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Development of a Mathematical Model for SFC for Single-Cylinder CI engine fueled with Diesel-PPO blend

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Abstract: *Increasing consumption of diesel fuel has raised concern over the depleting crude oil reserves. There arises the need for alternative fuel for the CI (compression-ignition) engine. Waste plastic disposal has also been a concern. Hence, many researchers studied waste plastic oil and found its properties to be suitable as diesel fuel for CI engines. The experimental setup consists of a four-stroke single-cylinder water-cooled diesel engine. The engine is connected with an eddy current dynamometer which is utilized to apply load on the engine. Several sensors are there in the engine to measure different parameters like load, temperature etc. Also, a calorimeter, tachometer, rotameter and stopwatch are utilized. This research utilizes RSM (Response Surface Methodology) CCD (Central Composite Design) to create and analyze the model. One factor is analyzed at a time, resulting in a prediction model that is then utilized to compare the experimented and predicted values. Waste plastic is converted to oil by the pyrolysis process. Pyrolysis is the thermal degradation of a substance in the absence of oxygen. The optimum value for SFC is obtained with 50 BR, 18 CR and 0 Load. The SFC (Specific fuel consumption) of 50 BR (blend ratio) is marginally lesser than the SFC of 0 BR i.e. 100% diesel.*
This research is focused on utilizing PPO (Plastic Pyrolysis Oil) as an alternative fuel for the CI engine and developing a mathematical model for SFC. The oil is then tested and its properties are compared to that of diesel. The fuel is then utilized to run in the CI engine. Three parameters with three levels were taken i.e. Blend Ratio % (0,50,100), CR (compression ratio) (16,17,18) and Load (0,4,8). The DOE (Design of Experiment) was done using Minitab 18. RSM approach was taken to design the experiment. A total of 20 experimental run table was generated using Minitab 18. Later, the experimental table was utilized to predict the value of SFC. These values were then put in Minitab and the design was analyzed. The analysis gave a variance equation for all three parameters using which an FFD (Full Factorial Method) was calculated. Load and CR were the most significant factors for SFC.

Key Word: *Parametric Optimization, Diesel-PPO, PPO, Pyrolysis, RSM, RSM CCD*

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I. Introduction

Diesel engines or CI engines are most widely used in transport vehicles as well as commercial vehicles. Diesel engines have a longer life as compared to petrol engines. They also have higher thermal efficiencies. Usually, the diesel variant of any vehicle is always priced at a higher side as compared to the petrol variant of the same vehicle. In diesel engines air is compressed inside the cylinder and later fuel is injected. As the air inside the cylinder is already compressed and is of high temperature and high pressure, once the diesel is injected, combustion starts to take place. Hence, diesel engines have less fuel consumption compared to petrol engines. This is because only the quantity of air getting into the cylinder is controlled by throttle response but the fuel injected into the cylinder to ignite the fuel does not vary as much. Due to these advantages, the demand for diesel vehicles has increased, increasing diesel fuel consumption. Diesel is obtained from crude oil obtained from fossil fuels that take millions of years to get converted into crude oil. Therefore, there arrives the need for alternative fuel for diesel engines. Waste plastic disposal has been a concern worldwide over the last few years. Also, the increasing consumption rates of plastic have resulted in more waste plastic. This waste plastic is usually dumped into landfills, and rivers, burning in open fields. This is increasing pollution and harming the environment. One of the most common methods for the conversion of plastic to oil is pyrolysis. Pyrolysis is the thermal degradation of a substance in the absence of oxygen.

