Investigation on the effect of compression ratio on the performance and emission characteristics of pongamia biodiesel diesel blends in CI engine using response surface methodology

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Abstract. The present work focusses on the interactive effect of variables such as compression ratio, blend and loading conditions on the performance and emission characteristics of biodiesel in diesel engine. Response Surface Methodology (RSM) based on the factorial design of 3^3 is used to design the experiments. The experiments are conducted on single cylinder, water cooled CI engine according to the design matrix and results are tabulated. Mathematical models are developed to study the interactive effect of performance parameters such as Brake specific fuel consumption (BSFC), Brake thermal efficiency (BTE) and emission parameters such as carbon monoxide (CO), unburnt hydro carbon (UHC) using regression methodology. Optimization of the problem is formulated using desirability approach to get better performance and lower CO, UHC emissions. Statistical analysis revealed the optimum combination for the blend B60, CR-18 and load 42% is considered for the pongamia biodiesel-diesel blends.

Key words: Biodiesel, Response surface methodology, desirability approach, optimization.

1. Introduction

The fossil fuel resources is depleted within few years. This is due to the increased energy consumption across the world. Rising petroleum prices, increasing environment pollution due to vehicle exhaust emissions and the major concern is to address the global warming at international level by developing alternative fuels for IC engines. The economy of any country mainly depends on availability of its energy resources [1], [2]. Biodiesel is one of the important alternate fuels selected for transportation and agriculture sectors. It is basically consists of mono-alkyl esters in long chain fatty acids extracted from vegetable oils or animal fat and made through a chemical process called trans esterification [3]-[11]. The synthesized biodiesels exhibit different physical properties such as lower calorific value, higher cetane number, higher flash-point and viscosity than the diesel fuel. These properties in turn affect the engine performance, and emissions characteristics. The properties of biodiesel can be modified by mixing with correct quantity of biodiesel with regular diesel in order to overcome the deficient characteristics and to get a stable biodiesel blend. In general, the combustion phenomena in diesel engine can be analysed using proper quantity of biodiesel in the blends to get lower HC and CO emissions than diesel fuel [12], [13].
In internal combustion engine, too many input variables such as blends, compression ratio and load are considered to study the output parameters such as performance and emissions characteristics in an engine. Hence it is difficult to select the correct combination of parameter which increase the performance of engine and reduce the emissions. Some of the studies reported that the design of experiments is more suited to tackle these issues in internal combustion engine applications. Response surface methodology (RSM) is considered as the most efficient technique for process optimization used in certain situations where several input variables affect invariably the performance characteristics of the process [14].

Shivarama Krishnan et al [15] used four different blends of Karanja biodiesel (B10 to B50), compression ratio (17.5 to 18.1) and power (3.64 kW to 5.2 kW) for the RSM by considering design of experiments. In this study, design matrix was considered by using 3 level factor and response models were developed to predict the performance characteristics and emission characteristics. Banapurmath et al [3] verified the stability of the model was done using analysis of variance (ANOVA) and regression statistics gives goodness of fit (R²) for all responses that the data fit the model very well. Pandian et al [16] used experimental design for RSM to model input responses using experiments. Input parameters considered for the study were injection pressure, injection timing, and nozzle tip protrusion. The optimization has been done using desirability method of RSM for getting better engine performance and reduced exhaust emissions. Jagannath Hirkude et al [17] used biodiesels blends (B50, B70, B90 and B100) with brake load (0.5kW to 4kW) as input variable and analyzed the output responses such as BTE, BSFC, EGT, and smoke opacity with the help of response curves. The input response considered for the study T. Ganapathy et al [18] selected experimental design matrix was created using factorial design with 27 runs. RSM models predictions were very close to the experimental values. N. Maheshwari et al [19] carried out nonlinear regression analysis to predict the values using experimental data. The fuel used for the study was Pongamia biodiesel and different blends with improved efficiency and lower HC emissions.

It is evident from the literature survey, the biodiesel blends from B10 to B100 can be used in the engine without any modifications after transesterification process. Several studies shows that the higher blends of biodiesel in the engine results in better performance and lower emissions than the diesel fuel [15][20]. The diesel engine running for longer period with higher blends of biodiesel doesn’t create any engine problems.

The objectives of the this work is to study interactive effect of each input parameter on the engine performance and emission characteristics using Pongamia biodiesel blends (B20 to B60) using surface response methodology. The other objective of the work is to get the optimal solutions of blend, compression ratio and loading conditions results in the improved performance and lower emission of biodiesel blends using desirability approach.

