ENHANCING PERFORMANCE OF COMPRESSION IGNITION ENGINE FUELED WITH DIESEL BLENDS OF LINSEED AND COTTONSEED OIL BY OPTIMIZING ITS TECHNOLOGICAL PARAMETERS

by

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In this paper an attempt was made to evaluate the performance of the fossil fuels in the modern world has tremendously increased. As the energy efficiency is greater than other fuel sources. For enhancing the sustainability, it is important to develop alternative fuels with properties similar to petroleum waste of these biodiesel proofs to be a viable option to achieve good engine performance. In this pattern attempt was made to evaluate the performance of compression ignition engine which was fueled using diesel blends of linseed oil and cottonseed oil. Important input process parameters were varied such as load, time taken for consumption of 10 cc of fuel, ratio of biodiesel mixture. For achieving enhanced performance, a central composite design model was used to set the process parameter values for 20 sets of experiments. Accordingly, the experiments were conducted and the responses were recorded. Analysis of variance was used to evaluate the significance of the developed model. Optimization was done using response surface methodology for obtaining maximum possible brake thermal efficiency and least possible hydrocarbon emission. The model was validated with validation experiments and it was observed that the error between the experimental and predicted values were less than 4% which indicated that the model was developed with very high level of predictability.

Key words: *linseed oil, cottonseed oil, bio-diesel, response surface methodology, optimization*

Introduction

This in the recent times the growing demand for highly efficient and low pollutive fuels as made researches to investigate various combinations of biodiesel. The environmental pollution and its recent increase due to the uncontrolled emissions of exhaust gases by burning fossil fuels have made the researches to boldly shift towards biodiesel has received huge attention. The advantage is they are bio-degradable and do not produce toxic emissions on combustion [1-3].

Researchers have conducted experiments by combining different additives to diesel. Meng *et al.* [4] conducted experiments by using waste cooking oil as additives and observed that performance of Diesel engine remained normal. The combustion which reduced the emissions of Diesel engine remained normal. The combinations which reduced the emissions of

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CO and HC were evaluated. Kumar *et al.* [5] and Murillo *et al.* [6] conducted experiments on Diesel engine (four-stroke) by running it in a blend of 10% cooking oil to 90% diesel, 30% cooking oil to 70% diesel, and 50% cooking oil to 50% diesel. It was observed that they were more environment friendly than conventional diesel. Dorado *et al.* [7] conducted experiments by blending diesel with olive oil in various ratios and used them in three cylinder, four-stroke direct injection engine (capacity of 2.5 liters). In which reduction in the emission of CO, CO_2 and an appreciable reduction in SO_2 emission were observed. The effect of variations in NO_x emissions on fluctuating the ratio of olive oil to diesel were critically evaluated [8].

In addition to that, identifying proper additives for obtaining biodiesel. The ratio, loading conditions, and the other important process parameters that directly affects are the major objectives of this research. The performance of engine should be properly controlled. Optimization techniques can be used for attaining the desired results without spending time and labor on trial and error methods. Datta *et al.* [9] used Taguchi optimization technique in enhancing the weld quality of joints fabricated by using sub-merged arc welding techniques. The vital parameters which indicated the joints were height of weld bead the extent of depth in penetration. The width of the bead joint and percentage of dilution. Rao *et al.* [10] used Taguchi optimization methodology for enhancing the efficiency of CO_2 and other undesirable emissions were controlled. Jayaraman *et al.* [11] used Taguchi optimization methodology by incorporating grey relation analysis for enhancing friction stir welded aluminum joints. The important friction stir welding process parameter which are optimized were the rotational speed of the non-consumable friction stir welding tool. Speed of moment of the spindle for welding and shoulder to pin ratio. Experiments were conducted to evaluate the surface characteristics of turned mild steel product [12, 13]. The important process parameters which fluctuated the output surface qualities were optimized by using Taguchi optimization methodology. From the study of literatures and previous investigations it was observed that research in use of biodiesel blended with linseed oil and cottonseed oil in compression ignition (CI) engine was not found. Hence in this research an attempt was made to optimize the technological parameters involved in use of diesel blends of linseed and cottonseed oil in CI engine system.

