Mathematical Modeling of Specific Fuel Consumption Using Response Surface Methodology for CI Engine Fueled with Tyre Pyrolysis Oil and Diesel Blend

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Abstract In this study, response surface methodology (RSM)-based prediction model was prepared for specific fuel consumption (SFC) as a response. A regression model was designed to predict SFC using RSM with central composite rotatable design (CCRD). In the development of regression models, injection timing, compression ratio, injection pressure, and engine load were considered as controlled variables. Injection pressure and compression ratio were observed as the most influencing variables for the SFC. The predicted SFC values and the succeeding verification experiments under the optimal conditions established the validity of the regression model.

Keywords Specific fuel consumption (SFC) · Compression ignition engine (CI) · Tyre pyrolysis oil (TPO) · Response surface methodology (RSM)

1 Introduction

The diesel engines are generally used for transportation, engineering industrial, and agricultural machinery due to its better fuel efficiency. The increasing cost of fuel has made nation to depend on diesel-based engines. Due to reduction and high cost of petroleum-based fuels investigators around the globe look for alternate fuel and trying to discover the best alternative fuel.

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2 Literature Review

Atmanlı et al. investigated optimal blend ratios for compression ignition (CI) engine applications for diesel, *n*-butanol, and cotton seed oil by using RSM. Experiments were performed at rated load and steady speed to found engine performance and emission parameters. Results showed that optimization was done by using RSM to recognize the optimum blend. According to performance tests BT, BP, Brake thermal efficiency, and Brake mean effective pressure of DnBC diminished as SFC increased relative to diesel [1]. Researcher was investigating the performance and exhaust parameters of CIDI engine for the result of injection factors. The included parameters were IP, nozzle tip protrusion, and IT. The biodiesel fuel used in experiment was derived from pongamia seeds. RSM and DoE methods were used to design experiments. RSM results were helpful to predict BSFC, BTHE, CO, HC, NOx, burn opacity and additional to recognize the important relations between the contribution parameters on the output parameters [2]. One of the researchers was optimizing performance parameters related to BP and economy of fuel during experimental investigation and RSM. CR, IP, and IT were used as performance parameters and BTE and BSFC was the response parameters. A single cylinder engine was used in experimentation. RSM was used to design experiments. The results showed that at most favorable factors, the values of the Brake thermal efficiency and Brake specific fuel consumption were found to be 29.76%, respectively [3, 4]. Silva et al. investigated the parameters which affect the transesterification process. The RSM and factorial design method were used to optimize the biodiesel production process. RSM method was used to finding out the combined effects of various factors. The optimum conditions were catalyst concentration (1.3 M), mild temperature (56.7 °C), molar ratio (9:1), and reaction time (80 min) [5]. Rashid et al. investigated optimum condition for the transesterification of Moringa oleifera oil using RSM with CCRD. In optimization various parameters were used [6].

Theme of present work is to examine the influence of performance variables of CI engine utilizing tyre pyrolysis oil (TPO) as fuel using RSM-based experimental design. The other objective is to determine the optimal values parameters which would be resulting in improved.

3 Experimental Details

In this study, TPO and diesel blend were used as a working fluid in CI engine. In experiments, four parameters (injection timing, compression ratio, injection pressure, and engine load) with five levels for each were used to find out optimization. The TPO and diesel blend were taken as D85T15 for better performance [7]. During experiments, vibrometer was used for homogeneous mixing of blend. An engine

Fig. 1 The engine test rig

test rig with computer based data acquisition system was used. Figure 1 shows the engine test rig. Table 1 shows the engine specifications.

