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ORIGINAL PAPER

Optimization of operational parameters on performance and emissions of a diesel engine using biodiesel

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Abstract This work investigates the influence of compression ratio on the performance and emissions of a diesel engine using biodiesel (10, 20, 30, and 50 %) blended-diesel fuel. Test was carried out using four different compression ratios (17.5, 17.7, 17.9 and 18.1). The experiments were designed using a statistical tool known as design of experiments based on response surface methodology. The resultant models of the response surface methodology were helpful to predict the response parameters such as brake specific fuel consumption, brake thermal efficiency, carbon monoxide, hydrocarbon and nitrogen oxides. The results showed that best results for brake thermal efficiency and brake specific fuel consumption were observed at increased compression ratio. For all test fuels, an increase in compression ratio leads to decrease in the carbon monoxide and hydrocarbon emissions while nitrogen oxide emissions increase. Optimization of parameters was performed using the desirability approach of the response surface methodology for better performance and lower emission. A compression ratio 17.9, 10 % of fuel blend and 3.81 kW of power could be considered as the optimum parameters for the test engine.

Keywords Biofuel · Compression ratio · Energy · Karanja · Response

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Introduction

The combustion of the fossil fuel produced from diesel engines has polluted the environment through the exhaust emissions of hydrocarbons (HCs), oxides of nitrogen (NO_x), carbon monoxide (CO), and oxides of sulfur (SO_x). Moreover, NO_x and CO_2 are the green house gases, and SO_x causes acid rain. On the other hand, vegetable oils present a very promising alternative to diesel oil since they are renewable and have similar properties. Many researchers have studied the use of vegetable oils in diesel engines. Vegetable oils offer almost the same power output, with slightly lower thermal efficiency when used in diesel engines. Reduction of engine emissions is a major research aspect in engine development with the increasing concern on environmental protection and the stringent exhaust gas recirculation. The tremendous growth of vehicular population of the world has led to a steep rise in the demand for petroleum products. Biodiesel such as Jatropha, Karanja, sunflower, and rapeseed are some of the popular biodiesel currently considered as substitutes for diesel. These are clean burning, renewable, non-toxic, biodegradable, and environmentally friendly transportation fuels that can be used in neat form or in blends with petroleum derived from diesel engines. Methyl and ethyl esters of Karanja oil can be used as fuel in compression ignition engine.

When biodiesel is used as a substitute for diesel, it is highly essential to understand the parameters that affect the combustion phenomenon, which will in turn have direct impact on thermal efficiency and emission. In the present energy scenario, lot of effort is being focused on improving the thermal efficiency of IC engines with reduction in emissions (Srivastava Prasad 2000; Ramanik 2003; Demirbas 2005). The present analysis reveals that biodiesel from unrefined jatropha, Karanja, and polanga seed oil is quite suitable as an alternative to diesel (Sahoo and Das 2009; Agrawal and Agrawal 2007). In developed and developing countries, fossil fuels are used in diesel engines. Diesel engines have a negative effect on environment, since diesel fuels include high amounts of sulfur and aromatics. CO, SO_x, NO_x, and smoke are produced from fossil fueled diesel engine exhaust emissions (Kalam et al. 2003). It has been observed that engine parameters such as injection timing, compression ratio (CR) have considerable effects on the performance and emissions of diesel engine running on biodiesel blends. The oxygenated nature of biodiesel becomes more advantageous which tends to result in more complete combustions and reduce the CO emissions (An et al. 2012). Many innovative technologies are developed to tackle these problems. Modification is required in the existing engine designs. Some optimization approach has to be followed so that the efficiency of the engine is not comprised. As far as the internal combustion engines are concerned, the thermal efficiency and emission are the important parameters for which the other design and operating parameters have to be optimized. The most common optimization techniques used for engine analysis are response surface method, gray relational analysis (Agrawal and Rajamanoharan 2009), non-linear regression (Banapurmath et al. 2008), genetic algorithm (Alonso et al. 2007), and Taguchi method; Taguchi technique has been popular for parameter optimization in design of experiments. Multi objective optimization of parameters using non-linear regression has found optimum value to be 13 % biodiesel–diesel blend with an injection timing of 24° Btdc (Maheswari et al. 2011). Blend of B30 thumba biodiesel, a CR of 14, a nozzle opening pressure of 250 bar, and an injection timing of 20° produces maximum multiple performance of a diesel engine with minimum multiple emissions from the engine (Karnwal et al. 2011). A thermodynamic model analysis of jatropha biodiesel engine in combination with Taguchi's optimization approach to determine the optimum engine design and operating parameters was found out to maximize the performance of biodiesel engine (Ganapathy et al. 2009). Artificial neural network (ANN) has been used to predict the performance and exhaust emissions of blended fuels (Xue et al. 2011; Najafi et al. 2009). It was reported that ANN can predict engine emissions and exhaust gas temperature, quite well with correlation coefficients in the range of 0.983–0.996 (Canakci et al. 2006; Sayin et al. 2007; Ganapathy et al. 2009). Many researches about optimization and modification on engine, low temperature performances of engine, new instrumentation and methodology for measurements should be performed when petroleum diesel is substituted completely by biodiesel (Celik and Arcaklioglu 2005). From the review of literature, it can be seen that while a lot of work has been carried out to improve the performance of biodiesel fueled compression ignition, studies on multi-objective optimization to determine the most suitable set of operating variables, with modern optimization techniques are not many. Hence, the aim of the present research is to set up an experimental study and to study the individual and combined effects of combustion parameters on the performance and emission characteristics of the diesel engine, employing Karanja biodiesel–diesel blend, using response surface methodology (RSM)-based experimental design, and the other objective is to determine the optimal values of CR, blend, and power, which would be resulting in improved performance with less emissions using the desirability approach. This research was done in Research laboratory of IC Engines at Anjalai Ammal Mahalingam Engineering College India from June 2011 to March 2012.

