International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:10, No:8, 2016

Performance Evaluation of Karanja Oil Based Biodiesel Engine Using Modified Genetic Algorithm

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***Abstract*—**This paper presents the evaluation of performance (BSFC and BTE), combustion (P_{max}) and emission (CO, NO_x, HC and smoke opacity) parameters of karanja biodiesel in a single cylinder, four stroke, direct injection diesel engine by considering significant engine input parameters (blending ratio, compression ratio and load torque). Multi-objective optimization of performance, combustion and emission parameters is also carried out in a karanja biodiesel engine using hybrid RSM-NSGA-II technique. The pareto optimum solutions are predicted by running the hybrid RSM-NSGA-II technique. Each pareto optimal solution is having its own importance. Confirmation tests are also conducted at randomly selected few pareto solutions to check the authenticity of the results.

***Keywords*—**Karanja biodiesel, single cylinder direct injection diesel engine, response surface methodology, central composite rotatable design, genetic algorithm.

I. INTRODUCTION

ENERGY is the most important input for the growth of every sector including industries, transport services, agriculture etc. Around the world, the demand for energy is increasing continuously, specifically based on petroleum. The predicted shortage of petroleum and its products have increased the search for the substitute of petroleum derivatives. The fossil fuels are depleting day by day and there is a need to find an alternative fuel to fulfil the energy demand. Biodiesel is one of the best available sources to fulfil the growing demand of energy. It derives from animal fats, edible and non-edible oils including waste cooking oils. Biodiesel refers to “mono alkyl esters of long chain fatty acids derived from vegetable oils or animal fats”. Biodiesels are generally used in compression ignition engines by blending it with commercial diesel. The biodiesels are environment friendly as the emissions produced are lower.

Sheih et al. [1] utilized lipase based catalyst for the optimization of soybean biodiesel production in the presence of methanol through response surface methodology (RSM) based on central composite rotatable design (CCRD). An optimum biodiesel conversion of 92.2% in trans-esterification process was observed at 3.4:1 molar ratio of methanol to soybean oil, 0.9 BAUN (Batch Acidolysis Units), 5.8% water content, 36.5 °C temperature in 6.3 hours. Ghadge and Rehman [2] evaluated optimum trans-esterification process parameters for mahua oil using RSM. Firstly, the pre-treatment process was done to mahua oil (to decrease the free fatty acid) and then trans-esterification process was performed at various experiments suggested by CCRD of RSM. The FFA value was reduced to less than 1% at 60 °C reaction temperature, 0.32 v/v methanol to oil ratio, 1.24% v/v H_2SO_4 catalyst and 1.26 hours reaction time. The maximum conversion of biodiesel was achieved at 0.25 v/v methanol to oil ratio and 0.7% KOH (as an alkaline catalyst). Similar works have been reported by [3] and [4] for predicting optimized trans-esterification process parameters. Bouaid et al. [5] experimentally investigated high oleic sunflower oil (HOSO), high and low erucic Brassica carinata oils (HEBO and LEBO) for optimization of biodiesel production with ethanol in the presence of an acid (H_2SO_4) or alkaline (KOH) catalyst. Factorial design and RSM approach were used for the required purpose. The model was found to be of second order for LEBO process in order to adequately study the biodiesel conversions as a function of temperature and catalyst concentration. The best result was found to be at 32 °C with 5:1 ethanol/oil molar ratio and 1.5% of KOH for HEBO and HOSO while 20 °C with 6:1 ethanol/oil molar ratio and 1.5% of KOH for LEBO. The performance tests of biodiesels from edible and non-edible oils have been conducted by various researchers [6]-[12] for predicting the variation of brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), emission parameters (CO, NO_x, HC, smoke etc.) with load, speed and injection timing. The multi-objective optimization techniques like NSGA (Non-dominated sorting genetic algorithm), MOGA (Multi-objective genetic algorithm), desirability approach etc. have been applied for predicting the optimal sets of solution. Deb et al. [13] proposed the modified version of NSGA in multi-objective technique (NSGA-II) by evaluating the best optimal solutions. Sharing parameter was then eliminated by the modification of NSGA-II. NSGA-II helps in predicting the different sets of optimal solution for different process parameters involved. In the present work an attempt has been made to maximize BTE, P_{max} (peak cylinder pressure) and minimize BSFC, CO, NO_x, HC, SO (smoke opacity) in a single cylinder direct injection CI engine running on blended karanja (*Pongamia pinnata*) biodiesel. Therefore, multi-objective optimization problem is formulated. Multi-objective optimization of performance, combustion and emission parameters of biodiesels produced have been carried out using hybrid RSM-NSGA-II.