Poompipatpong et al. (2014) studied the effect of diesel-waste plastic oil blends on engine performance characteristics. They concluded that the increase of mixing ratio to WPO 75% greatly decreases engine output torque and power approximately by 23.79%. Consequently, the thermal efficiency can be reduced by 5.97%, while specific fuel consumption can be increased by 31.22% **[1]**. **Nileshkumar et al. (2015)** studied the effect of blend ratio on plastic pyrolysis oil and diesel fuel on the performance of single cylinder CI engine. PPO10, PPO20, PPO30 and PPO50 blends were used as fuel. They concluded that with an increase in blend proportion efficiency increases and fuel consumption decreases, exhaust emissions increase after 30% blend proportion of PPO. Considering performance and exhaust emissions, PPO30 has optimum values **[2]**. **Kalargaris et al. (2016)** studied about combustion, performance and emission analysis of a DI diesel engine using PPO. The study gave the conclusion that the engine thermal efficiency decreased by 3-4% when PPO blends were used. All emissions increased with a higher PPO blending ratio **[3]**. **Venkatesan et al. (2018)** studied combustion and performance characteristics in a DI CI engine fuelled with blends of waste plastic oil. The study gave the conclusion that the at full load PO 30% exhibited higher peak pressure and a higher rate of heat release. The BTHE was found to be higher for all fuel blends at no load and the fuel consumption was reduced with an increase in load **[4]**. **Vasava et al. (2018)** studied about combine effect of injection pressure and compression ratio on performance of single cylinder CI engine using diesel - WPO blend by Taguchi's design of experiment approach. They concluded that for Maximum brake thermal efficiency is compression ratio 18, blend ratio 0B100D, injection pressure L (160 bar), engine load 12. For maximum mechanical efficiency is compression ratio 16, blend ratio 100B0D, injection pressure M (180 bar), engine load 12. Engine performance is mostly influenced by engine load and is least influenced by compression ratio **[5]**. **Singh et al. (2020)** studied waste plastic to pyrolytic oil and its utilization in CI engine: Performance analysis and combustion characteristics. The study gave the conclusion that the higher presence of PPO increases the BTE and reduces the bthe with an increase in load. The utilization of crude PPO with diesel in different blend ratios shows an increase in exhaust emission **[6]**.

The literature review suggests –

- There has been a lot of research work carried out on the blend analysis of PPO-Diesel blends.
- There has been some research done on the effect and optimization of certain parameters (Injection timing, injection pressure, EGR rates etc.) but little research has been done on the effect and optimization of parameters (CR, Load, %PPO) using Diesel-PPO blends CI engine.

The objectives of this research are -

- To develop an RSM model for the prediction of SFC.
- To optimize SFC for CI engine.

II. Material and Methods

Waste plastic has been converted to plastic pyrolysis oil with the assistance of the pyrolysis method. Pyrolysis is one of the efficient methods to recover waste plastic. Pyrolysis is the thermal degradation of a substance in the absence of oxygen. Pyrolysis requires certain materials i.e. a pyrolysis reactor, a copper coil, storage with cold water, and a pipe to connect the chamber open end with the copper coil.

- Waste plastic is cleaned of any dust or other material apart from plastic and filled in the pyrolysis chamber.
- The chamber is provided with heat.
- At the initial stages, the gas would appear in the pipe, but that is burned gas released from combustion inside the chamber with all the oxygen present inside.
- Once the combustion is completed, the flow of gas would stop and the chamber starts to heat up.
- Pyrolysis takes place at high temperatures, and hence requires a large amount of heat in order to covert to PPO.
- Once the chamber is heated, pyrolysis gas comes out of the chamber and through the pipe passes through the condenser.
- The condenser changes the phase of the gas from gas to liquid and PPO is obtained.

The pyrolysis process takes place as shown in Figure 1.