2. Materials and Methods

2.1. Fuel preparation
In the present work, Pongamia oil was considered for the preparation of biodiesel using transesterification process. The formation of 1litre biodiesel requires 200ml of methyl alcohol, and 16 g of NaOH was selected on the mass basis. First, the oil was preheated to 70°C-80°C for 10 min to remove traces of moisture and sodium hydroxide crystals were completely dissolved in the methanol solution and get sodium methoxide. Next, solution was added to the preheated oil. The reaction temperature of mixture of 55°C-60°C was maintained and stirred the mixture at 300 rpm for 1h using magnetic stirrer. The stirred mixture was allowed to settle down for minimum period of 8h and two separate distinct layers were observed. One layer was methyl ester and another was glycerol. Biodiesel was separated from glycerol using water wash method.
2.2. Fuel characterization

Pongamia biodiesel was mixed with the commercially available diesel fuel on volume basis to get the various blends such as B20, B40 and B60. The biodiesel blends along with diesel fuel were characterized by determining viscosity, calorific value, density, flash point and fire point according to ASTM standard procedure. Hydrometer was used to measure the specific gravity of fuel at 15°C. The density of fuels were determined using specific gravity data. The Redwood viscometer was used to find the kinematic viscosity fuels at the specified temperature. The calorific value of the diesel, and blended fuel was measured by using an isothermal bomb calorimeter. ASTM D-93 pensky marten closed cup tester was used for measuring the flash and fire points of fuel samples. The Fuel properties of diesel and Pongamia biodiesel blends were tabulated in Table 1.

| Property                | Diesel | Karanja biodiesel blends | Procedure   |
|-------------------------|--------|--------------------------|-------------|
| Calorific value (kJ/kg) | 44500  | 43084 42534 39667        | ASTM D-420  |
| Kinematic viscosity (cSt)@40°C | 2.576  | 2.723 3.21 4.003        | ASTM D-445  |
| Flash point (°C)        | 46     | 55 68 80                  | ASTM D-93   |
| Fire point (°C)         | 54     | 61 74 89                  | ASTM D-93   |
| Density (kg/m³)         | 826    | 839 848 863               | ASTM 1298   |

2.3. Experimental setup

The diesel engine test rig shown figure 1 was used to determine the combustion, performance and emissions characteristics of the fuels. This engine was able to develop power of 3.75 kW running at a rated speed of 1500 rpm, water cooled engine. The loading of the engine was done using eddy current dynamometer along with load cell, required instrumentation and data acquisition. The technical specifications of diesel engine test rig were given in the Table 2. Tilting cylinder head method was adopted to vary the compression ratio in test engine. Pressure transducer (piezo electric) was connected on the engine top head and synchronization of the pressure data with crank angle were done using crank angle encoder when the piston is at TDC. Crank angle encoder resolution 1°, speed 5500 rpm with TDC pulse was connected to the output shaft. The engine speed was measured using non-contact proximity sensor, range from 0-9999 rev/min. Inlet and exhaust temperatures of the engine were measured using K-type thermocouple range from 0 -1500°C. Air flow and fuel flow measurements were done by using differential transducers, range 0-99 kg/h .All the data were captured using data acquisition system.

![Figure 1. Diesel engine test rig.](image-url)
Table 2. Technical specifications of diesel engine test rig

| Parameters                  | Specifications                                                                 |
|-----------------------------|-------------------------------------------------------------------------------|
| Engine type                 | Water cooled, Single cylinder four stroke diesel engine, maximum power output 3.75 kW(5 hp) at 1500 rpm |
| Dynamometer                | Eddy current                                                                   |
| Bore                       | 80 mm                                                                         |
| Stroke                     | 110 mm                                                                        |
| Connecting rod length      | 235 mm                                                                        |
| Compression ratio (Variable)| 13:1 to 22:1                                                                   |
| Pressure transducer        | Range 5000 psi                                                                 |
| Crank angle encoder        | Resolution 1 deg, speed 5500 rpm with TDC pulse                               |
| Temperature sensor         | Type RTD, K type                                                               |
| Load cell                  | Range 0-50 kg                                                                  |

2.4. Exhaust gas analyzer
The emissions obtained from combustion fuels in an engine at the exhaust manifold were effectively measured with the help of exhaust gas analyzers SCT G-05. Gas analyzer was procured from Smart Caps Technologies and sensitive enough to find small traces of exhaust gases and even it is present in diluted form with any other gases. Non-Dispersive Infrared (NDI) technique is used in the exhaust gas analyzer to measure exhaust pollutants such as CO, HC, NOx, and CO2. Basically, gas analyser consists of HC, O2, CO, CO2, and NOx sensors. The calibration of these measurements were done using the option of zero calibration in the instrument. Normally, the analyser takes 10 min to capture the data. Before capturing the data it removes all the traces of gases from its path using zero calibration. The range, data resolution and accuracies of each measurements are given in the table 3.