Materials and methods

Fuel preparation

The vegetable oils were obtained from commercial sources and used without further purification. The samples were converted to methyl esters by alkali catalytic and non-catalytic super critical methanol transesterification methods. Transesterification (also called alcoholysis) is the reaction of a fat or oil with an alcohol to form esters and glycerol (Singh and Singh 2010).

Therefore, methanol (CH_3OH) as an alcohol and potassium hydroxide (KOH) as a catalyst were used in the transesterification. Molar ratio between alcohol and oil used was 6:1, whereas catalyst amount was 1 % of the oil's weight. The experiments were performed in a laboratory scale apparatus. Transesterification was carried out in a 2,000 ml reaction flask, equipped with reflux condenser, magnetic stirrer, and thermometer. The catalyst was dissolved in methanol by stirring in a small flask. About 1,000 g of oil was added to the reaction flask and heated. When the temperature reached 65 °C, the alcohol/catalyst mixture was added into the oil and then the final mixture was stirred for 3 h. After completion of stirring, the mixture was allowed to settle down for 24 h. After the transesterification, the glycerin layer was separated in a separating funnel. The ester layer was washed with warm water four times. After the final washing, the ester was subjected to a heating at 100 °C to remove excess alcohol and water. The fuel blend was prepared just before commencing the experiments, to ensure the mixture homogeneity. The properties of the fuel blend and diesel have been determined as per the ASTM Standards in an analytical lab. The fuels properties were tested using standard measuring devices shown in Table 1.

Experimental setup

The experimental setup consists of a direct injection single cylinder four stroke cycle diesel engine connected to an eddy current type dynamometer for loading. It is provided with necessary instruments for pressure and crank-angle measurements. These signals are interfaced to computer through engine indicator for P–θ AND PV diagrams. Provision is also made for interfacing air flow, fuel flow, temperatures, and load measurements. This setup has stand-alone panel box consisting of air-flow, fuel measuring unit, transmitters for air and fuel flow measurements, process indicator, and engine indicator. Rotameters are provided for cooling water and calorimeter for water flow measurement. Details of the engine specification are shown in Table 2. The signals from the combustion pressure sensor and the crank angle encoder are interfaced to a computer for data acquisition. The control module system was used to control the engine load, monitor the engine speed, and measure the fuel consumption. Windows based engine performance analysis software package "Engine soft" was provided for online performance evaluation. HC, CO, CO_2, and K (air surplus rate) NO_x emissions were measured with an infra red gas analyzer with an accuracy shown in Table 4. In every test, volumetric fuel consumption and exhaust gas emissions such as CO, HC, and NO_x were measured. From the initial measurement, brake thermal efficiency (BTHE), brake specific fuel consumption (BSFC), brake power (BP) for different blends and different CR were calculated and recorded.

Error analysis

Errors and uncertainties in the experiments can arise from instrument selection, condition, calibration, environment, observation, reading, and test planning. Errors will creep into all experiments, regardless of the care which is exerted. Uncertainty analysis is needed to prove the accuracy of the experiments. In any experiment, the final result is calculated from the primary measurements. The error in the final result is equal to the maximum error in any parameter used to calculate the result. Percentage uncertainties of various parameters like total fuel consumption; BP, BSFC, and BTHE were calculated using the percentage uncertainties of various instruments used in the experiment. For the typical values of errors of various parameters given in Table 4, using the principle of propagation of errors, the total percentage uncertainty of an experimental trial can be computed.

The total percentage uncertainty = Square root of [(uncertainty of brake power)^2 + (uncertainty of SFC)^2 + (uncertainty of TFC)^2 + (uncertainty of BTHE)^2 + (uncertainty of HC)^2 + (uncertainty of CO)^2 + (uncertainty of NO_x)^2 + (uncertainty of pressure pick up)^2] = ±1.85 %.