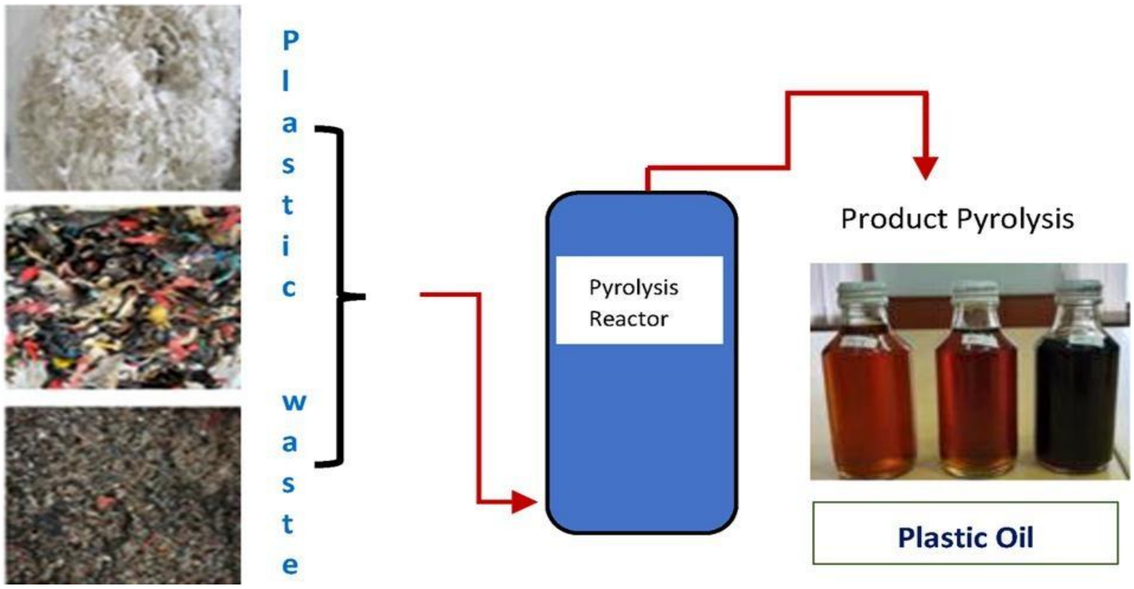


Figure 1: Pyrolysis of Plastic Waste **[7]**.

Experimental Setup

The experimental setup as shown in Figure 2. consists of Single-cylinder, four-stroke, water-cooled computerized research engine connected with the Engine test rig. Load exhibited on the engine by eddy current dynamometer. Parameter measurement (Speed, temperature, air consumption, etc) takes place with the assistance of various sensors.

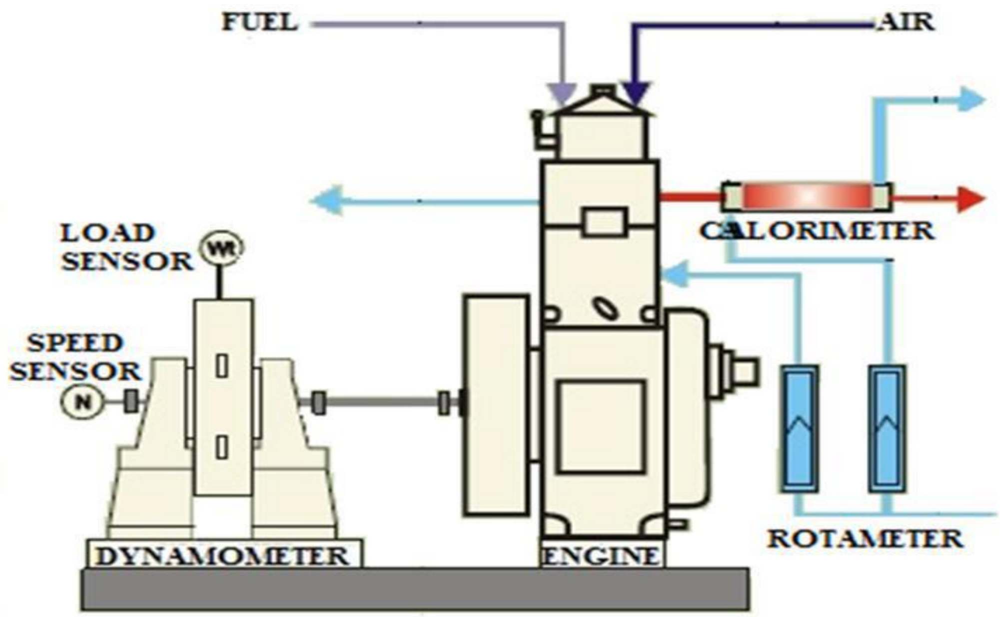


Figure 2: Schematic diagram of Experimental Setup.