Investigation has been carried out using developed empirical model of RSM in order to check the effect of variables (injection timing, compression ratio, injection pressure, and engine load) on the response (SFC). Variables are varied up to five different levels and each design position for the proposed methodology is simulated multiple times in order to eliminate the chance of error. Table 2 shows the

Table 1 Engine Specifications

Sr no.	Item	Specification
1	Model	TV1
2	Make	Kirlosker oil engines
3	Type	Four stroke, water cooled, diesel
4	No. of cylinder	One
5	Bore	87.5 mm
6	Stroke	110 mm
7	Compression ratio	12–18
8	Power rating	7.5 HP
9	Injection timing	$\leq 25^0$ BTDC

Table 2 Variables with range

Variables/range	Lowest	Lower	Centre	Higher	Highest
Injection timing	21	22	23	24	25
Compression ratio	14	15	16	17	18
Injection pressure	140	160	180	200	220
Engine load	1	4	7	10	13

experiments conditions. RSM and DFA have been employed simultaneously for the purpose of optimizing the variables and conformation experiments have been conducted in order to check the validity of prediction model.

4 Results

Table 3 indicates 21 sets of experiment based on the central composite rotatable design. Some of the replications are having same set of parameters in order to obtain a more precise result and to estimate the experimental error. Hence, it is not

Table 3 Experimental results

Experiment no.	Injection timing (°BTDC)	Compression ratio	Injection pressure (bar)	Engine load (kg)	Specific fuel consumption (kg/kwh)
1	21	16	180	7	1.259988
2	23	16	180	1	1.938195
3	24	15	200	4	0.383044
4	23	16	180	7	0.096909
5	23	16	180	7	0.096909
6	22	15	200	10	1.033158
7	23	16	180	7	0.096909
8	24	17	200	4	0.821836
9	23	16	220	7	0.0557
10	23	16	180	13	0.425037
11	23	16	180	7	0.096909
12	23	16	180	7	0.096909
13	24	17	160	4	1.010105
14	22	17	160	4	0.671339
15	24	15	160	4	0.115779
16	23	16	140	7	0.934611
17	23	18	180	7	0.819101
18	22	17	200	10	0.386156
19	25	16	180	7	1.033265
20	22	15	160	4	1.757947
21	23	14	180	7	0.01955

obligatory to obtain the same results with same set of parameter due to uncontrollable conditions/error/variables.

The regression equation in terms of actual factors for the SFC as a function of four input process variables was developed using experimental information. The insignificant coefficients identified from ANOVA of some terms of the quadratic equation have been omitted. Equation (1) represents the prediction equation for SFC in terms of actual variables.

$$\begin{aligned} \mathrm{SFC} = {} & 169.16187 - 20.14749 * \mathrm{IT} + 10.08648 * \mathrm{C} - 0.25033 * \mathrm{IP} + 4.51159 * \\ & \mathrm{LOAD} + 0.38334 * \mathrm{IT} * \mathrm{CR} + 6.80605\mathrm{E}-003 * \mathrm{IT} * \mathrm{IP} + 0.044350 * \mathrm{IT} * \mathrm{LOAD} - \\ & 9.95550\mathrm{E}-005 * \mathrm{CR} * \mathrm{IP} - 0.35156 * \mathrm{CR} * \mathrm{LOAD} - 1.72260\mathrm{E}-003\ 8\ \mathrm{IP} * \mathrm{LOAD} + \\ & 0.27004 * \mathrm{IT}^2 - 0.54779 * \mathrm{CR}^2 + 2.67929\mathrm{E}-004 * \mathrm{IP}^2 + 0.011424 * \mathrm{LOAD}^2 \end{aligned} \tag{1}$$

The ANOVA table for quadratic model for the SFC is given in Table 4. The value of p for the term of model is less than 0.05 indicates the significance of the term or model, as the confidence level of experiment is set at 95% for the proposed