Response surface methodology

Response surface methodology is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes.

Table 2 Engine specification

Make and model	Kirloskar model TV 1
Engine type	Single cylinder four stroke direct injection
Bore × stroke	87.5 mm × 110 mm
Maximum power output	5.2 kW at 1,500 rpm
Displacement	661 cc
CR	17.5
Loading	Eddy current dynamometer, water cooling
Fuel injection	23 bTDC
Engine speed	1,500 rpm
Software used	Engine soft
Governor type	Mechanical centrifugal type
Eddy current dynamometer	
Model	AG-10
Type	Eddy current
Maximum	7.5 kW at 1,500–3,000 rpm

Table 1 Properties of biodiesel-blends—Karanja and diesel

Fuel blend	Kinematics viscosity, ν (mm^2/s)	Heating value, HV (KJ/kg)	Flash point, FP (°C)	Density, ρ (kg/l)	Cetane number
Diesel	2.71	44,800	55	0.836	51.00
B20	3.04	43,690	96	0.851	51.70
B40	3.51	43,150	99	0.854	52.82
B50	3.62	43,307	106	0.856	53.15
B60	3.81	42,937	123	0.859	53.86
B100	4.37	42,133	163	0.900	54.53
Measurement and apparatus standard test method	Redwood viscometer ASTM D445	Bomb calorimeter ASTM D240	Penksy martens ASTM D93	Hydrometer ASTM D941	Ignition quality tester ASTM D613

Table 3 Experimental design matrix

Run order	Compression ratio	Fuel blends (%)	Power (kW)	BTHE (%)	BSFC (kg/kW h)	CO (%)	HC (ppm)	NO_x (ppm)
1	17.5	10	3.64	34.84	0.24	0.22	69	1,258
2	17.5	10	4.16	35.42	0.23	0.42	69	1,319
3	17.5	10	4.68	34.94	0.24	1.11	70	1,335
4	17.5	10	5.2	33.41	0.26	2.28	71	1,306
5	17.5	20	3.64	31.31	0.28	0.14	69	1,239
6	17.5	20	4.16	31.63	0.27	0.3	69	1,282
7	17.5	20	4.68	30.89	0.28	0.84	74	1,279
8	17.5	20	5.2	29.10	0.31	1.76	84	1,232
9	17.5	30	3.64	29.45	0.30	0.11	69	1,206
10	17.5	30	4.16	29.50	0.29	0.25	67	1,230
11	17.5	30	4.68	28.50	0.31	0.72	81	1,209
12	17.5	30	5.2	26.45	0.34	1.53	112	1,143
13	17.5	50	3.64	30.68	0.27	0.17	67	1,097
14	17.5	50	4.16	30.22	0.28	0.34	61	1,084
15	17.5	50	4.68	28.69	0.30	0.93	110	1,027
16	17.5	50	5.2	26.12	0.34	1.95	214	924
17	17.7	10	3.64	34.38	0.26	0.12	69	1,061
18	17.7	10	4.16	35.28	0.24	0.26	70	1,173
19	17.7	10	4.68	35.12	0.25	0.74	69	1,241
20	17.7	10	5.2	33.91	0.27	1.58	68	1,264
21	17.7	20	3.64	30.97	0.30	0.06	70	1,075
22	17.7	20	4.16	31.60	0.28	0.17	70	1,169
23	17.7	20	4.68	31.19	0.29	0.55	67	1,218
24	17.7	20	5.2	29.72	0.32	1.20	62	1,223
25	17.7	30	3.64	29.21	0.31	0.04	70	1,074
26	17.7	30	4.16	29.59	0.31	0.13	71	1,150
27	17.7	30	4.68	28.91	0.32	0.47	63	1,181
28	17.7	30	5.2	27.18	0.35	1.04	47	1,167
29	17.7	50	3.64	30.67	0.29	0.08	70	1,031
30	17.7	50	4.16	30.53	0.29	0.20	74	1,070
31	17.7	50	4.68	29.32	0.31	0.62	48	1,064
32	17.7	50	5.2	27.07	0.34	1.34	73	1,013
33	17.9	10	3.64	33.17	0.27	0.10	69	883
34	17.9	10	4.16	34.39	0.26	0.23	69	1,048
35	17.9	10	4.68	34.56	0.25	0.68	72	1,167
36	17.9	10	5.2	33.67	0.27	1.45	78	1,242
37	17.9	20	3.64	29.87	0.31	0.05	69	929
38	17.9	20	4.16	30.83	0.30	0.15	66	1,076
39	17.9	20	4.68	30.74	0.30	0.05	87	1,177
40	17.9	20	5.2	29.59	0.32	1.10	133	1,234
41	17.9	30	3.64	28.23	0.33	0.02	67	962
42	17.9	30	4.16	28.93	0.35	0.11	59	1,090
43	17.9	30	4.68	28.57	0.31	0.42	122	1,173
44	17.9	30	5.2	27.16	0.30	0.95	256	1,211
45	17.9	50	3.64	29.91	0.31	0.06	61	984
46	17.9	50	4.16	30.09	0.30	0.18	33	1,075
47	17.9	50	4.68	29.21	0.32	0.56	248	1,121
48	17.9	50	5.2	27.28	0.35	1.23	70	1,122
49	18.1	10	3.64	31.22	0.29	0.16	69	726
50	18.1	10	4.16	32.77	0.27	0.33	68	942
51	18.1	10	4.68	33.25	0.26	0.91	78	1,114
52	18.1	10	5.2	32.69	0.27	1.90	98	1,240