List of Instruments –

1. Single-cylinder four-stroke diesel engine (Power: 3.5 kW at 1500 rpm)
2. Hydraulic Dynamometer Load
3. Calorimeter and Tachometer
4. Temperature sensor
5. Speed sensor
6. Rotameter
7. Stopwatch

Procedure Methodology

DOE is a systematic approach, that enables researchers to study the relationship between many input variables (i.e. factors) and their desired output variables (i.e. responses). Response surface methodology is typically used in the later stages of experimentations when significant factors have been identified. It usually has 2 to 8 continuous factors. RSM shows the relation between the input variables and output variables and identifies the significant factors. The methodology for this research is shown in the flowchart in Figure 3.

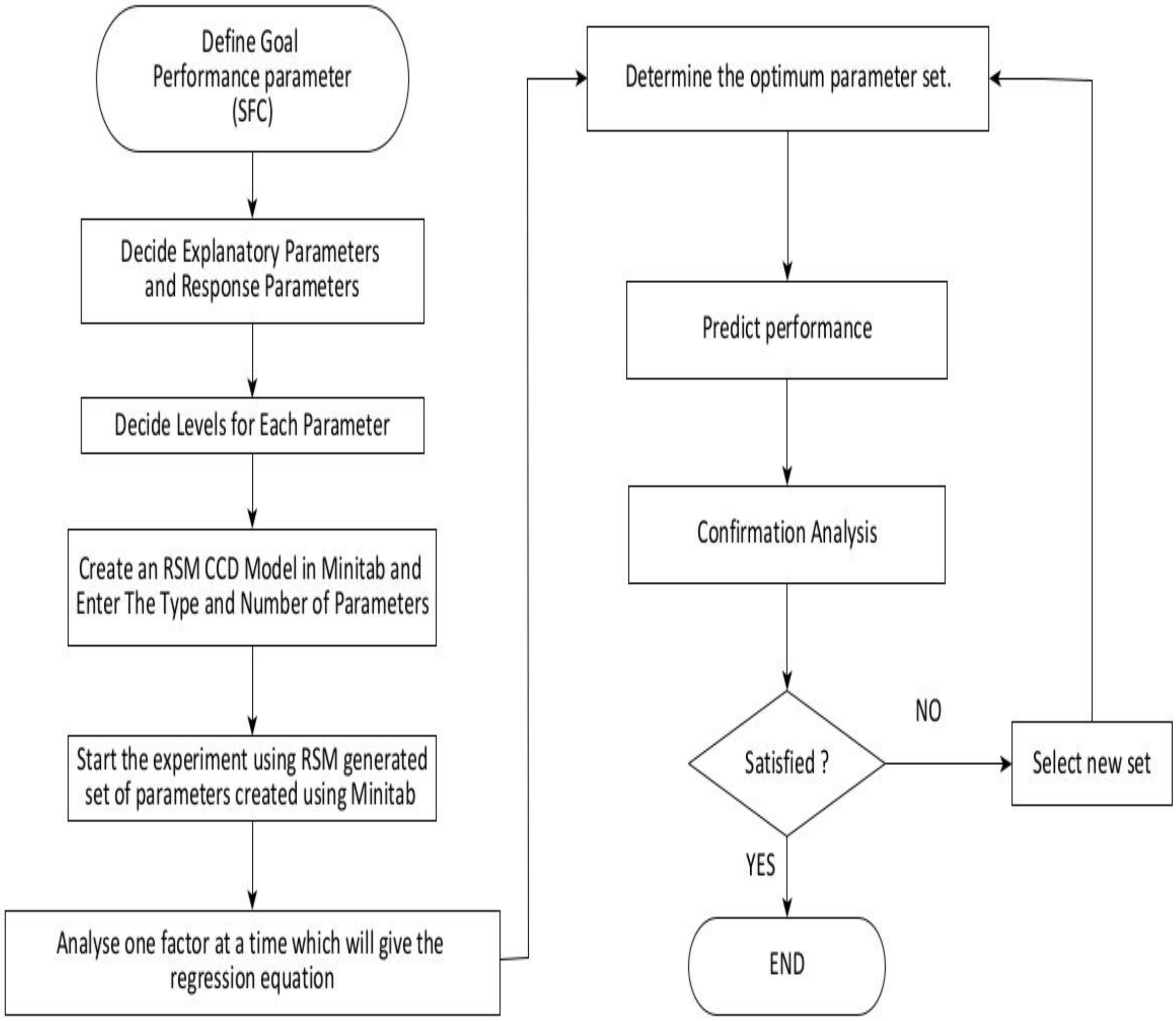


Figure 3: Methodology in RSM.

- Firstly, the goal needs to be defined (i.e. SFC in this case).
- Next, the explanatory parameters (input parameters) and response parameters (output parameters) need to be decided.
- Later levels for each factor need to be decided.
- An RSM CCD model is then created using Minitab V18 and details like type and number of parameters are entered.
- The experiment is started using RSM generated set of parameters that are created using Minitab V18.
- The significant factors are then analyzed and several graphs are plotted.
- From the analysis of significant factors, a regression equation for each significant factor is generated.
- This equation is used to create an FFD, from which an optimum parameter set is to be selected.