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II. MATERIALS AND METHODOLOGY

Karanja (*Pongamia Pinnata*) biodiesel was produced in the laboratory of UIET, MDU Rohtak, India from magnetic stirrer. A single cylinder direct injection variable compression ratio engine was then used to evaluate karanja biodiesel performance as shown in Fig. 1. Data acquisition system, five gas analyzers and smoke meter are attached to the engine for evaluating various responses of the engine.

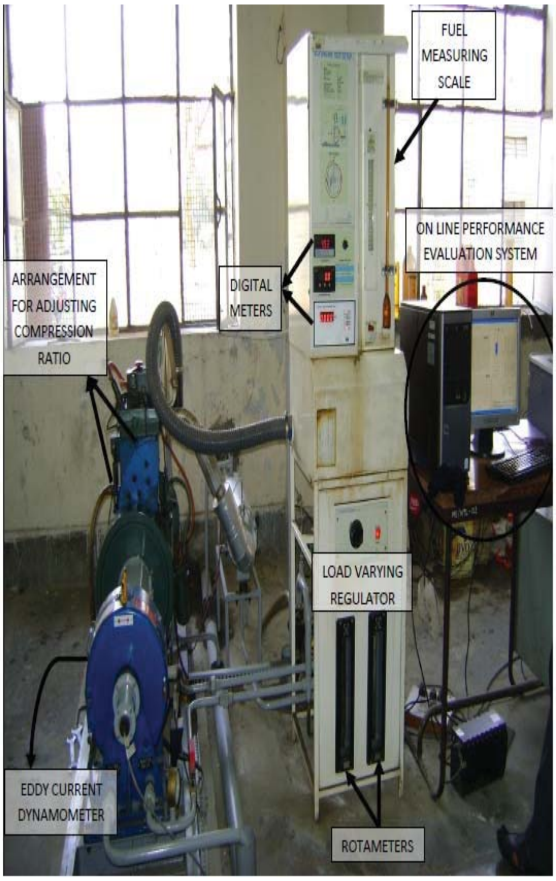

Fig. 1 Pictorial view of a single cylinder engine setup

III. MAIN EXPERIMENTATION

The important engine input parameters considered are: Blending ratio (BR), load torque (LT) and compression ratio (CR). The different responses (BSFC, BTE, P_{max}, CO, NO_x, HC and SO) of a single cylinder direct injection diesel engine are measured for 15 combinations of engine input parameters (BR, LT and CR) as mentioned in Table I with one replication. Table I shows the various responses of engine at proposed combinations of control parameters (BR, LT and CR) using RSM based on CCRD. The provisions for varying engine input parameters (BR, LT and CR) were provided in the engine setup at following constant parameters:

(i) Injection timing: 345 CAD
(ii) Engine speed: 1500 rpm
(iii) Injection pressure: 220 bar

TABLE I
MULTI OBJECTIVE FUNCTIONS OF KARANJA BIODIESEL ENGINE AT SUGGESTED EXPERIMENT DESIGN

Exp. No	Engine input parameters			Objective functions						
	BR	LR	CR	BSFC	BTE	$P_{max.}$	CO	NO_x	HC	SO
1	10	4.57	13.5	0.73	15.03	19	2.59	734	11.89	37.66
2	30	4.57	13.5	0.69	18.71	18	2.62	734	12.2	38.07
3	10	17.99	13.5	0.54	16.24	21	2.67	762.7	9.79	59.07
4	30	17.99	13.5	0.56	14.75	18	2.66	759	18.08	12.84
5	10	4.57	16.5	0.80	14.71	23	2.54	719.5	12.4	38.68
6	30	4.57	16.5	0.70	17.93	26	2.61	734	13.09	39.04
7	10	17.99	16.5	0.46	19.05	19	2.98	801.5	7.79	64.83
8	30	17.99	16.5	0.49	15.02	21	2.74	757.6	15.19	65.82
9	5	11.28	15	0.62	14.81	16	2.66	734	9.08	48.68
10	35	11.28	15	0.60	14.83	18	2.65	734	10.07	49.05
11	20	0	15	0.91	14.77	18	2.89	828.7	12.34	31.1
12	20	22.56	15	0.42	22.02	17	3.04	857.6	8.84	70.63
13	20	11.28	12	0.62	16.85	17	2.68	763.6	10.4	44.84
14	20	11.28	18	0.64	15.05	31	2.71	762.9	11.1	47.95
15	20	11.28	18	1.02	29.27	35	4.49	999	37.34	37.66