Table 3 continued

Run order	Compression ratio	Fuel blends (%)	Power (kW)	BTHE (%)	BSFC (kg/kW h)	CO (%)	HC (ppm)	NO_x (ppm)
53	18.1	20	3.64	28.30	0.33	0.10	66	805
54	18.1	20	4.16	29.32	0.31	0.23	56	1,003
55	18.1	20	4.68	29.54	0.31	0.68	133	1,156
56	18.1	20	5.2	28.72	0.32	1.45	298	1,264
57	18.1	30	3.64	26.50	0.35	0.07	60	870
58	18.1	30	4.16	27.52	0.33	0.18	31	1,050
59	18.1	30	4.68	27.49	0.33	0.58	258	1,184
60	18.1	30	5.2	26.40	0.35	1.26	74	1,274
61	18.1	50	3.64	28.41	0.32	0.12	39	957
62	18.1	50	4.16	28.91	0.31	0.27	60	1,100
63	18.1	50	4.68	28.35	0.32	0.76	71	1,198
64	18.1	50	5.2	26.74	0.35	1.61	235	1,251

The most extensive applications of RSM are in the particular situations, where several input variables potentially influence some performance measure or quality characteristic of the process. Thus, performance measure or quality characteristic is called the response. The input variables are sometimes called independent variables, and they are subject to the control of the scientist or engineer. The field of RSM consists of the experimental strategy for exploring the space of the process or independent variables, empirical statistical modeling to develop an appropriate approximating relationship between the yield and the process variables, and optimization methods for finding the values of the process variables that produce desirable values of the response.

Response surface methodology was employed in the present study for modeling and analysis of response parameters to obtain the characteristics of the engine. The design and analysis of experiment involved the following steps:

The first step was the selection of the parameters that influence the performance and emission characteristics. In this study, the CR, fuel blends, and power were considered as the input parameters.

The CR (denoted by 'CR') was varied at four levels in steps of 0.2 from 17.5 to 18.1. The fuel blends (denoted by '*B*') too was varied from 10 to 50 %. The power (denoted by '*P*') was varied from 3.64 to 5.2 kW.

The advantage of using design of experiments is to evaluate the performance of the engine over the entire range of variation of CR and other parameters with minimum number of experiments. The design matrix was selected based on the 3 level factor design of RSM generated from the software "Design Expert" version 8.0.7.1 of stat ease, US, which contained 64 experimental runs as shown in Table 3.

As per the run order, the experiments were conducted on the engine, and the responses were fed on the responses column.

Table 4 The accuracies and uncertainty of the measured and calculated results

Measurements	Accuracy	Percentage uncertainty
Engine speed	±1 rpm	±0.2
Temperatures	±1° C	±0.1
Carbon monoxide	±0.02 %	±0.2
Hydrocarbon	±10 ppm	±0.2
Carbon dioxide	±0.03 %	±1.0
Nitrogen oxides	±20 ppm	±0.2
Burette measurement	±2 CC	±1.5
Crank angle encoder	±0.5° CA	±0.2
Load	±1 N	±0.2
Calculated results		
Power	–	±0.2
Fuel consumption	–	±1.5
Brake thermal efficiency	–	±2.58

A multiple regression analysis was carried out to obtain the coefficients and the equations can be used to predict the responses. Using the statistically significant model, the correlation between the process parameters and the several responses were obtained.

Finally, the optimal values of the CR, fuel blends, and power parameters were obtained by using the desirability approach of the RSM.

Desirability approach

The real-life problems require optimization with the multiple responses of interest. Techniques like overlying the contour plots for each response, constrained optimization problems, and desirability approach are found to have benefits like simplicity, availability in the software, and flexibility in weighting and giving importance for individual response. In the present work, RSM-based, desirability approach is used for the optimization of input parameters like CR, fuel blends, and power for the measured properties of responses (BTHE, BSFC, CO, HC, and NO_x). The optimization analysis is carried out using Design Expert software, where each response is transformed to a dimensionless desirability value (d) and it ranges between $d = 0$, which suggests that the response is completely unacceptable and $d = 1$, which suggests that the response is more desirable. The goal of each response can be either maximum, minimum, target, in the range and/or equal to depending on the nature of the problem. The desirability of each response can be calculated by the following equations with respect to the goal of each response.