- Later Depending on the goal, the optimum parameter set is identified from the FFD created using the regression equation.
- Performance is predicted for the optimum set and is confirmed. If satisfied, the research is complete. If not satisfied, another optimum parameter set is identified and again performance is predicted for the optimum set and is confirmed.

The analysis for the experiments was conducted with the input factors set as levels as shown in Table. Three levels were taken for each factor. Overall, 20 experiments were performed using the response surface methodology. Three independent variables were taken i.e. %PPO, CR & Load. These factors have three levels as shown in Table 1.

Table 1: Levels for each factor

Independent Variable	Symbol	Level (Uncoded)
% PPO	B	0
		50
		100
CR	C	16
		17
		18
LOAD	D	0
		4
		8

III. Results and Discussion

Minitab designed a 20 experimental run table for 3 factors, to find the SFC for different sets of input factors as shown in Table 2.

All the values mentioned in Table 2 have been found by analyzing the model prepared in Minitab.

Table 2: Minitab Model for SFC

Run	%PPO	CR	Load (kg)	SFC (kg/kWh)
1	100	16	0	17.725
2	50	17	8	0.236
3	100	18	0	14.261
4	100	17	4	0.669
5	50	17	4	0.693
6	0	18	8	0.379
7	0	16	8	0.450
8	50	17	4	0.693
9	50	17	4	0.693
10	50	18	4	0.651
11	50	16	4	0.647
12	0	17	4	0.668
13	50	17	0	13.649
14	0	16	0	14.801
15	50	17	4	0.693
16	100	18	8	0.454
17	50	17	4	0.693
18	100	16	8	0.430

Run	%PPO	CR	Load	SFC
19	0	18	0	13.156
20	50	17	4	0.693

If the p-value of a variable is less than 0.05, then the variable is significant. In this case, the p-value of the load is less than 0.05, hence load is the significant factor for SFC.