IV. RESULTS AND DISCUSSION

A. Analysis of Results and Multi-Objective Optimization of Performance, Combustion and Emission Parameters of Karanja Biodiesel Engine

RSM is a group of statistical tools for predicting optimum responses based on different input conditions. It is useful for analysing the problems in which a response is influenced by several variables. The experimental design is developed from the levels of variables affecting the various responses. A CCRD is selected for predicting the behaviour of objective function with LT, BR and CR. Five levels of three factors are proposed by Design Expert 6.0.8® stat ease inc. USA along with their limits to perform the experiments.

A total of 30 experiments (15 experiments with one replication) are performed by choosing full fraction in the Design Expert software. Objective functions are measured by the standard instruments as previous section. The predictive ability and accuracy of this polynomial model can be checked by the coefficient of determination (R^2).

First the desirability approach has been adopted in the evaluation of performance, combustion and emission parameters. The quadratic models are proposed for seven responses (BSFC, BTE, P_{max}, CO, NO_x, HC and smoke opacity) by Design Expert 6.0.8® software. Adequacy tests of models are checking by using ANOVA at 95% confidence levels. The p-values of various objective functions of the diesel engine running on karanja biodiesel using ANOVA are summarized in Table II based on the backward elimination regression. A quadratic model is significant at 95% confidence level. The model terms are significant for p-values < 0.05 and insignificant for value < 0.05. The two factor interactions were found to be significant while three or more factor interactions were not found to be significant as suggested by the software. The precision index values for different response models are shown in Table III. R^2, adjusted R^2 and predicted R^2 are found to be closer to '1' for all the response models which indicate that error between actual and predicted responses is less. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. It has been shown in Table IV that all the response models have adequate precision (greater than 4). So these models can be used to navigate the design space. Moreover, PRESS values of predicted models are smaller that shows the model predictions are closer to the experimental values.

TABLE II
PROBABILITY VALUES OF VARIOUS OBJECTIVE FUNCTIONS OF KARANJA BIODIESEL ENGINE USING ANOVA

	Probability (p) values						
Source	BSFC	BTE	P_{max}	CO	NO_x	HC	SO
Model	<0.0001	<0.0001	>0.05	<0.0001	<0.0001	<0.0001	<0.0001
BR	0.1932	<0.0001	0.6040	<0.0001	0.3941	0.00057	0.1936
LT	<0.0001	0.0581	0.3408	0.00015	<0.0001	<0.0001	0.7818
CR	<0.0001	0.8421	0.0014	<0.0001	0.6951	0.7359	0.0078
BR^2	0.1573	<0.0001	<0.0001	<0.0001	0.4921	0.0064	<0.0001
LT^2	<0.0001	<0.0001	0.4791	0.00035	<0.0001	0.7384	0.8315
CR^2	0.1732	<0.0001	<0.0001	<0.0001	0.1752	<0.0001	<0.0001
BR x LT	<0.0001	<0.0001	0.6612	0.5931	<0.0001	<0.0001	<0.0001
BR x CR	<0.0001	0.3829	<0.0001	0.1391	0.6294	0.7931	0.7319
LT x CR	0.0082	<0.0001	0.2474	<0.0001	0.7395	<0.0001	0.8419
Lack of fit	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05