Table 3. Range, resolution and accuracy of exhaust gas analyzer.

| Gas  | Range        | Data Resolution | Accuracy |
|------|--------------|-----------------|----------|
| CO   | 0 to 15%     | 0.01%           | ± 0.1%   |
| CO2  | 0 to 20%     | 0.01%           | ± 0.5%   |
| HC   | 0 to 30000ppm| 1ppm            | ± 3ppm   |
| NOx  | 0 to 5000ppm.| 1ppm            | ± 1ppm   |
| O2   | 0 to 25%     | 0.01%           | ± 0.2%   |

2.5. Response surface methodology (RSM)
It is one of the statistical tool used to predict optimal response based on different input variables. These input variables affects the performance or quality characteristics of the process response. Normally, the experimental design matrix is constructed based on input variables levels affecting the various output process response. The RSM field consider the experimental strategy, explores the information about the process variables. It is used to develop empirical statistical modelling, gives an approximate relationship between the output results and input variables.
In the present work, RSM was used to analyze the input response variables in order to optimize the engine performance and emission characteristics required for the combustion analysis. The following steps were adopted for process optimization:

i) In the first step, three input parameters were chosen based on the initial runs varied the composition of pongamia biodiesel in the blends from 20% to 60% separately. The compression ratio varied from 14:1 to 18:1 and brake load from 10% to 70%.

ii) Factorial design of $3^4$ was considered for the experimental design. The design matrix was selected, which contains 27 runs. Experiments were conducted on the engine according to run order for three times and average values of output responses were considered for study.

iii) Output response performance characteristics of an engine such as BSEC, BTE and emission characteristics such as HC, CO, and NOx were recorded for pongamia blended biodiesel according to the design matrix shown in the table 4.

iv) The effect of input variables on output variables of an engine were analyzed and correlation between process variables and output responses were made. Multiple regression analysis was used to obtain the coefficients and equations, to predict various responses.

v) Finally, the optimization was done using desirability approach based on the input values of fuel blend, CR and load for getting good performance and reduced emissions.

Table 4. Experimental design matrix for Pongamia blended biodiesel

| Run Order | Blends (%) | CR | Load (%) | BSEC (MJ/kWh) | BTE (%) | CO (%) | HC (ppm) | NOx (ppm) |
|-----------|------------|----|----------|---------------|---------|--------|----------|----------|
| 1         | 20         | 14 | 14       | 43.515        | 9.6     | 0.302  | 126      | 19       |
| 2         | 20         | 14 | 42       | 17.664        | 20.59   | 0.561  | 124      | 75       |
| 3         | 20         | 14 | 70       | 15.510        | 23.37   | 0.736  | 192      | 142      |
| 4         | 20         | 16 | 14       | 35.759        | 10.25   | 0.326  | 105      | 52       |
| 5         | 20         | 16 | 42       | 18.526        | 19.31   | 0.595  | 126      | 96       |
| 6         | 20         | 16 | 70       | 15.510        | 23.54   | 0.813  | 194      | 184      |
| 7         | 20         | 18 | 14       | 32.744        | 10.77   | 0.313  | 159      | 210      |
| 8         | 20         | 18 | 42       | 18.957        | 19.97   | 0.510  | 88       | 124      |
| 9         | 20         | 18 | 70       | 15.510        | 23.18   | 0.798  | 159      | 210      |
| 10        | 40         | 14 | 14       | 39.556        | 9.00    | 0.275  | 132      | 48       |
| 11        | 40         | 14 | 42       | 18.715        | 19.25   | 0.535  | 140      | 86       |
| 12        | 40         | 14 | 70       | 16.163        | 22.37   | 0.766  | 171      | 164      |
| 13        | 40         | 16 | 14       | 34.878        | 10.32   | 0.251  | 104      | 65       |
| 14        | 40         | 16 | 42       | 17.439        | 20.49   | 0.533  | 114      | 88       |
| 15        | 40         | 16 | 70       | 15.737        | 22.76   | 0.761  | 177      | 173      |
| 16        | 40         | 18 | 14       | 34.452        | 10.58   | 0.276  | 87       | 63       |
| 17        | 40         | 18 | 42       | 17.439        | 20.72   | 0.494  | 87       | 104      |
| 18        | 40         | 18 | 70       | 14.461        | 24.86   | 0.659  | 152      | 180      |
| 19        | 60         | 14 | 14       | 33.717        | 10.80   | 0.292  | 115      | 25       |
| 20        | 60         | 14 | 42       | 17.850        | 20.28   | 0.598  | 128      | 74       |
| 21        | 60         | 14 | 70       | 15.073        | 24.76   | 0.768  | 180      | 130      |
| 22        | 60         | 16 | 14       | 31.733        | 11.34   | 0.286  | 110      | 55       |
| 23        | 60         | 16 | 42       | 18.247        | 19.53   | 0.550  | 115      | 86       |
| 24        | 60         | 16 | 70       | 14.676        | 24.62   | 0.761  | 174      | 173      |
| 25        | 60         | 18 | 14       | 32.130        | 11.29   | 0.324  | 84       | 77       |
| 26        | 60         | 18 | 42       | 16.660        | 21.69   | 0.485  | 77       | 104      |
| 27        | 60         | 18 | 70       | 13.883        | 25.78   | 0.550  | 99       | 189      |
2.6. Response desirability approach