Materials and methods

Experimental set-up and procedure

In this paper linseed oil and cottonseed oil were subjected to transesterification methodology for preparing biodiesel. The important properties of the diesel and oils are indicated in tab. 1. For biodiesel preparation alcohol was used in the presence of sodium hydroxide as a catalyst to break the molecules of linseed oil and cottonseed oil and convert them into methyl esters. Using press squeezing equipment, linseed and cottonseed were squeezed to produce oil. The obtained oil was mixed with methanol and potassium hydroxide and heated to an elevated temperature of 135 °C for 20 minutes with continuous stirring. Then it was allowed to settle as

Table 1. Properties of the components used in the biodiesel blend

Properties	Diesel	Linseed oil	Cottonseed oil
Density [kgm^{-3}]	832	930	917
Specific gravity	0.82	0.93	0.91
Flash point	40	43	45
Fire point	45	54	57
Calorific value [kJkg^{-1}]	44800	42650	41380
Free fatty acid [%]	0.110	0.069	0.083

two distinct faces. As crude ester at top and glycerol at the bottom which was separated using funnel. The methyl ester in crude form was purified by washing it in water to remove residual by products. The washed in methyl ester was heated to a little more than 100 °C for 5 minutes till evaporation of remaining water content. Then appropriate blends of biodiesel were prepared by varying the proportions of its volume with diesel. For conducting the experiments, a direct injection type single cylinder diesel engine (naturally aspired) test rig was used.

Identifying feasible limits

From previous literatures, involving the performance studies of CI engines, and from trial and error experiments, the feasible limits of the technological parameters were evaluated. The three important technological process parameters that fluctuate the performance characteristics of CI engine, fueled with biodiesel blended with linseed and cotton seed oil, were the ratio of biodiesel mixture, time taken for consumption of 10 cc of fuel and the loading under which the experiments were conducted. From trial and error experiments the following conclusions were drawn.

- When the experiments were conducted with blend less than 2.5% of linseed oil and 2.5% of cotton seed oil in diesel, the efficiency of the engine was found to be low and undesirable. NO_x content in the emissions were beyond tolerable limits.
- When the experiments were conducted with blend less than 7.5% of linseed oil and 7.5% of cotton seed oil in diesel, the specific fuel consumption undesirably due to the enhanced concentration of linseed and cottonseed oil.
- If the time duration for consumption of 10 cc of fuel was fixed less than 60 seconds, excessive fuel input at shorter time caused wastage of fuel and concentration of unburnt hydrocarbon in the exhaust was found to be more.
- If the time duration for consumption of 10 cc of fuel was fixed greater than 68 seconds, due to lack of enough supply of fuel at the required rate caused reduction in the engine performance.
- If the loading under which the experiments were conducted were less than 2 kg, the specific fuel consumption was found to be more, thereby reducing the engine efficiency.
- If the loading was done greater than 8 kg, the percentage of undesirable NO_x, CO, and CO_2 emissions started to increase.

Thus, within the blend ratio of 95% diesel + 2.5% linseed oil + 2.5% of cotton seed oil to 85% diesel + 7.5% linseed oil + 7.5% cottonseed oil, time duration of consumption of 10 cc of fuel 60-68 seconds and the load variation from 2 kg and 8 kg, the performance of the CI was acceptable. The range of the technological parameters are indicated in tab. 2. The experiments were conducted by fluctuating the technological process parameters. When the CI Diesel engine was run by the biodiesel, the brake thermal efficiency (BTE) was calculated and the amount of hydrocarbon content present in the exhaust gas was evaluated by exhaust gas analysis.