Table 4 Analysis of variance table

Source	Sum of squares	DF	Mean square	F value	p-value prob > F	
Model	6.38	14	0.46	14.97	0.0016	**Significant**
A-injection timing	0.026	1	0.026	0.84	0.3938	
B-compression ratio	0.41	1	0.41	13.50	0.0104	
C-injection pressure	0.39	1	0.39	12.68	0.0119	
D-load	0.15	1	0.15	5.07	0.0652	
AB	1.18	1	1.18	38.59	0.0008	
AC	0.15	1	0.15	4.87	0.0695	
AD	0.071	1	0.071	2.32	0.1782	
BC	3.172E-005	1	3.172E-005	1.041E-003	0.9753	
BD	0.36	1	0.36	11.80	0.0139	
CD	0.043	1	0.043	1.40	0.2811	
A2	1.69	1	1.69	55.60	0.0003	
B2	0.40	1	0.40	13.12	0.0111	
C2	0.27	1	0.27	8.76	0.0253	
D2	0.011	1	0.011	0.37	0.5659	
Residual	0.18	6	0.030			
Lack of fit	0.18	2	0.091			
Pure error	0.000	4	0.000			
Cor total	6.57	20				

study. This value showed that the quadratic model fits well to the experimental results.

The value of p for the term of model is less than 0.05 indicates that it is considered to be statistically significant. This value showed that the quadratic model fits well to the experimental results. ANOVA results in Table 4 indicate compression ratio and injection pressure are the most significant variables. It has been also observed that linear effects of injection timing and engine load are insignificant parameters even though their quadratic effects are significant.

Figure 2 shows the RSM predictions against the experimental results. Figure 3 shows that the low specific fuel consumption can be achieved at smaller value of injection pressure and compression ratio. The iterative effect of compression ratio and injection pressure on the specific fuel consumption is shown in Fig. 4. Consider a measure of the model's overall performance referred to as the coefficient of determination and denoted by R^2. In the model, R^2 is obtained equal to 97.22%. The R^2 value indicates that the burnishing parameters explain 97.22% of variance in SFC.

The validating experiments was done using regression model on four sets of parameters, and results show that the numerical optimization technique confirm the effectiveness of RSM. Table 5 shows that percentage error of validating experiments.

