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PERFORMANCE OPTIMIZATION OF KARANJA BIODIESEL ENGINE USING TAGUCHI APPROACH AND MULTIPLE REGRESSIONS

K. Sivaramakrishnan[1] and P. Ravikumar[2]
[1]Department of Mechanical Engineering, Anjalai Ammal Mahalingam Engineering College, Kovilvenni, India
[1]Anna university of Technology, Tiruchirappalli, Tamil Nadu, India
[2] St. Joseph College of Engineering and Technology, India
E-Mail: Sivaporkodi2000@yahoo.co.in

ABSTRACT

The objective of this work is to optimize the direct injection (DI) single cylinder diesel engine with respect to brake power, fuel economy and emissions through experimental investigations and DOE methods. A single cylinder 5.2 kW diesel engine was selected for test. Five parameters, Power (P), Static injection pressure (IP), Injection timing (IT), Fuel fraction (B) and Compression ratio (CR) was varied at four levels and the responses brake power, fuel economy and emissions were investigated. The optimum n values of the response could be predicted using Signal - Noise ratio(S/N ratio) and optimum combination of control parameters were specified. Results of confirmation tests showed good agreement with predicted quantities. Thus the relationship between the diesel engine parameter, brake power, b.s.f.c and Emissions could be understood using design of experiments. The best results for brake specific fuel consumption (BSFC), brake thermal efficiency (BTHE) were observed at increased CR, IP, and IT. The emissions CO, HC were reduced while NO_x emissions increase. The results of the study revealed that the combination of a blend of 30% karanja biodiesel (B30), a compression ratio of 17.9, a nozzle opening pressure of 230 bar, injection timing of 27° bTDC and at 70% load produces maximum multiple performance of diesel engine with minimum emissions from the engine.

Keywords: biodiesels, Karanja, diesel engine performance, emissions, Taguchi approach.

1. INTRODUCTION

Biodiesels such as Jatropha, Karanja, Sunflower and Rapeseed are some of the popular biodiesels currently considered as substitute for diesel. 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 efforts is being focused on improving the thermal efficiency of IC engines with reduction in emissions. [1-3]. Direct injection diesel engines occupy an important place in the developing countries since they power agricultural pumps, small power tillers, light surface transport vehicles and other machineries. The problem of increasing demand for high brake power and the fast depletion of the fuels demand severe controls on power and a high level of fuel economy. 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 is 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, grey relational analysis [4], non linear regression [5], genetic algorithm [6] and Taguchi method. Taguchi technique has been popular for parameter optimization in design of experiments. DOE has introduced the loss function concept which combines cost, target and variations into one metric. The signal to noise ratio (S/N) is a Figure of merit and relates inversely to the loss function. It is defined as the ratio of the amount of energy for intended function to the amount of energy wasted [7]. Orthogonal arrays are significant parts of Taguchi methods. Instead of one factor at a time variation all factors are varied simultaneously as per the design array and the response values are observed. It has the ability to evaluate several factors in a minimum number of tests. Design of experiments (DOE) approach is cost effective and the parameters are varied simultaneously and then through statistical analysis the contribution of individual parameters towards the response value observed also could be found out. The engine operating parameters play an important role to reduce the emissions the design and operating parameters are the main factors responsible for the engine emissions and fuel economy. The fuel injection parameters like injection valve opening pressure and the compression ratio also have influence on emissions and fuel economy. In this work DOE approach is used to find the effect of design and operating parameters on brake power and specific fuel consumption (BSFC).