Table 2. Feasible range of technological parameters

Parameter	Levels				
	–1.68	–1	0	1	+1.68
Biodiesel blend –% of linseed, cotton seed oil each	2.5	3.5	5	6.5	7.5
Time for consumption of 10 cc of fuel	60	61.5	64	66.5	68
Load	2	3.2	5	6.7	8

Developing central composite design model

For evaluation, a central composite design model was selected. As the range of the individual values were found to be high, twenty sets of coded conditions were used. With eight sets of design points, a five-level central composite design model was used consisting of six star and central points. The most positive coded value of the CI Diesel engine running with biodiesel blend technological parameters was coded as +1.68 and the least negative technological parameters was coded to be –1.68. the values of the intermediate range of process parameters were obtained by Montogomery DC:

$$Hi = 1.682 \frac{2H - (H_{\max} + H_{\min})}{(H_{\max} + H_{\min})} \tag{1}$$

In eq. (1) the coded variable value of H was Hi. From the value ranging from $H_{\min}$ to $H_{\max}$, H is made to assume any value of the variable. The least value of the coded parameter was termed as $H_{\min}$ and the highest value of coded parameter value was termed as $H_{\max}$. The central composite design model formed with twenty different conditions are shown in tab. 3.

The BTE of the biodiesel fueled CI Diesel engine was evaluated for the various running conditions and are indicated in tab. 3. Shown are also the amount of HC content [ppm] emitted in the exhaust were observed using exhaust gas evaluation techniques and the values.

Table 3. Range of central composite design model with experimental values

Run	*B* [%]	*T* [seconds]	*L* [kgf]	*BTE* [%]	*HC* [ppm]
1	5.00	60.00	5.00	56.6	133.6
2	5.00	68.00	5.00	58.6	128.8
3	6.49	61.62	6.78	61.7	136.6
4	7.50	64.00	5.00	59.2	135.7
5	3.51	61.62	3.22	52.7	136.3
6	3.51	66.38	3.22	59.1	127.8
7	5.00	64.00	2.00	55.4	127.4
8	6.49	66.38	3.22	57.0	127.2
9	5.00	64.00	5.00	59.8	123.9
10	6.49	61.62	3.22	56.3	132.2
11	5.00	64.00	5.00	59.7	122.1
12	3.51	61.62	6.78	57.0	132.9
13	5.00	64.00	5.00	59.9	122.6
14	2.50	64.00	5.00	57.0	133.4
15	5.00	64.00	5.00	59.9	123.3
16	5.00	64.00	5.00	59.8	123.7
17	5.00	64.00	5.00	59.5	123.5
18	5.00	64.00	8.00	59.4	135.4
19	3.51	66.38	6.78	58.6	131.1
20	6.49	66.38	6.78	58.0	137.3

Results and discussion

Establishing empirical relationships

Aavudaiappan *et al.* [14] and Dinesh *et al.* [15] developed empirical models for predicting the responses using RSM, ANOVA, and neural network modelling. Between biodiesel fueled CI Diesel engine combustion technological process parameter values and responses, relationships were developed in empirical form. The responses were observed in the form of BTE and the HC, content in the exhaust fumes. These responses were attributed to be functions of the important biodiesel fueled CI Diesel engine combustion technological process parameters such as blend percentage of linseed oil and cottonseed oil, B [%], time taken for consumption for 10 cc fuel, T [seconds], load connected [kg]. As per the relationship indicated by Paventhan *et al.,* [3] the relations are given in eqs. (2)-(5).

$$BT = f(B, T, L) \tag{2}$$

$$HC = f(B, T, L) \tag{3}$$

The response surface, L, of the tensile strength, TS, and weld region micro-hardness, WH, of the super duplex joints are represented by using a polynomial regression equation of second order:

$$L = g_0 + \Sigma g_i x_i + \Sigma g_{i1} x_{i2} + \Sigma g_{ij} x_i x_j \tag{4}$$

For blend ratio of linseed and cottonseed oil, B, time taken for 10 cc fuel consumption, T, load connected, L [kg], the second order polynomial equation is:

$$\frac{BT}{HC} HC = \{g_0 + g_1(B) + g_2(T) + g_3(L) + g_{12}[B \times T] + g_{13}[B \times L] + g_{23}[T \times L] + \\ + g_{11}(B)^2 + g_{22}(T)^2 + g_{33}(L)^2\} \tag{5}$$

where g_0 is the average of all responses. The coefficients of the regression equation g_1, g_2, g_3, and g_{nn} depend upon the various types such as linear term, interaction term and squared terms of the three input factors. The values of the coefficients were evaluated by using design expert software. The significance of the individual coefficient values was identified using student t tests and p values.