For a goal of minimum, $d_i = 1$ when $Y_i \leq \text{Low}_i$; $d_i = 0$ when $Y_i \geq \text{High}_i$ and

$$d_i = \left[\frac{\text{High}_i - Y_i}{\text{High}_i - \text{Low}_i}\right]^{wti} \text{ when Low}_i < Y_i < \text{High}_i$$

For a goal of maximum, $d_i = 0$ when $Y_i \leq \text{Low}_i$; $d_i = 1$ when $Y_i \geq \text{High}_i$ and

$$d_i = \left[\frac{Y_i - \text{Low}_i}{\text{High}_i - \text{Low}_i}\right]^{wti} \text{ when Low}_i < Y_i < \text{High}_i$$

For goal as target, $d_i = 0$, when $Y_i < \text{Low}_i$; $Y_i > \text{High}_i$.

$$d_i = \left[\frac{Y_i - \text{Low}_i}{T_i - \text{Low}_i}\right]^{wt1i} \text{ when Low}_i < Y_i < T_i$$

$$d_i = \left[\frac{Y_i - \text{High}_i}{T_i - \text{High}_i}\right]^{wt2i} \text{ when } T_i < Y_i < \text{High}_i; \text{ and}$$

For the goal within the range, $d_i = 1$ when $\text{low}_i < Y_i < \text{high}_i$ and $d_i = 0$.

Here "i" indicates the response, "Y" the value of response, "Low" represents the lower limit of the response, "High" represents the upper limit of the response, "T" means the target value of the response, and "wt" indicates the weight of the response. The shape of the desirability function can be changed for each response by the weight field. Weights are used to give more emphasis to the lower/upper bounds. Weights can be ranged from 0.1 to 10; a weight greater than 1 gives more emphasis to the goal, weights less than 1 give less emphasis. When the weight value is equal to one, the desirability function varies in a linear mode. Solving of multiple response optimizations using the desirability approach involves a technique of combining multiple responses into a dimensionless measure of performance called the overall desirability function. In the overall desirability objective function (D), each response can be assigned an importance (r), relative to the other responses. Importance varies from the least important value of 1, indicated by (+), the most important value of 5, indicated by (+++++). A high value of D indicates the more desirable and the best functions of the system, which is considered as the optimal solution. The optimum values of factors are determined from value of individual desired functions (d) that maximizes D (Pandian et al. 2011).

Results and discussion

Analysis of the model

The principal model analysis was based on the analysis of variance (ANOVA) which provides numerical information for the p value. The models found to be significant as the values of p were less than 0.05. The different models for the responses were developed in terms of actual factors and are given below as Eqs. (1)–(5).

$$\begin{aligned}\text{BTHE} = & -2636.22 + 314.053 \times A - 1.39518 \times B \\ & - 37.2864 \times C + 0.055847 \times A \times B + 3.09128 \\ & \times A \times C - 0.050291 \times B \times C - 9.32265 \\ & \times A^2 + 8.28488 \times 10^{-4} \times B^2 - 1.94840 \times C^2\end{aligned} \quad (1)$$

$$\begin{aligned}\text{BSFC} = & -2.21394 + 0.084203 \times A + 6.26954 \times 10^{-3} \\ & \times B + 0.52798 \times C - 1.06040\text{E} - 004 \times A \times B \\ & - 0.046050 \times A \times C + 7.12892 \times 10^{-4} \times B \times C \\ & + 4.9192 \times 10^{-3} \times A^2 - 1.03086 \times 10^{-4} \\ & \times B^2 + 0.032402 \times C^2\end{aligned} \quad (2)$$

Table 5 Response surface model evaluation

Model	BTHE	BSFC	CO	HC	NO_x
Mean	30.2839	0.30499	0.630491	152.48	1124.66
SD	2.554	0.032	0.579192	314.8	130.059
R	1.000	1.000	0.9958	0.9392	1.000
Model degree	Quadratic	Quadratic	Modified	Modified	Quadratic
Adj. R^2	1.000	1.000	0.9939	0.9307	1.000
Pred. R^2	1.000	1.000	0.9867	0.9147	1.000

$$\begin{aligned} CO = {} & -3570.26684 + 404.90374 \times A - 2.84265 \times B \\ & + 1012.05362 \times C + 0.32413 \times A \times B - 115.68034 \\ & \times A \times C - 0.042085 \times B \times C - 11.45397 \times A^2 \\ & + 1.02510 \times 10^{-4} \times B^2 + 4.23397 \times C^2 + 3.29041 \\ & \times A^2 C - 0.20116 \times AC^2 + 6.44070 \times 10^{-3} \times B^2 C \end{aligned} \quad (3)$$

