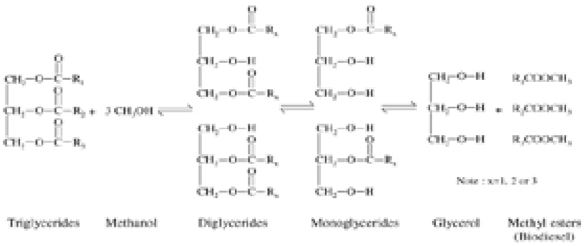
Transesterification process used for to converting this soybean oil into a soybean biodiesel. It is the displacement of alcohol from an ester by another alcohol in a similar process to hydrolysis [3].



Transesterification process.

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	≤ 25˚ BTDC

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.

Following step are carried out for RSM

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 [5]:

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

Where,

X = coded variable

x = natural variable

x_{max} ,x_{min} = maximum and minimum values of the natural variable

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 (R2) values are used. These values are determined by following equation [1]:

$$RSME = \left[\frac{1}{n}\sum_{j=1}^{n}\left|a_j - p_j\right|^2\right]^{1/2} \qquad (3)$$

$$R^2 = 1 - \left[\frac{\sum_{j=1}^{n}(a_j-p_j)^2}{\sum_{j=1}^{n}(p_j)^2}\right] \qquad (4)$$

Where,

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a_j = Experimental mech eff,

p_j = Predicted mech eff

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.

EXPERIMENTAL METHOD

TABLE – 3
ACTUAL AND CODED LEVELS OF THE INDEPENDENT VARIABLES IN THE EXPERIMENTAL DESIGN

Variable	Symbol		Level	
	Actual	Coded	Actual	Coded
BR	A	x_1	0	-1
			50	0
			100	1
CR	B	x_2	16	-1
			17	0
			18	1
IP	C	x_3	160	-1
			200	0
			240	1
Load	A	x_4	1	-1
			6	0
			11	1

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.

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 mechanical efficiency.

RESULT AND DISCUSSION

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 Mechanical efficiency 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 MECHANICAL EFFICIENCY.

RUN	Variable properties				Mechanical Efficiency
	% of Biodiesel	Compression Ratio	Injection Pressure(bar)	Load (kg)	(%)
1	50	17	200	6	40.4
2	100	16	240	1	9.7
3	50	17	200	1	9.03
4	0	16	240	11	57.56
5	100	18	240	1	9.51
6	50	17	200	6	39.08
7	100	18	160	11	54.72
8	0	16	160	11	56.42
9	50	17	200	11	53.93
10	0	18	240	11	55.27
11	50	17	240	6	40.28
12	50	17	200	6	39.65
13	50	17	200	6	39.62
14	0	18	160	11	55.71
15	0	17	200	6	40.86
16	50	16	200	6	39.74
17	100	16	160	1	11.85
18	100	17	200	6	40.54
19	50	17	200	6	40.3
20	50	17	200	6	39.49
21	0	18	160	1	9.78
22	100	16	240	11	55.46
23	0	18	240	1	10.47
24	0	16	240	1	11.52
25	50	18	200	6	39.62
26	50	17	200	6	39.59
27	100	16	160	11	56.6
28	100	18	160	1	10.74
29	0	16	160	1	11.08
30	50	17	160	6	40.16
31	100	18	240	11	54.97

The ANOVA Table for Mechanical efficiency are shown below in which Coefficient and p-value of parameters are shown.

TABLE – 5
ANOVA FOR RESPONSE SURFACE MODEL

Source of variation	Coefficient	p-Value probability
Constant	40.4148	0.000
BR (A)	- 0.04175	0.040
CR (B)	-2.0910	0.000

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IP (C)	0.1681	0.275
Load (D)	8.7031	0.000
A^2	0.0004	0.003
B^2	0.0382	0.900
C^2	0.0003	0.072
D^2	-0.3264	0.000
AB	0.0021	0.399
AC	-0.0001	0.006
AD	-0.0005	0.281
BC	0.0015	0.620
BD	- 0.0215	0.388
CD	0.0006	0.303
Lack of fit		0.455
R^2	99.96	
Adj. R^2	99.93	

Statistical inferences:

1. The "Adj R-Squared" of 99.93 % is in reasonable agreement with the "Pred R-Squared" of 99.79%.

2. The "Lack of Fit p-value" is not significant which give the null hypothesis. So insignificant lack of fit is good.

3. Values of "p-value" less than 0.0500 indicate model terms are significant. In this case percentage of biodiesel A, compression ratio B, load D etc are significant model terms.