Using analysis of variance (ANOVA), tests were conducted for maximization of BTE model and HC content minimization model. The ANOVA test results for BTE model is indicated in tab. 4 and the ANOVA results for HC content minimization model is indicated in tab. 5. The value of Prob > F, lesser than 0.05, is a very good indication that the developed model is significant at 95% confidence level. The range of values 0.10 shows that the model terms are insignificant. Break thermal efficiency of the biodiesel fueled CI diesel engine is indicated as:

$$BT = 59.81 + 0.67B + 0.63T + 1.24L - 1.37B \times T + 0.32B \times L - \\ -1.15\, T \times L - 0.59\, B^2 - 0.76T^2 - 0.84L^2 \tag{6}$$

The HC emission of the biodiesel fueled CI diesel engine is indicated:

$$HC = 123.24 + 0.65B - 1.67T + 2.03L + 0.74B \times T + 1.83B \times L + \\ + 1.55T \times L + 3.95B^2 + 2.77T^2 + 2.86\, L^2 \tag{7}$$

Table 4. The ANOVA test results for BTE model

Source	SS	Dof	F - ratio	p-value Prob > F
Model	78.51	9	571.43	< 0.0001
B	6.07	1	397.79	< 0.0001
T	5.39	1	352.82	< 0.0001
L	20.84	1	1365.23	< 0.0001
$B \times T$	14.97	1	980.37	< 0.0001
$B \times L$	0.84	1	54.93	< 0.0001
$T \times L$	10.62	1	695.78	< 0.0001
B^2	4.96	1	324.78	< 0.0001
T^2	8.43	1	552.10	< 0.0001
L^2	10.17	1	665.90	< 0.0001
Res	0.15	10		
LOF	0.042	5	0.38	0.8438
Std. dev	0.12	R^2		0.9957
Mean	58.31	Adj		0.9963
C.V.%	0.21	Pred		0.9937
Press	0.49	Adeq pres		101.233

Table 5. The ANOVA test results for HC content minimization model

Source	SS	Dof	F - ratio	p-value Prob>F
Model	532.30	9	129.14	< 0.0001
B	5.81	1	12.70	0.0052
T	37.94	1	82.83	< 0.0001
L	56.38	1	123.09	< 0.0001
$B \times T$	4.44	1	9.69	0.0110
$B \times L$	26.93	1	58.81	< 0.0001
$T \times L$	19.23	1	41.98	< 0.0001
B^2	225.05	1	491.38	< 0.0001
T^2	110.70	1	241.71	< 0.0001
L^2	117.47	1	256.50	< 0.0001
Res	4.58	10		
LOF	2.09	5	0.84	0.5750
Std. dev	0.68	R^2		0.9915
Mean	129.78	Adj		0.9838
C.V.%	0.52	Pred		0.9635
Press	19.60	Adeq pres		30.773

Empirical relationship evaluation

For evaluation of the developed empirical relationship, ANOVA technique was applied. From the response surface model which was developed, the adequacy of the results was verified. The R^2 was termed to be the determination coefficient. For the developed model of BTE enhancement and HC emission reduction model, the value of R^2 can be used to indicate the goodness of fit. On evaluation of the various values from the results of ANOVA analysis in tabs. 4 and 5, it could be inferred that only around 5% of the variations were left unexplained. As the value of adjusted R^2 was found to be high, it could be inferred that the level of significance of the developed model was very high. The adjusted coefficient of determination was found to be in good agreement with the value of predicted R^2 value. The value of adequate precision is used to evaluate the error obtained during the prediction and compare the predicted range of values. As the value of the determination coefficient was found to be greater than 0.95, it could be observed that the experimental values were in good correlation with the predicted values of BTE and HC emissions. The correlation between the predicted and actual BTE of biodiesel fueled CI Diesel engine is shown in fig. 1(a) and that for HC emission is shown in fig. 1(b).