The equation used for the prediction of FFD for SFC is derived from Table 3, in the uncoded form in equation (1)

SFC = 89.9 + (0.0638 × %PPO) - (8.04 × CR) - (7.484 × Load) + (0.000092 × %PPO × %PPO) + (0.210 × CR × CR) + (0.4028 × Load × Load) - (0.00378 × %PPO × CR) - (0.001231 × %PPO × Load) + (0.1522 × CR ×Load)……………………………………………………………………………………………...…..(1)

Table 3: p-value and Co-efficient for SFC

Source of variation	Co-efficient	p-value probability
% of PPO (B)	0.0638	0.202
CR (C)	-8.04	0.006
Load (D)	-7.484	0
B^2	0.000092	0.414
C^2	0.21	0.455
D^2	0.4028	0
BC	-0.00378	0.26
CD	0.1522	0.003
BD	-0.001231	0.15
R^2(%) = 99.72		

3-D Surface plot and Contour plot were drawn keeping input parameters in the range in order to analyze the effect of significant factors on SFC as shown in Figure 4.

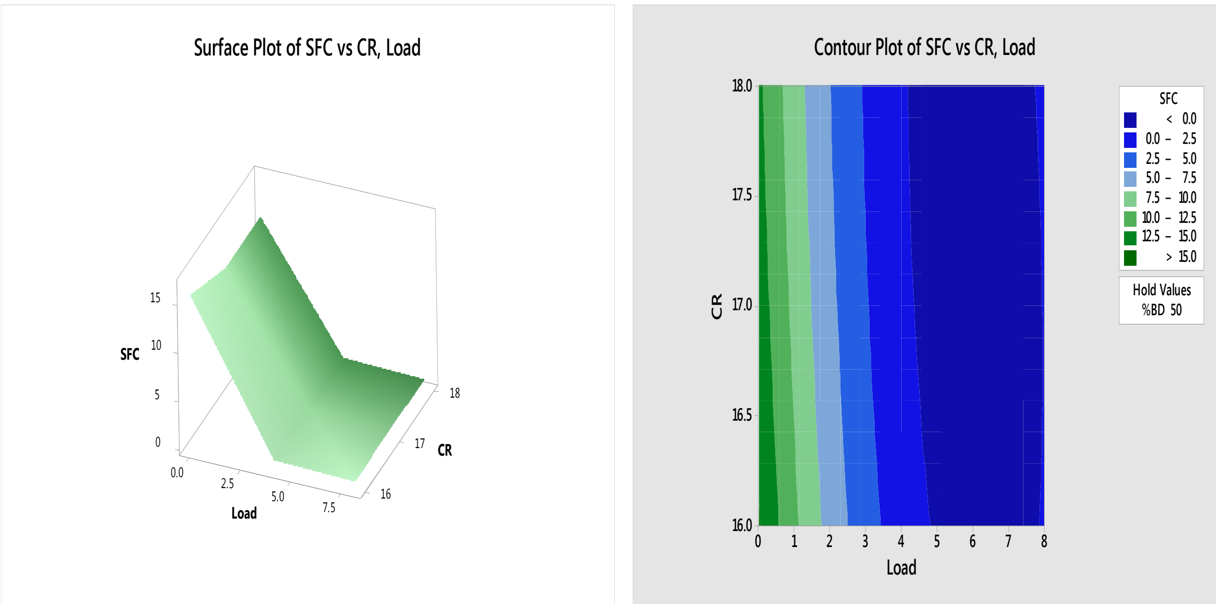


Figure 4: 3-D Surface Plot for SFC and Contour Plot for SFC

P-value probability and the coefficient for different parameters were obtained by analyzing the model as shown in Figure 5.