Optimization is very much required to solve the problems occurred in real life by considering various responses. Various techniques like overlying contour plots, constrained optimization and response desirability approach are used for giving more importance and weightage for each individual response.

In the present study, response desirability approach was used to optimize input conditions like fuel blends, compression ratio and load for the measured output response like BSEC, BTE, HC, CO and NOx. Software used for the analysis was STATISTICA version 7. Here, each response is changed to a dimensionless desirability value (d). The value of the desirability ranges between d=0, which indicates that the response is completely undesirable and d=1, indicates that the response is more desirable. Desirability of each response is found out using the following equations by considering the goal of each response.

For achieving minimum goal, \( d_i = 1 \) when \( Y_i < L_i \); \( d_i = 0 \) when \( Y_i > H_i \),

\[
d_i = \frac{H_i - Y_i}{H_i - L_i}, \quad \text{when } L_i < Y_i < H_i.
\]  

(1)

For achieving maximum goal, \( d_i = 0 \) when \( Y_i < L_i \); \( d_i = 1 \) when \( Y_i > H_i \),

\[
d_i = \frac{Y_i - L_i}{H_i - L_i}, \quad \text{when } L_i < Y_i < H_i.
\]  

(2)

Next consider goal as target, \( d_i = 0 \) when \( Y_i < L_i \); \( d_i = 1 \) when \( Y_i > H_i \),

\[
d_i = \frac{T_i - Y_i}{H_i - L_i}, \quad \text{when } L_i < Y_i < H_i.
\]  

(3)

\[
d_i = \frac{T_i - Y_i}{H_i - T_i}, \quad \text{when } T_i < Y_i < H_i.
\]  

(4)

The goal of each variable will be within the range for \( d_i = 1 \), when \( L_i < Y_i < H_i \) and \( d_i = 0 \). In the above equations, \( i \) represents the response, \( Y \) represents the value of response, \( L_i \) indicates lower limit of each response, \( T_i \) indicates response of the target value and \( W_i \) represents response of each weight. Optimal parameters were determined by considering the desirability of each variable which gives the maximum ’D’ value.

3. Results and discussions

3.1. RSM model analysis

In the statistical method, experimental results of Pongamia blended fuels were analyzed and curves fitted with second order polynomial equation. The effects of input variables such as blend, compression ratio and load are studied by developing equations to analyze the output variables such as BSEC, BTE, HC, CO and NOx. Model analysis is primarily validated using analysis of variance (ANOVA), which provides the P value for determining significance. The developed model is remarkable for the values of P less than 0.05.

\[
BSEC = 284.8406 + 4.7301X_1 - 0.0783X_1^2 - 27.0228X_2 + 0.7576X_2^2 - 12.0494X_3 + 0.1065X_3^2 - 0.5402X_1X_2 + 0.0165X_1X_2^2 + 0.0087X_1^2X_2 - 0.0003X_1^2X_2^2 - 0.0178X_1X_3 + 0.0002X_1X_3^2 + 0.0003X_1^2X_3 + 1.2887X_2X_3 - 0.0115X_2X_3^2 - 0.0371X_2^2X_3 + 0.0003X_2^2X_3^2
\]  