Optimization of technological parameters

With mathematical techniques and statistical methodologies, the relation between the biodiesel fueled CI Diesel engine combustion process parameters and the output responses were

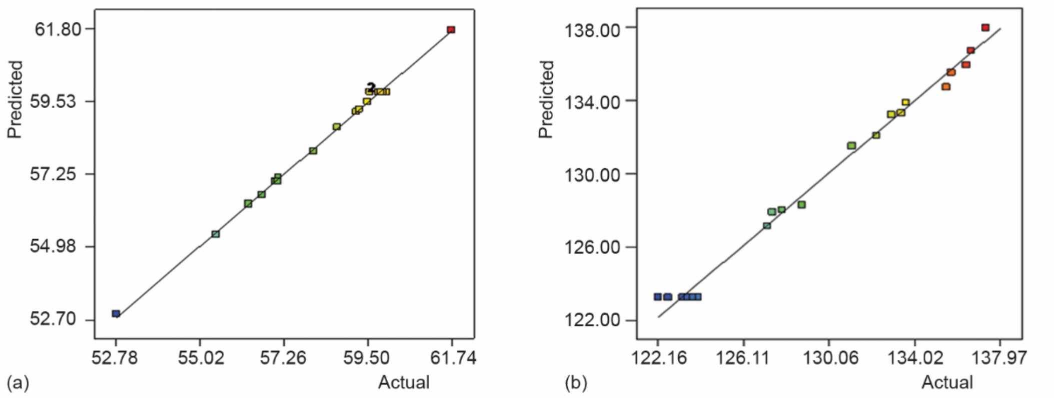

Figure 1. Correlation between predicted and actual values; (a) BTE, (b) HC emission

identified. In this investigation, response surface methodology has been used for optimization of the linseed oil and cottonseed oil blended biodiesel fueled CI Diesel engine combustion process parameters. As the number of variables were more, such as the ratio of biodiesel mixture, time taken for consumption of 10 cc of fuel and the loading under which the experiments were conducted, response surface methodology was very efficient in optimization. The fluctuations in dependent variables such as BTE and HR emission were evaluated using response surface methodology:

$$J = \Phi(z_1, z_2 \ldots z_k) \pm er$$

The response is indicated by J and the factors in qualitative nature are indicated by z_1, $z_2 \ldots z_k$. The surface of response (response function) has been indicated. The experimental errors are indicated by the residual error, er. A characteristic surface region was plotted for the independent variables

Developing 3-D surface plots and contours

Using circular shapes, the dependence between the important factors such as the ratio of biodiesel mixture, time taken for consumption of 10 cc of fuel and the loading under which the experiments were conducted and the responses in the form of BTE and emission of HC were indicated in the form of contours. The stationary point is made to attain the value of either maximum, minimum or saddle. By characterizing the stationary point the response surface study could be conducted and optimization can be done. Contours were developed with the help of design expert software. By studying the shape of the surface, the optimum region can be understood with good amount of accuracy. Circular contours indicate the independence between the factors. Elliptical shapes of the contours indicate interaction between the factors. By using two of the biodiesel fueled CI Diesel engine combustion process parameters at the middle range and plotting them in the two-reference axis such as x-axis and y-axis, the responses such as the BTE and emission of HC in the exhaust were traced in the z-axis. The point of optimality was attained by using 3-D surface plots of the responses. The contour plots for BTE is indicated in fig. 2. Figure 2(a) indicates the contour plots for blend percentage of linseed oil, cottonseed oil each and time taken for consumption of 10 cc of biodiesel. Figure 2(b) indicates the contour plots for blend percentage of linseed oil, cottonseed oil each and load. Figure 2(c) indicates the contour plots for time taken for consumption of 10 cc of biodiesel and load. Figure 3 indicates the 3-D surface plots for BTE enhancement model.