4. The coefficient of determination (R2) and adjusted coefficient of determination (R2 adj) were 99.96% and 99.93%, 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, R2 should be at least 80 %. The R2 for these response variables was higher than 80 %, indicating that the regression models explained the mechanism well [4].

The second-order polynomial models used to express the Mechanical efficiency as a function of independent variables (Eq. (5)) is shown below in terms of coded level:

Mechanical efficiency (Coded) =

40.4148 - 0.04175x1 -2.0910x2 - 0.1681x3 + 8.7031x4 + 0.0004x12 + 0.0382x22 + 0.0003x32 - 0.3264x42 + 0.0021x1x2 - 0.0001x1x3 - 0.0005x1x4 + 0.0015x2x3 - 0.0215x2x4 + 0.0006x3x4 (5)

From Equation (5) the predicted result of mechanical efficiency for different set of parameters can be calculated.

The complete set of 81 combination of mechanical efficiency can also be predicted from equation (5). For to evaluate the generated model are good predicted or not the value of the R2 and RMSE are computed. For good predicted model the value of R2 are come closer to 1 and value of RMSE are come close to 0(zero) [5].

TABLE – 6
TARGET VS PREDICTED MECH EFF

RUN	Target Mech Eff	Predicted Mech Eff	Error	R^2	RMSE
1	40.4	39.69094	0.70906	0.999924361	0.347837719
2	9.7	10.07082	-0.37082		
3	9.03	8.920305	0.109695		
4	57.56	57.24253	0.317475		
5	9.51	9.602771	-0.09277		
6	39.08	39.69094	-0.61094		
7	54.72	55.23333	-0.51333		
8	56.42	56.60276	-0.18276		
9	53.93	54.13812	-0.20812		
10	55.27	55.92448	-0.65448		
11	40.28	40.14034	0.139661		
12	39.65	39.69094	-0.04094		
13	39.62	39.69094	-0.07094		
14	55.71	55.03972	0.670283		
15	40.86	41.00365	-0.14365		
16	39.74	40.23698	-0.49698		
17	11.85	11.47105	0.378949		
18	40.54	40.49476	0.045238		
19	40.3	39.69094	0.60906		
20	39.49	39.69094	-0.20094		
21	9.78	10.0244	-0.2444		
22	55.46	55.49114	-0.03114		
23	10.47	10.39416	0.075839		
24	11.52	11.28221	0.237795		
25	39.62	39.22143	0.398566		
26	39.59	39.69094	-0.10094		
27	56.6	56.37637	0.223629		
28	10.74	10.75801	-0.01801		
29	11.08	11.15744	-0.07744		
30	40.16	40.39808	-0.23808		
31	54.97	54.59309	0.376909		

Here error is show the difference between the targeted and predicted value of Mechanical efficiency. The value of R2 and RMSE are calculated by equation (3) and (4). The value of R2 is 0.99 which are close to the 1 and the value of RMSE is 0.3 which is close to 0. So, the model is making a good prediction.

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COMPARISON OF RESULTS

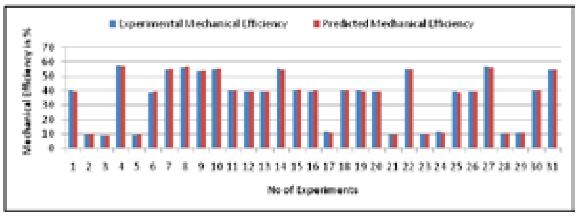

Figure 2: Experimental & Predicted Mechanical Efficiency

The predicted value of Mechanical efficiency of model is compared with the actual target value of experiment is shown in Fig.2 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.

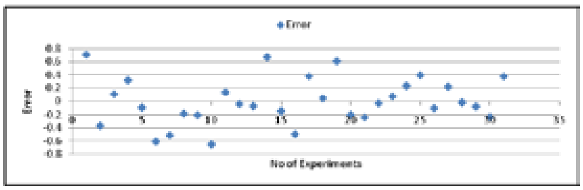

Figure 3: Experiment vs. Error

The errors of the experiments are shown in Fig.3 which are above and below the 0 value.