(5)
\[ BTE = 7.8185 - X_1 - 0.0783X_1^2 - 27.0228X_2 + 0.7576X_2^2 - 12.0494X_3 + 0.1065X_3^2 - 0.5402X_1X_2 + 0.0165X_1X_2^2 + 0.0087X_1^2X_2 - 0.0003X_1^2X_2^2 - 0.0178X_1X_3 + 0.0002X_1X_3^2 + 0.0003X_1^2X_3 + 1.2887X_2X_3 - 0.0115X_2X_3^2 - 0.0371X_2^2X_3 + 0.0003X_2^2X_3^2 \]  
(6)

\[ CO = 4.13985 + 0.29183X_1 + 3.29 \cdot 10^{-3}X_1^2 + 0.52545X_2 + 1.507 \cdot 10^{-2}X_2^2 + 5.803 \cdot 10^{-2}X_3 + 9 \cdot 10^{-5}X_3^2 + 3.718 \cdot 10^{-2}X_1X_2 + 1.14 \cdot 10^{-3}X_1X_2^2 + 4.3 \cdot 10^{-4}X_1^2X_2 + 1 \cdot 10^{-6}X_1^2X_2^2 + 8 \cdot 10^{-5}X_1X_3 + 9.38 \cdot 10^{-3}X_2X_3 + 3.3 \cdot 10^{-4}X_2^2X_3 \]  
(7)

\[ HC = 1507.32 + 132.93X_1 + 1.8X_1^2 + 212.87X_2 + 6.85X_2^2 + 21.54X_3 + 1 \cdot 10^{-2}X_3^2 + 16.95X_1X_2 + 0.53X_1X_2^2 + 0.23X_1^2X_2 + 1 \cdot 10^{-2}X_1^2X_2^2 + 6 \cdot 10^{-2}X_1X_3 + 2.57X_2X_3 + 1 \cdot 10^{-2}X_2X_3^2 + 9 \cdot 10^{-2}X_2^2X_3 \]  
(8)

\[ NO_x = 1707.73 + 52.62X_1 + 0.71X_1^2 + 167.21X_2 + 3.7X_2^2 + 62.23X_3 + 0.79X_3^2 + 4.35X_1X_2 + 7 \cdot 10^{-2}X_1^2X_2 + 6 \cdot 10^{-2}X_1X_3 + 6 \cdot 10^{-2}X_2X_3 + 0.1X_1^2X_3 + 7.28X_2X_3 + 0.22X_2^2X_3 \]  
(9)

Where \( X_1, X_2, \) and \( X_3 \) be the input variables of blend, compression ratio and load respectively.

### 3.2. Model validation

The model was developed using RSM, and stability of model is verified using analysis of variance (ANOVA). The developed models were considered to be significant for the value of \( P \) less than 0.05. The regression statistics is used to indicate goodness of fit (\( R^2 \)). Table 5 shows the regression model of all output variables. \( R^2 \) value shows the total response variability after taking significant factors in to account. The \( R^2 \) value indicates the predicted values are close to experimental values.

| Model       | BSEC  | BTE   | CO     | HC     | NOx    |
|-------------|-------|-------|--------|--------|--------|
| Mean        | 23.835| 18.1489| 0.522889 | 127.9259 | 106.3704 |
| SD          | 9.38284 | 5.848939 | 0.191124 | 35.46496 | 53.63635 |
| Model Degree| Quadratic | Quadratic | Quadratic | Quadratic | Quadratic |
| R^2         | 0.99024 | 0.99625 | 0.98379 | 0.96966 | 0.99703 |
| Adjusted R^2 | 0.96828 | 0.9878 | 0.9473 | 0.90138 | 0.99033 |

### 3.3. Interactive effects of input variables on engine performance

#### 3.3.1. Brake specific energy consumption (BSEC)

The effects of biodiesel blend, \( CR \) and load on BSEC are indicated in response curves shown in figure 2a and figure 2b. It can be observed from curves that the BSEC is decreases significantly at higher load, whereas BSEC slightly more with higher content of Pongamia blended biodiesel, when the engine is operated at lower CR. But, biodiesel blended biodiesel shows decrease in BSEC at higher CR was noticed. This is because higher blends of biodiesel contact with hot combustion chamber, evaporation takes place completely results in better combustion develops more power and fuel consumption per brake power reduces[20].
Response curves of blend, load and CR on BSEC

3.3.2 Brake Thermal Efficiency (BTE)

The interactive effects of biodiesel blend, CR and load on BTE are indicated in response curves shown in figure 3a and figure 3b. Brake thermal efficiency is used to assess the efficiency of an engine by combustion of fuel, utilizing its chemical energy in to useful work. It is determined by considering the ratio of BP of an engine to the energy supplied to system. It can be noted from response curves that the BTE is increases with increase in concentration of Pongamia biodiesel in the blend at higher loads. This is because of the presence of oxygen in the fuel droplets results in better combustion efficiency. When the engine is operated at higher CR and load, the fuel evaporation takes place completely due to hot combustion chamber and better mixing of biodiesel blends results in higher BTE [20].