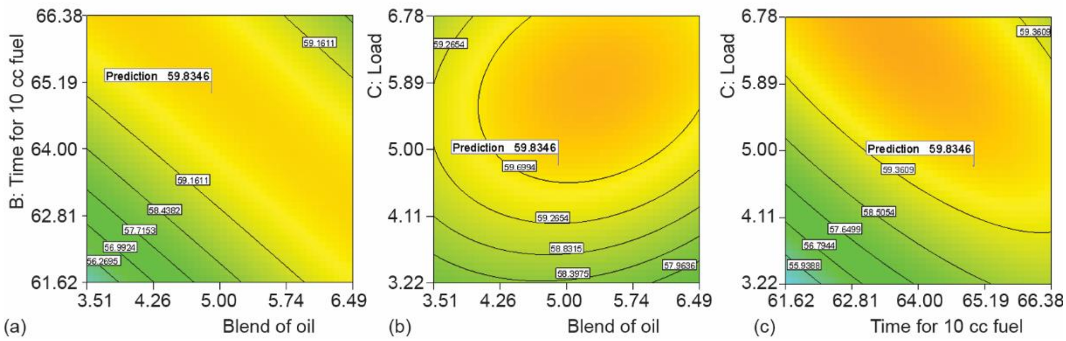

Figure 2. Contour plots for BTE maximization model; (a) blend of linseed, cottonseed oil each with time taken for 10 cc fuel consumption, (b) blend of linseed, cottonseed oil each with load applied during the running of the engine, (c) time taken for 10 cc fuel consumption with load

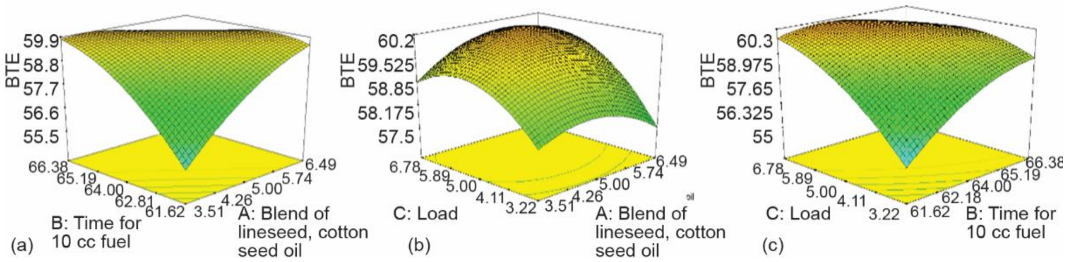

Figure 3. The 3-D surface plots for BTE maximization model; (a) time for 10 cc fuel consumption *vs.* blend of linseed, cottonseed oil, (b) load *vs.*. blend of linseed, cottonseed oil, (c) load *vs.*. time taken for consumption of 10 cc of fuel

Figure 3(a) indicates the surface plots for time taken for 10 cc fuel consumption *vs.* blend of linseed, cottonseed oil. Figure 3(b) indicates the surface plots for load *vs.* blend of linseed, cottonseed oil. Figure 3(c) indicates the contour plots for load *vs.* time taken for consumption of 10 cc of fuel. Figure 4 indicates the contours for minimization model of HC. Figure 4(a) indicates the contours of blend of linseed, cottonseed oil each with time taken for 10 cc fuel consumption. Figure 4(b) indicates the contours for blend of linseed, cottonseed oil with load. Figure 4(c) indicates the contours of time for 10 cc fuel *vs.* load. Figure 5 indicates the 3-D surface plots for minimization model of HC. Figure 5(a) indicates the surface plot for time for 10 cc fuel consumption with blend of linseed, cottonseed oil. Figure 5(b) indicates the surface plot for load *vs.* blend of linseed, cotton seed oil. Figure 5(c) indicates the surface plot for load *vs.* time for consumption of 10 cc of fuel. From study of the contours and surface plots the optimized values could be attained.