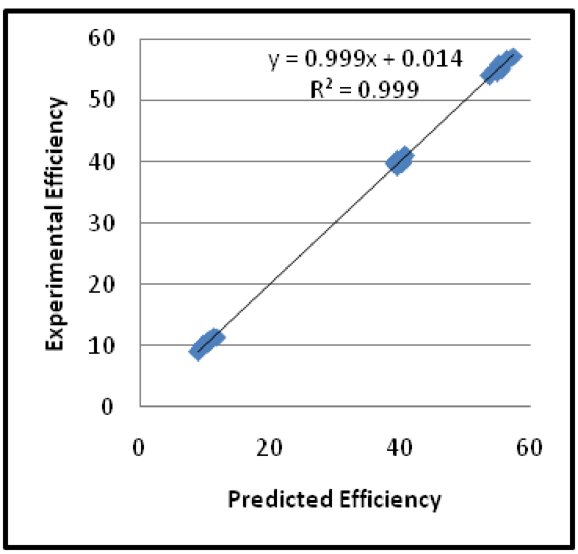

Fig 4: Experimental vs. Predicted Efficiency

Fig. 4 shows the experimental versus predicted Mechanical efficiency obtained from Eq. (5). A linear distribution is observed which is indicative of a well-fitting model. The values predicted from Eq. (5) were close to the observed values of Mechanical efficiency.

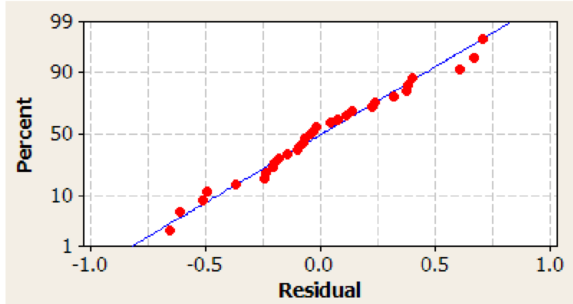

Figure 5: Normal probability of residuals

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.

Effect of independent processing parameters

The effect of the four independent variables on the mechanical efficiency is shown in Fig. 6.

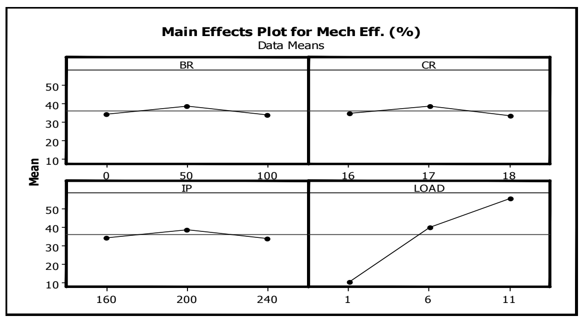

Figure 6: Main Effect Plot of Mechanical Efficiency

- Mechanical efficiency improved with increasing percentage of biodiesel(A) from 0 to 50% in diesel as shown in Fig. 6. However, after that increasing biodiesel percentage gives decrease in mechanical efficiency. So 50 % biodiesel portion in diesel is optimum for mechanical efficiency.

- Mechanical efficiency increasing with increase in compression ratio(B) from 16 to 17, then after there is decrease in mechanical efficiency from 17 to 18. So 17 chosen as an optimum compression ratio.

- Mechanical efficiency improved with increasing injection pressure(C) from 160 to 200 bar then after decreasing mechanical efficiency with increase in injection pressure.

- As shown in Fig.6 increasing load improve mechanical efficiency. As load increase from 1 to 11 kg the mechanical efficiency increase from 10.4 to 55.6%.

CONCLUSIONS

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

- It has been proved that predicted mechanical efficiency 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 Mechanical efficiency.

- Optimum set of Mechanical efficiency for pure diesel is 57.24% when compression ratio, injection pressure and load are at 16, 240 bar and 11 kg.

- Optimum set of Mechanical efficiency for 50% biodiesel is 55.43% when compression ratio, injection pressure and load are at 16, 160 bar and 11 kg.

- Optimum set of Mechanical efficiency for pure soybean biodiesel is 56.37% when compression ratio, injection pressure and load are at 16, 160 bar and 11 kg.

Appendix
Nomenclatures:

Mech Eff	Mechanical Efficiency
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
CCD	Central Composite Design
CR	Compression Ratio
IP	Injection Pressure
BTE	Brake thermal efficiency
RMSE	Root mean square error
Adj R-square	Adjusted R-square
Pre R-square	predicted R-square

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