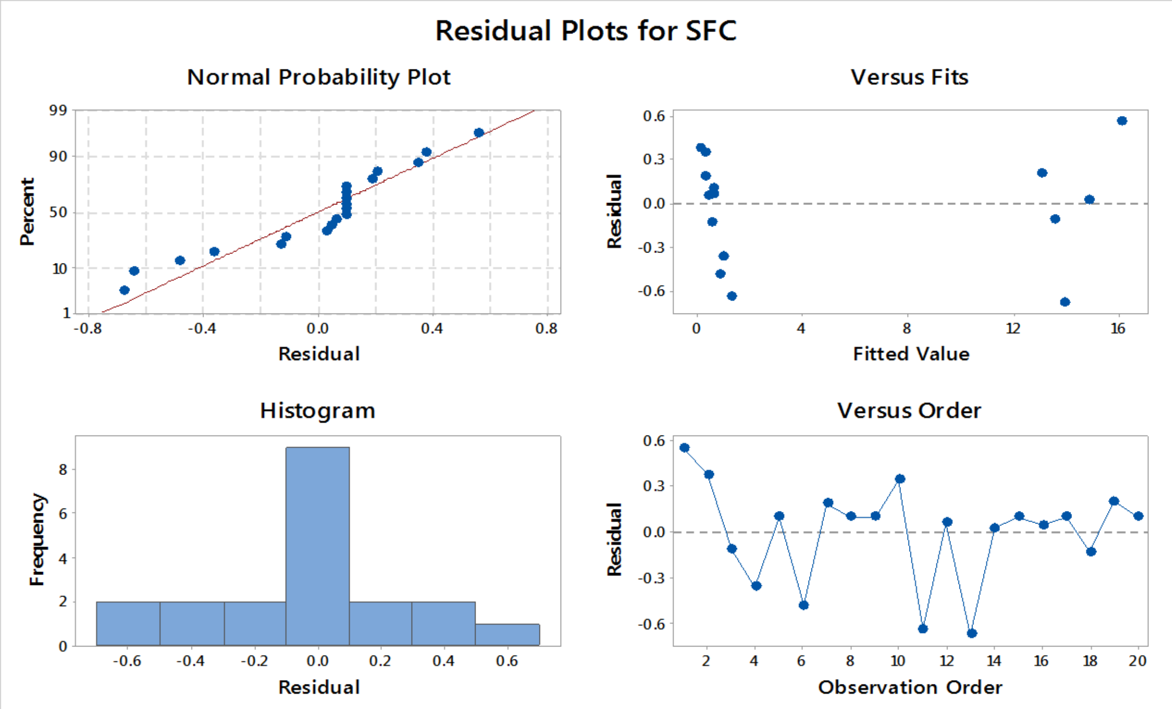


Figure 5: Residual Plots for SFC

The residuals follow a similar pattern, approximately a straight line in the normal probability plot. The histogram shows the frequency of the residual is evenly distributed with the maximum frequency at 0 residual. From Versus fits plot, residuals are observed to spread evenly amidst a definite range i.e. -0.6 to 0.6. In Versus Order plot, residuals can be observed for different observations. The residual fluctuates around 0 for most of the observations. The normal probability plot, residuals versus the fitted values, histogram plot, and residual versus observation order plot of these residuals tell that the model is good.

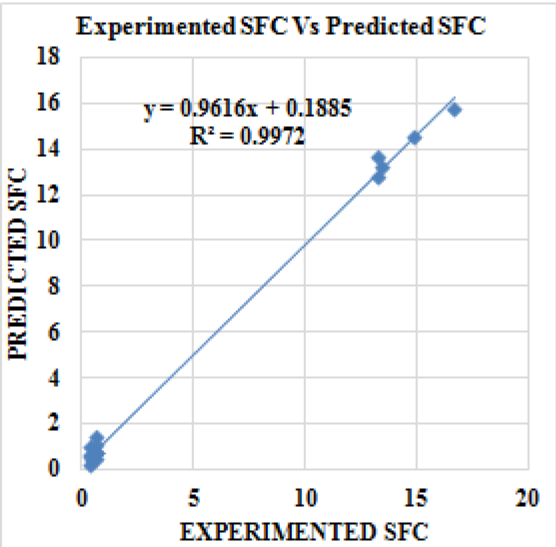
The predictability of a model can be known using the coefficient of determination (R^2). R^2 must be close to 1, for a good predicted model. The value of R^2 is 0.99, which is close to 1 and the value of RMSE is 0.0345 which is close to 0, hence the model is making a good prediction. The value of R^2 and RMSE for this research is shown in Table 4.