A second order weight equation is formulated where several parameters are used to make sensitivity analysis. Design optimization is also done with several design parameters. BTHE varied widely with different injection timings than with different load, Static injection pressure, Compression ratio, were taken as parameters for the design optimization study. The effect of the parameters - injection pressure, Compression ratio, Load, and engine speed on brake power and smoke were investigated [8]. An increase in injection pressure contributes to fuel economy by improved mixing [9]. Simultaneous reduction of NO_x and particulate emissions were reported by combining the varying compression ratio and retarded injection timing [10]. Optimal combination of design and operating parameters were identified that can regulate emissions and improve brake specific fuel consumption. For identifying the optimal combination of injection schedule and fuel spray cone angle, genetic algorithm process was used [11]. The effect of changes in the operating parameters like, piston to head clearance, injection pressure, start of injection timing on emissions were studied using Taguchi design of experiment methods. This method was found to be useful for simultaneous optimization [12]. It has been studied the effects of injection timing, fuel quantity per fuel pulse and injection rate on brake specific fuel consumption and has observed that among the various factors relevant to diesel combustion, fuel injection plays a major role in the fuel air mixing and combustion process thus determining the exhaust emissions [13]. It was also observed that the injection timing and injection rate play a major role in brake power using design of experiment method and factorial design the percentage contributions of the effect of parameters - speed, load, injection timing plunger diameter, nozzle valve opening pressure nozzle hole diameter, number of nozzle holes and nozzle tip protrusion were investigated on engine noise, emissions and brake specific fuel consumption [14]. Without considering the combustion parameters engine design and operating parameters can be optimized and engine efficiency can be increased by applying Taguchi method [15]. It is known from DOE procedure that for 5 parameters with 4 levels, the number of trial runs will be 625. In this present work an attempt is made to carry out an optimization analysis of direct injection diesel engine run by karanja biodiesel using a model in combination with taguchi method.

Implementation of biodiesel in India will lead to many advantages like green cover to waste land, support to agriculture and rural economy and reduction in dependence on imported crudeoil and reduction in air pollution [16]. The karanja plant having advantages namely; effectively yielding oilseeds from the third years onwards, rapid growth, easy propagation, life span of 40 years and suitable for tropical and subtropical countries like India [17].

It has been observed from the literature review, both bio-diesel-diesel blends and operating parameters has lot of influence on engine performance and exhaust emissions. But the effects of operating conditions such as injection pressure, injection timing, compression ratio on the engine performance and exhaust emissions of a diesel engine using biodiesel have not been clearly studied. Therefore this focus of research is about modification on engine parameters for the best output using optimization techniques.

2. EXPERIMENTAL DETAILS AND METHODOLOGY

2.1. Experimental set up

The experimental set up consists of a direct injection single cylinder diesel engine connected to an eddy current type dynamometer for loading which is shown in Figure.1. Details of the engine specification are shown in Table-1. 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" is provided for online performance evaluation. HC, CO, CO_2, K (air surplus rate) NO_x emissions were measured with an infra red gas analyzer with an accuracy shown in Table-2. The fuels properties were tested using standard measuring devices shown in Table-3 and results are shown in Table-4.

2.2. Procedure

Compression ratio is altered by adding different number of gaskets between the cylinder head and the block since this method does not need major modification in the engine. In this study the number of gaskets has been increased from the original one to maximum modification of four gaskets.

Injection timing was altered by adjusting the number of shims under the seat of the mounting flange of the fuel pump. When the number of shims were added timing was retarded. Each time the number of shims are added the timing of the start of injection was found by rotating the flywheel and the correct position is marked in the fly wheel when the fuel spray appears first through the spray holes .Thickness of one shim, located in connection place between engine and fuel pump, is 0.20 mm and adding or removing one shim changes the IT 2°, This exercise was repeated five times to get the correct timings in terms of crank angle.

Changing the nozzle spring tension adjusted the nozzle opening pressure. When the spring preload is increased by tightening the nut above the spring, the nozzle opening pressure increases.

Engine cylinder pressure was measured using quartz miniature pressure transducer mounted in the cylinder head of the engine.