TABLE III
PRECISION INDEX VALUES OF DIFFERENT RESPONSE MODELS OF KARANJA BIODIESEL ENGINE

	Precision index values							
Model	R^2	Adjusted R^2	Predicted R^2	PRESS	Adequate Precision	Standard deviation	Mean	CV
BSFC	0.990	0.985	0.976	0.058	36.54	0.029	0.68	5.73
BTE	0.970	0.968	0.896	186.84	17.85	1.41	23	8.52
P_{max}	0.987	0.978	0.974	161.52	44.85	1.37	35.8	4.92
CO	0.989	0.997	0.969	0.950	29.93	0.14	2.82	4.74
NO_x	0.975	0.983	0.964	39482.5	19.83	26.73	954.8	2.62
HC	0.953	0.964	0.958	130.7	34.96	1.54	19.94	7.84
SO	0.979	0.974	0.982	456.3	29.56	2.86	44.73	5.29

Simultaneous optimization of seven objectives is achieved by using hybrid RSM-NSGA-II. The regression equations obtained using RSM are utilized in NSGA-II code for creating fitness function. The minimum and maximum values of engine input parameters (BR, LT and CR) as obtained from desirability approach (Table IV)) are also used as input in NSGA-II. In simultaneous optimization of BSFC, BTE, P_{max}, CO, NO_x, HC and smoke opacity: Two objective functions, namely, BTE and P_{max} need to be modified to suit the requirements of NSGA-II. Other objective functions remain the same.

- Objective (1) = BSFC
- Objective (2) = - (BTE)
- Objective (3) = - (P_{max})
- Objective (4) = CO
- Objective (5) = NO_x
- Objective (6) = HC
- Objective (7) = Smoke opacity

where +ve sign indicates minimization and –ve sign shows maximization.

The pareto optimum solution sets (100) of engine input parameters and corresponding objective function values are obtained after 1000 generations. Among these, selection of solutions is done on the basis of rank and crowding distance. Few optimum solutions (30) are shown in Table V. It is seen from these optimum solutions that no solution in the non-dominated sets is absolutely better than any other solution. Any of the selected solutions is better in terms of individual objective requirements.

TABLE IV
OPTIMUM RANGE OF ENGINE PARAMETERS RUNNING ON KARANJA BIODIESEL USING DESIRABILITY APPROACH

Parameter	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
BR (% v/v)	5-35	11.08	28.92	1	1	3
LT (Nm)	0-22.56	4.57	17.98	1	1	3
CR (v/v)	12-18	13.21	16.78	1	1	3
BSFC (kg/kWh)	Minimize	0.276	0.87	1	1	3
BTE (%)	Maximize	13.84	29	1	1	3
P_{max} (bar)	Maximize	17.5	62	1	1	3
CO (volume %)	Minimize	1.86	3.74	1	1	3
NO_x (ppm volume)	Minimize	54.32	1136	1	1	3
HC (ppm volume)	Minimize	5.48	37	1	1	3
SO (volume %)	Minimize	28.32	68.83	1	1	3

TABLE V
PARETO OPTIMUM SOLUTION SETS OF ENGINE INPUT PARAMETERS AND CORRESPONDING OBJECTIVE FUNCTION VALUES OF KARANJA BIODIESEL ENGINE