$$\begin{aligned} HC = {} & 81.67 + 14.19 \times A + 1.59 \times B + 47.2 \times C + 8.84 \\ & \times A \times B + 32.45 \times A \times C + 24.05 \times B \times C + 17.60 \\ & \times A^2 - 15.96 \times B^2 + 26.43 \times C^2 + 15.02 \\ & \times A \times B \times C + 8.15 \times A^2 \times B + 30.90 \times A^2 \\ & \times C - 10.93 \times A \times B^2 + 17.05 \times A \times C^2 - 29.74 \\ & \times B^2 \times C + 12.23 \times B \times C^2 + 1.758E-004 \times A^3 \\ & + 1.250E-004 \times B^3 + 1.758E-004 \times C^3. \end{aligned} \quad (4)$$

$$\begin{aligned} NO_x = {} & 1.28147 \times 10^5 - 11691.4 \times A - 273.185 \times B \\ & - 7934.06 \times C + 16.3619 \times A \times B + 499.11 \\ & \times A \times C - 3.54044 \times B \times C + 247.846 \times A^2 \\ & - 0.071363 \times B^2 - 83.0965 \times C^2. \end{aligned} \quad (5)$$

where A CR, B fuel fraction in %, C power in kW

Evaluation of the model

The stability of the models was validated using Analysis of variance (ANOVA). The output showed that the model was significant with p values less than 0.0001. The reference limit for p was chosen as 0.05. The regression statistics goodness of fit (R^2) and the goodness of prediction (Adjusted R^2) are shown in Table 5 for all the responses. The R^2 value indicates the total variability of response after considering the significant factors. The (adjusted R^2) value accounts for the number of predictors in the model. Both the values indicate that, the model fits the data very well.

Brake thermal efficiency (BTHE)

Brake thermal efficiency evaluates how efficient the engine transforms the chemical energy of the fuel into useful work. This parameter is determined by dividing the BP of the engine by the amount of energy input to the system.

The percentage change in the BTHE is shown in Table 3. The BTHE usually increases with the increase in biodiesel percentage in the fuel blend. Thus, the primary reason for the decrease in the BTHE of biodiesel is the higher BSFC in spite of lower LHV of biodiesels. The maximum BTHE is 35 % for the CR 17.9 and fuel blend between B10 and B20, whereas low BTHE lies in the region around 17.7 CR and fuel blend between B30 and B40. The effects of the variation in CR on the BTHE indicate that higher CRs improve the engine efficiency. This can be attributed to better combustion and higher lubricity of biodiesel. As seen in Table 3, the increased CR increased the BTHE by 2 % for B10 compared to the results of original CR. By increasing the CR of the engine, the BTHE also gets increased for all the fuel types tested. BTHE is directly proportionate to the CR.

Brake specific fuel consumption (BSFC)

As shown in Table 3, the BSFC generally increased with the increase in biodiesel percentage in the fuel blend. It can be considered that the decrease in the lower heating value of the blends by adding biodiesel requires more fuel to be injected into the cylinder to get the same power output, leading to the increase in the BSFC (Doddayaraganalu et al. 2010). When there is an increase in CR, the maximum cylinder pressure increases due to the fuel injected in hotter combustion chamber and this leads to higher effective power. Therefore, fuel consumption per output will decrease. As the BSFC is calculated on weight basis, obviously higher densities resulted in higher values for BSFC. As density of Karanja biodiesel was higher than that of biodiesel for the same fuel consumption, on volume basis, pure biodiesel yields higher BSFC. The higher densities of biodiesel blends caused higher mass injection, for the same volume, at the same injection pressure. The calorific value of the biodiesel is less than diesel. Due to these reasons, the BSFC for the other blends was higher than that for diesel. Similar trends of decrease in the BSFC value with increasing load for different biodiesel were also reported by other researchers (Baiju et al. 2009) while testing biodiesel obtained from Karanja.

Engine emissions

Conversion of biodiesel chemical energy under high pressure and temperature in CI engines produces emissions

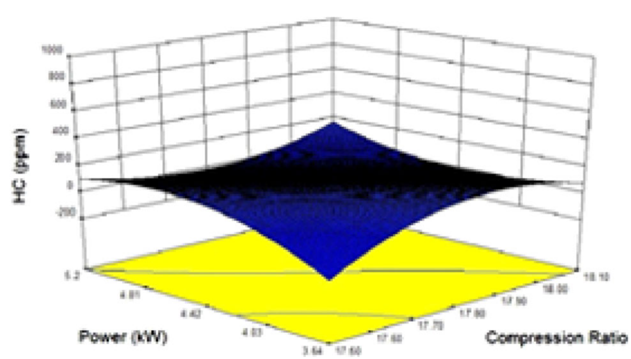

Fig. 1 The HC variations against compression ratio and power

such as CO_2, NO_x, PM, CO, HC, and aromatic compounds (Jo-Han et al. 2010).