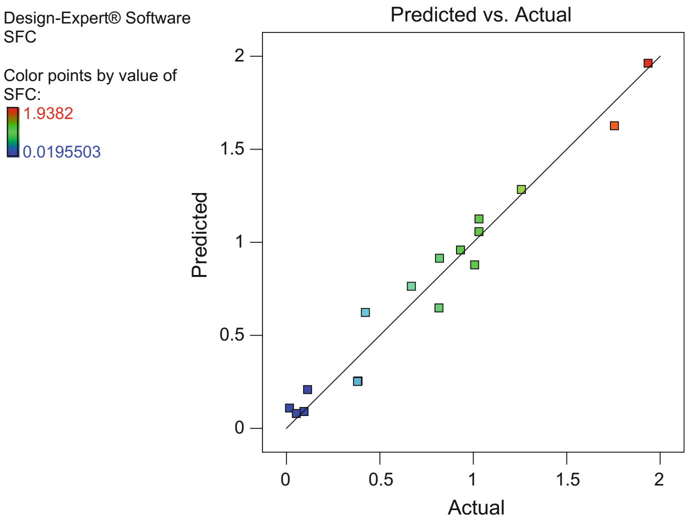

Fig. 2 RSM predictions against the experimental results

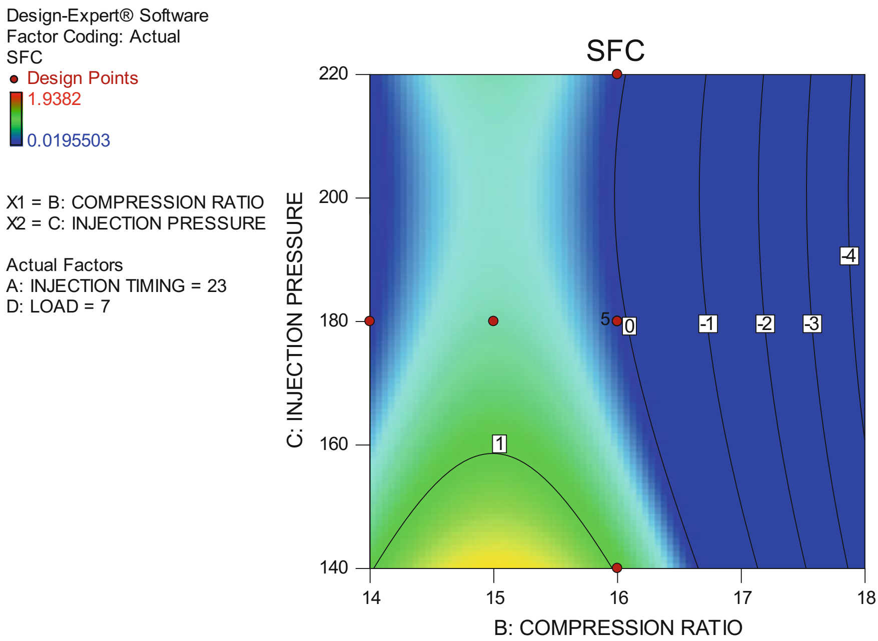

Fig. 3 Desirability function for IP versus CR

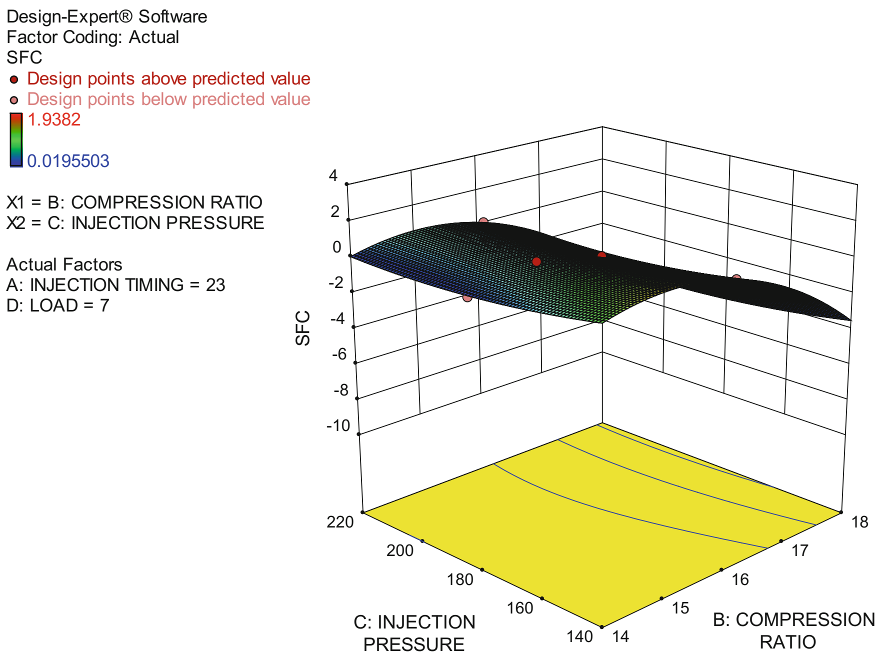

Fig. 4 Three dimensional plot of SFC

Table 5 Percentage error of validating experiments

Experiment no.	Injection timing (°BTDC)	Compression ratio	Injection pressure (bar)	Engine load (kg)	% Error
1	22	16	220	13	0.025
2	21	18	200	10	0.019
3	23	17	180	13	0.028

5 Conclusion

In this present work, combined approach of RSM and DFA has been implemented to investigate the effect of the four process variable engine load, injection timing, compression ratio, and injection pressure. It is clearly indicated from the results that the quadratic model in all the characteristics does not demonstrate a significant lack of fit; hence the adequacy of quadratic model is confirmed at 95% confidence level.

Injection pressure and compression ratio are observed as the most influencing variables for the SFC. In order to check the validity of the developed model, conformation experiments have been carried out. RSM was found to be a useful approach, and it should be recommended that this methodology be adapted to all optimization studies.

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