Sol. No	Engine input parameters			Objective functions						
	BR	LR	CR	BSFC	BTE	$P_{max.}$	CO	NO_x	HC	SO
1	11.08	17.98	16.78	0.448	19.0	19.0	2.86	794.36	6.53	63.96
2	28.91	7.83	16.75	0.766	18.5	34.8	3.03	790.95	18.4	40.69
3	19.99	4.57	14.93	1.017	24.7	42.8	3.85	925.66	28.8	30.42
4	20.16	11.04	15.26	1.02	29.0	55.1	4.45	966.98	37.0	37.47
5	19.91	11.71	15.03	1.011	29.2	54.8	4.46	1000.1	37.1	38.45
6	20.64	11.19	14.98	1.019	29.2	54.8	4.46	998.53	37.2	37.52
7	19.84	12.16	15.02	1.00	29.2	54.6	4.46	1000.4	37.0	39.32
8	19.40	7.84	15.1	1.051	29.7	52.0	4.28	975.26	35.0	32.77
9	19.95	12.0	14.99	1.004	29.2	54.6	4.46	1000.3	37.1	38.98
10	26.66	16.1	16.51	0.665	21.2	35.8	3.42	862.03	22.2	55.64
11	11.08	4.57	14.98	0.809	13.42	22.9	2.51	755.94	12.3	38.68
12	28.91	17.98	16.78	0.459	15.6	21.3	2.72	769.23	12.2	64.96
13	23.68	11.25	16.11	0.936	26.4	51.0	4.10	948.46	32.7	40.43
14	25.42	10.89	16.07	0.916	25.5	49.0	3.98	929.34	31.3	40.55
15	20.39	7.04	14.72	1.04	27.2	49.4	4.19	964.81	33.7	31.93
16	25.16	10.9	16.28	0.899	25.0	48.2	3.91	919.50	30.2	41.03
17	20.90	6.88	14.71	1.037	27.1	48.9	4.17	961.99	33.3	31.84
18	23.46	11.40	16.08	0.939	26.6	51.3	4.13	952.32	33.0	40.57
19	27.97	12.54	16.16	0.804	22.9	42.5	3.65	881.59	27.1	46.11
20	11.36	17.8	16.78	0.468	19.4	20.6	2.92	802.46	7.71	63.12
21	26.64	15.46	16.70	0.664	20.7	35.9	3.36	851.69	21.5	54.57
22	12.40	4.84	15.89	0.928	18.9	33.5	3.23	832.99	21.5	34.76
23	25.50	10.78	16.07	0.916	25.5	48.8	3.97	927.84	31.2	40.39
24	11.34	17.37	16.74	0.501	19.8	22.6	3.00	810.86	9.32	61.53
25	26.75	11.32	16.40	0.879	24.6	46.6	3.86	911.56	29.9	42.18
26	28.33	15.57	16.58	0.632	19.5	33.0	3.21	828.33	20.1	55.79
27	28.89	17.58	16.40	0.543	17.8	26.4	3.00	806.82	16.8	61.95
28	19.41	8.04	15.10	1.051	27.8	52.4	4.30	977.51	35.2	32.99
29	19.35	10.39	14.57	1.025	28.8	53.3	4.40	990.86	36.5	36.02
30	14.65	5.20	15.90	0.977	21.5	39.6	3.53	876.27	25.4	33.34

B. Validation of Experiments

Confirmatory experiments are performed to check the accuracy of the predicted results. Five solutions are randomly chosen from Table V and they are at serial number 1, 12, 17, 23 and 30. Experiments have been performed at these five optimum engine input parameter combinations with one replication and the responses have been measured. It is seen from Table VI that errors between the actual and predicted value of responses are less than 5% which shows the authenticity of the results as predicted by hybrid RSM-NSGA-II technique. These sets of pareto optimum solutions are valid for the compression ignition (CI) engine similar to one selected in the present study.

V. CONCLUSION

The work reveals that hybrid RSM-NSGA-II technique is an effective approach for predicting multi-objective optimum solution. It has been observed that none of the solutions is better than other and each solution is having its own importance. The end users can choose any solution set depending upon the requirement. Moreover, karanja biodiesel can act as an alternate fuel in CI engines by blending with diesel.

TABLE VI
CONFIRMATORY EXPERIMENTS OF KARANJA BIODIESEL ENGINE

Sol. No	Engine input parameters			Objective functions						
	BR	LR	CR	BSFC	BTE	$P_{max.}$	CO	NO_x	HC	SO
1	11.08	17.98	16.78	0.448	19.0	19.0	2.86	794.36	6.53	63.96(P)
				0.464	18.8	18.8	2.90	780.00	6.75	62.00(A)
12	28.91	17.98	16.78	0.459	15.6	21.3	2.72	769.23	12.2	64.96(P)
				0.465	15.0	22.3	2.65	755.50	12.7	63.50(A)
17	20.90	6.88	14.71	1.037	27.1	48.9	4.17	961.99	33.3	31.84(P)
				0.996	26.5	49.5	4.35	950.50	32.5	30.85(A)
23	25.50	10.78	16.07	0.916	25.5	48.8	3.97	927.84	31.2	40.39(P)
				0.936	24.5	49.5	3.85	915.00	30.5	39.50(A)
30	14.65	5.20	15.90	0.977	21.5	39.6	3.53	876.27	25.4	33.34(P)
				0.970	20.5	40.5	3.48	860.00	26.2	34.80(A)

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