The engine operating parameters, such as air–fuel equivalence ratio, fuel type, combustion chamber design, and atomization ratio affect, with all emissions emitted by internal combustion engines, especially, emissions of CO and unburned HC in the exhaust are very important, since they represent the low chemical energy that cannot be totally used in the engine. Emissions such as CO_2, NO_x emitted by diesel engine have important effects on ozone layer and human health (Aksoy 2011).

The engine emissions with Karanja biodiesel have been evaluated in terms of CO, HC, and NO_x at various CR, at different loading conditions of the engine.

Hydrocarbon (HC)

It is seen in Fig. 1 that there is a significant decrease in the HC emission level with Karanja oil as compared to pure diesel. The HC emission is a minimum of 33 ppm which occurs at CR (18.1) and blend B30, so the value of HC reduces as CR and fuel blend increases. At the higher CR, UBHC was low. This may be due to increased temperature and pressure at higher CR and better combustion can be ensured (Muralidharn and Vasudevan 2011). Hydrocarbon concentration decreases with biodiesel addition and this suggests that adding oxygenate fuels can decrease HC from the locally over rich mixture. Furthermore, oxygen enrichment is also favorable to the oxidation of HC in the expansion and exhaust process (Huang et al. 2005). As confirmed in Fig. 1, increased CR reduced the HC emissions by 4 % and reduced CR increased the HC emissions. At lower CR, insufficient heat of compression delays ignition, and so HC emissions increase (Jindal et al. 2010). These reductions indicate the more complete combustion of the fuels and, thus, HC level decreases significantly. The reduction in HC emission was linear with the addition of biodiesel for the blends. The maximum and minimum UBHC produced is 0.0299 g/Kw h and 0.01554 g/Kw h which is less than the EURO-IV norms (0.5 g/Kw h).

Carbon monoxide (CO)

The variation in CO of the engine is shown in Fig. 2. As viewed in Fig. 2, increased CR decreased the CO emissions by 37.09 % and reduced CR increased CO emissions by 9.67 % compared to the results of original CR for B 100. At lower CR, insufficient heat of compression delays ignition and so CO emissions increase (Sayin et al. 2007). The possible reason for this trend could be that the increased CR actually increases the air temperature inside the cylinder therefore reducing the ignition lag causes better and more complete burning of the fuel (Raheman and Ghadge 2008), the percentage of CO is less than 0.3 % at CR 17.7, B20 and maximum percentage of 1.9 % at CR 17.5, B50. The lower CO emissions of biodiesel blends may be due to their more complete oxidation as compared to diesel. Some of the CO produced during combustion of biodiesel might have been converted into CO_2 by taking up extra oxygen molecule present in the biodiesel chain and thus, reduces CO formation. The maximum and minimum CO produced is 2.886 g/Kw h and 0.222 g/Kw h, which is less than the EURO-IV norms (4 g/Kw h).

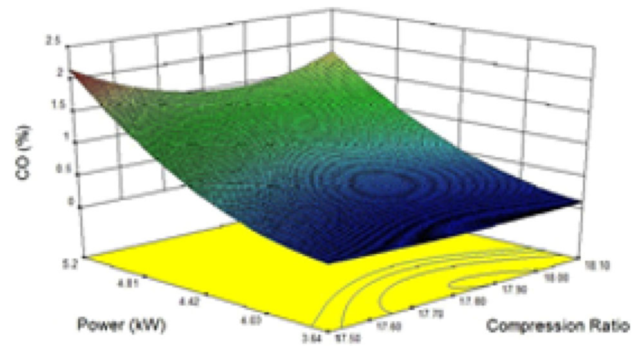

Fig. 2 The CO variations against compression ratio and power

Nitrogen oxides (NO_X)

The NO_x values for different fuel blends at various CR are shown in Table 3. The amount of NO_x produced for B10–B50 is the range of 720–1,300 ppm as compared to diesel which varies from 300 to 900 ppm. It can be seen that the increasing proportion of biodiesel in the blends increases NO_x as compared with diesel. This could be attributed to the increased exhaust temperatures and the fact that biodiesel had some oxygen content in it which facilitated NO_x formation. Since the size of injected particles of vegetable oils is bigger than that of diesel fuel, combustion efficiency and maximum combustion temperatures with vegetable oils were lower. Therefore, NO_x emissions were lower (Ramadhas et al. 2004). As illustrated in the Fig. 3 increased CR increased the NO_x emissions by 10 % and reduced CR decreased NO_x emissions by 12 %, compared to the results of original CR for B50. Reduced CR is to reduce the in-cylinder temperatures and thus flame temperatures during the combustion to suppress NO_x emissions (Raheman and Ghadge 2008). NO_x emissions were also higher at part loads for biodiesel. This is probably due to higher bulk modulus of bio-diesel, resulting in a dynamic injection advance, apart from static injection advance provided for optimum efficiency. Excess oxygen (10 %)