Evaluation of plots and validation

The optimized values for blend percentage of linseed oil, cottonseed oil each was 4.91% each, time for consumption of 10 cc fuel was 65 seconds, loading with which the experiments are to be conducted as 4.8 kgf were found using optimization technique. Also, the predicted maximum BTE was found to be 59.8% and the minimum possible HC emission was found to be 122.7 ppm in the exhaust gases. To validate the optimization model which was

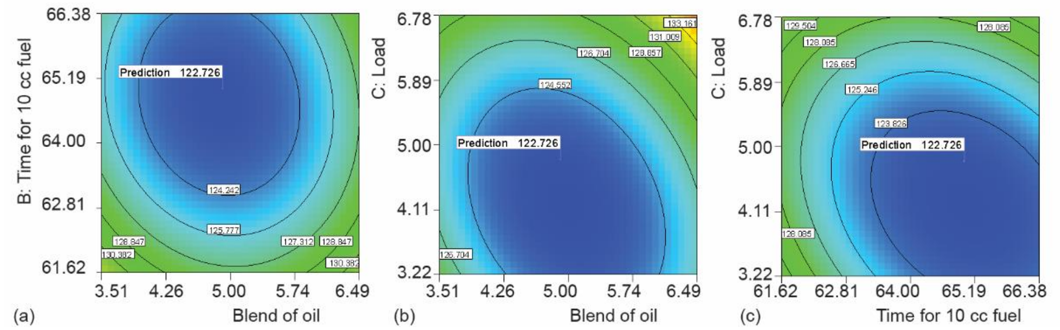

Figure 4 Contour plots for HC emission maximization model; (a) blend of linseed, cottonseed oil each with time taken for10 cc fuel consumption, (b) blend of linseed, cottonseed oil with load, (c) time for 10 cc fuel *vs.* load

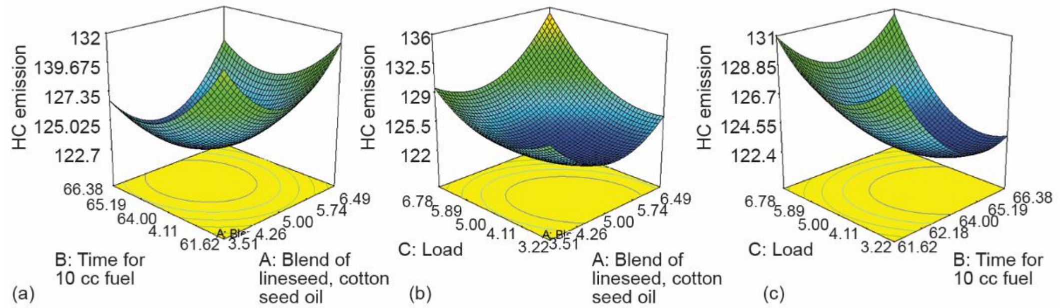

Figure 5. Surface plots for HC emission maximization model; (a) time for 10 cc fuel consumption with blend of linseed, cottonseed oil, (b) load *vs.* blend of linseed, cotton seed oil, (c) load *vs.* time for consumption of 10 cc of fuel

Table 6. Validation experiments and results

Response	Predicted	Experimental	Error
BTE	59.8%	58.6%	2%
		57.9%	3.1%
		58.4%	2.3%
HC emission	122.7 ppm	123.22 ppm	0.4%
		124.1 ppm	1.1%
		123.9 ppm	0.9%

developed, validation experiments were conducted to ascertain the predictability of the developed BTE enhancement had HC exhaust minimization model. Three similar experiment were conducted with the optimized vales of the technological process parameters and the results have been indicated in tab. 6. From validation experiments, it could be inferred that the error between the predicted and the actual values were less than 4%. This showed that the model was developed with very high predictability.

Conclusion

From the experimental evaluation of the of the linseed oil and cottonseed oil blended biodiesel fueled CI Diesel engine combustion process parameters, the following inferences were drawn. Central composite design model was used for developing empirical relationships between responses such as BTE and HC emission were formed with the important technological parameters such as blend percentage of linseed and cottonseed oil each, time taken for consumption of 10 cc fuel, loading in kgf. Using ANOVA analysis, the significance of the developed model was ascertained with greater than 95% significance. With optimized values of blend percentage of linseed oil, cottonseed oil of 4.91% each, time for consumption of 10 cc fuel for 65 seconds, loading as 4.8 kgf, a maximum BTE of 59.8% and minimum HC emission of 122.7 ppm in exhaust gases was predicted which was validated to a very high level of predictability.

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