Table 4: Value of R2 and RMSE for SFC

Run	Experimented SFC	Predicted SFC	Error	R^2	RMSE
1	14.801	14.519	0.282		
2	0.236	0.231	0.005		
3	0.668	0.768	-0.101		
4	13.156	12.75	0.407		
5	0.379	1.044	-0.665		
6	0.647	1.419	-0.772		
7	13.649	13.625	0.024		
8	0.693	0.729	-0.036		
9	0.693	0.729	-0.036		

10	0.693	0.729	-0.036	0.9972	0.0345
11	0.693	0.729	-0.036		
12	0.693	0.729	-0.036		
13	0.693	0.729	-0.036		
14	0.459	0.231	0.228		
15	0.651	0.459	0.192		
16	17.725	15.759	1.966		
17	0.43	0.676	-0.246		
18	0.669	1.15	-0.481		
19	14.261	13.233	1.028		
20	0.454	0.555	-0.101		

A line graph and a histogram are plotted as shown in Figure 6, to show the preciseness of the prediction model when compared to the experimented values. The figure shows the comparison of Experimented SFC vs Predicted SFC. The predicted values were found very close to the experimented values and followed a linear trend, which is indicative of a well-fitting model.
The optimum parameter set predicted value was validated and compared to the experimented value to identify the error as shown in Table 5.



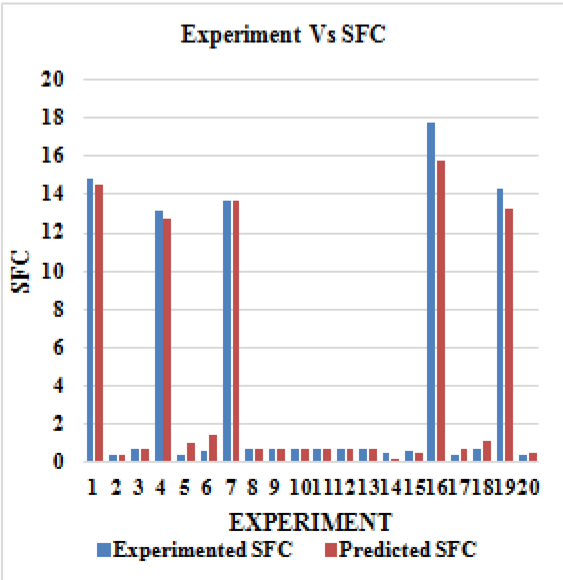


Figure 6: Comparison of Experimented SFC vs Predicted SFC.

Table 5: Validation of results for minimum SFC

%PPO	CR	Load	Predicted SFC	Experimented SFC	Error (%)
50	17	8	0.231	0.236	2.12

IV. Conclusion

- For SFC, Load and CR have a p-value probability <0.05, hence are the most significant factors.
- %PPO has a p-value probability >0.05 and hence it is the least significant factor for SFC.
- For SFC, the value of R^2 is 0.99, which is close to 1 and the value of RMSE is 0.03 which is close to 0. Hence, the model is making a prediction.

- From the surface plot, Figure 4, it can be seen that the value of SFC is maximum at low loads and low CR. The value of SFC decreases as the load increases.
- From the line graph, Figure 6 of experimented SFC vs, predicted SFC, it can be observed that the model is following a linear trend. Hence, it can be said that the model is making good predictions.
- The histogram graph in Figure 6, also showed the values were very close to each other showing the error is minimum between the experimented values and predicted values, which suggested the model is making good predictions.
- The mathematical model for SFC, shows excellent agreement with the RSM predicted results.

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