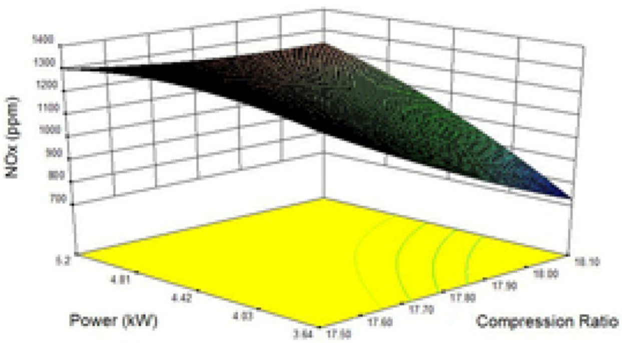

Fig. 3 The NO_x variations against compression ratio and power

present in bio-diesel would have aggravated the situation (Pradeep and Sharma 2007).The maximum and minimum NO_x produced is 0.3644 and 0.213 g/Kw h, which is less than the EURO-IV norms(3.5 g/Kw h).

Optimization

The criteria for the optimization, such as the goal set for each response for lower and upper limits used, weight used, and importance of the factors are presented in Table 6. In desirability-based approach, different best solutions were obtained. The solution with high desirability was preferred. Maximum desirability of 0.978 was obtained at the following compression system parameters like 17.9 of CR, 10 % of fuel blend, and 3.81 kW of power which could be considered as the optimum parameters for the test engine having 5.2 kW as rated power at 1,500 rpm.

Validation of optimized result

In order to validate the optimized result, the experiments were performed thrice at the optimum compression system parameters. For the actual responses, the average of three measured results was calculated. Table 7, summarizes the average of experimental values, predicted values and the percentage of error. The validation results indicated that the model developed was quite accurate as the percentage of error in prediction was in a good agreement.

Conclusion

Based on the results of this study, the following conclusions were drawn in terms of fuel properties and exhaust emission characteristics. Karanja oil methyl ester can be regraded as an alternative to diesel fuel.

The design of experiments was highly helpful to design the experiment and the statistical analysis helped to identify the significant parameters which are most influencing on the performance emission characteristics. This experimental design considerably reduced the time required by minimizing the number of experiments to be performed and provided statistically proven models for all response.

It is clear from this research that CO and HC emissions have been reduced when biodiesel is fueled instead of diesel.

Advancing the CR from 17.5 to 18.1 helped to decrease the CO and HC emissions.

Decreasing the fuel blend ratios contributed for better BTHE with lesser BSFC with lower CO, HC and NO_x values. However, when too low was the blend ratio, the results were good.

The maximum BTHE for B10 (35.42 %) was higher than that of diesel at full load.

Desirability approach of the RSM was found to be the simplest and efficient optimization technique. A high desirability of 0.97 was obtained at the optimum engine parameters of CR of 17.9, fuel blend B10, and 3.81 kW power, where the values of the BTHE, BSFC, CO, HC, and NO_x were found to be 33.65 %, 0.2718 $kg/kW^{-1}\ h^{-1}$, 0.109 %, 158, and 938 ppm, respectively.

Table 6 Optimization criteria and desirability response

Source	Lower limits	Upper limits	Weight		Importance	Goal	Desirability
			Upper	Lower			
Compression ratio	17.5	18.1	1	1	3	In range	1
Fuel fraction	10	50	1	1	3	In range	1
Power	3.64	5.2	1	1	3	In range	1
BTHE	26.12	35.42	1	0.1	5	Maximize	0.9963
BSFC	0.234	0.358	0.1	1	5	Minimize	0.9574
CO	0.028	2.287	0.1	1	5	Minimize	0.994
HC	31.73	298	0.1	1	5	Minimize	0.979
NO_x	725.6	1334.7	0.1	1	5	Minimize	0.9648
Combined							0.978

Table 7 Comparison of actual and predicted values

S. no.	Value	Compression ratio	Fuel fraction	Power (kW)	BTHE (%)	BSFC (Kg/Kw h)	CO (%)	HC (ppm)	NO_x (ppm)
1	Predicted	17.9	10	3.81	33.65	0.2718	0.109	158.03	938.3
2	Actual	17.9	10	3.81	33.24	0.2783	0.127	156.86	940.45
3	Error	–			−0.41	0.0065	0.018	−1.17	−2.15

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Nomenclature

P	Power (kW)
RSM	Response surface methodology
B	Blend fraction (%)
CR	Compression ratio
BTHE	Brake thermal efficiency
BSFC	Brake specific fuel consumption (kg kW^{-1} h^{-1})
bTDC	Before top dead center
FF	Fuel fraction

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