Interactive Effects of Input Variables on Engine Emissions

3.4. Carbon Monoxide (CO)
The interactive effects of input variables such as blend, CR and load on CO emissions are indicated in response curves shown in figure 4a and figure 4b. It can be observed from response curves that the CO emissions reduces with increase content of Pongamia biodiesel content in the blend and at higher compression ratio. This is may be due to more oxygen content and decrease in ignition delay of biodiesel leads to better combustion to occur.

![Figure 4](image)

**Figure 4.** Response curves of blend, load and CR on CO emissions

3.4.2 Hydro Carbon (HC)

The interactive effects of blend, CR and load on HC emissions are depicted response curves shown in figure 5a and figure 5b. Response curves indicates that the HC emissions decreases with increase concentration of biodiesel in the blend and at higher CR. This may be due to increased oxygenated content in blend, higher temperature and pressure of engine cylinder leads to better combustion to occur. HC emissions increases slightly up to 40% loading conditions and increases significantly for further increase in load.

![Figure 5](image)

**Figure 5.** Response curves of blend, load and CR on HC emissions

3.4.3 Nitrogen Oxides (NOx)

The interactive effects of blend, CR and load on NO\textsubscript{x} emissions are represented in response curves shown in figure 6a and figure 6b. At lower CR, response curves shows that the NO\textsubscript{x} emissions slightly reduces with increase in concentration of Pongamia biodiesel in the blend. Also, increased NO\textsubscript{x} emissions are observed at higher CR and load. This might be due to high engine cylinder temperature and pressure.
3.5. **Optimization**

Optimization of experimental results of Pongamia blended biodiesel in diesel engine was done using the option ‘desirability profile’ in STATISTICA software. In the desirability approach, best solutions of output variables are obtained. The combination of input variables are selected by considering the solution with high desirability value of 0.92. Desirability profiles of performance and emissions parameters are considered to get the optimum input parameters. The optimum combination of input variable for getting better BTE, lower BSFC and lower emissions is:

- **Blend**: B60
- **CR**: 18
- **Load**: 42%

3.6. **Validation of the optimized result**

The optimized result was validated, by conducting the experiments thrice for optimum combination of input variables. Average experimental values and predicted values and errors are tabulated in Table 6.

|                | BSEC (MJ/kWh) | BTE (%) | CO (%) | HC (ppm) | NOx (ppm) |
|----------------|---------------|---------|--------|----------|-----------|
| Actual value   | 16.66         | 21.69   | 0.485  | 77       | 104.00    |
| Predicted value| 17.695        | 21.056  | 0.474  | 71.03    | 107.59    |
| Error          | -1.035        | 0.634   | 0.011  | 5.97     | -3.59     |

Validated test shows that the predicted values had good agreement with experimental results.

4. **CONCLUSIONS**

The present paper on statistical analysis, reveals the use of experimental design to reduce the number of experiments on the engine required for the analysis. The significance each engine input variable on the engine performance and emission characteristics were studied and analyzed with the help of Response surface methodology (RSM). The optimum combination of the input data was done using desirability approach get better engine performance and lower emissions. The following conclusions were drawn based on the outcomes of the study:
• High BTE of the engine was noticed for higher blend of Pongamia biodiesel. At low CR, BSEC slightly more with higher content of Pongamia blended biodiesel, whereas it decreases with increase in compression ratio and load.
• CO emissions of Pongamia biodiesel blends B60 and B40 is lower than the blend B20.
• Pongamia biodiesel blends B40, B60 shows reduced HC emissions compared to the blend B20. Also, significant decrease in HC emissions of Pongamia blends were noticed for CR-18 compared with CR-14.
• NOx emissions reduces as the percentage of Pongamia biodiesel in the blend increases at lower CR and more NOx emissions were noticed at higher CR and loading conditions.
• The validated test shows that the predicted values had good agreement with the experimental results.

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