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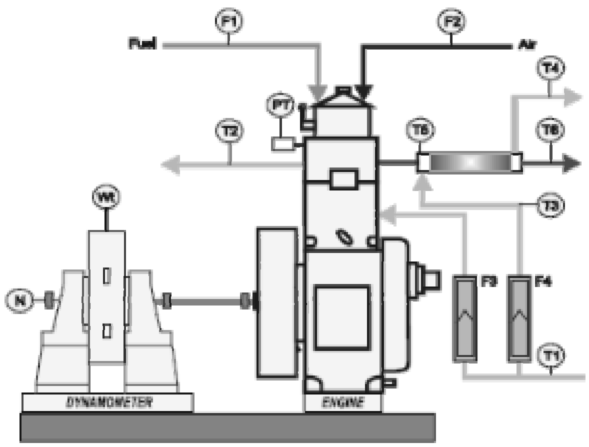

Figure-1. Experimental set up.

Table-1. Engine specification.

Make and model	**Kirloskar model TV 1**
Engine type	Single cylinder four stroke direct injection
Bore x stroke	87.5mm x 110 mm
Maximum power output	5.2.kW at 1500 rpm
Displacement	661 cc
CR	17.5
Loading	Eddy current dynamometer, water cooling
Fuel injection	23 bTDC

Table-2. Exhaust gas analyzer specification.

Measuring item	**Measuring method**	**Measuring range**	**Resolution**
CO	NDIR	0-9.99%	0.01%
HC	NDIR	0-5000 ppm	1 ppm
NOx	Electrochemical	0-5000 ppm	1 ppm

Table-3. Measuring devices and test methods for measuring fuel properties.

Properties	**Measurement apparatus**	**Standard test method**
Density	Hydrometer	ASTM D941
Flash and fire point	Penksy martins apparatus	ASTM D93
Calorific value	Bomb calorimeter	ASTM D240
Viscosity	Red wood viscometer	ASTM D445
Cetane number	Ignition Quality Tester	ASTM D613

Table-4. Properties of biodiesel-blends-karanja.

Biodiesel	**Kinematic viscosity** (mm^2/sec) **ν**	**Heating value** (MJ/kg) **HV**	**Flash point** (°C) **FP**	**Density** (kg/l) **ρ**	**Cetane number**
B0	2.71	42.5	55	0.836	51.00
B20	4.01	41.5	65	0.849	51.70
B40	5.23	39.9	77	0.858	52.82
B60	6.72	38.7	88	0.862	53.15
B80	8.19	37.0	101	0.878	53.86
B100	9.60	35.9	114	0.900	54.53

3. TAGUCHI PROCEDURE

The Taguchi method provides simple and effective solutions for investigating the effect of parameters on the performance as well as in the experimental planning. In this method, the signal -to-noise (S/N) ratio is used to represent a performance characteristic and the largest value of the S/N ratio is required. There are three types of S/N ratios-the lower-the-better, the -higher-the better and the-more-nominal -the -better

The criteria for optimization of the response parameters was based on the smaller the better S/N ratio.

$$S/N = -10\log\left[\frac{1}{r}\sum_{i=1}^{r} y_i^2\right] \quad (1)$$

Yi represents the measured value of the response variable *i*.

The S/N ratio with a higher –the-better characteristic can be expressed as:

$$S/N = -10\log\left[\frac{1}{r}\sum_{i=1}^{r} 1/y_i^2\right] \quad (2)$$

Yi represents the measured value of the response variable.

The negative sign is used to ensure that the largest value gives an optimum value for the response variable and therefore robust design.

The objective of the work is to investigate the engine operating and injection parameters having maximum potential for increasing brake power and for improving the fuel economy and to identify the optimized range of input parameters for higher brake power and better fuel economy.

DOE technique is used to identify the key factors that make the greatest contributions to the variation in response parameters of interest. It introduced the loss function concept which combines cost, target and variations into one metric. The signal-noise ratio is a Figure of merit and relates inversely to the loss function. It is defined as the ratio of the amount of energy for intended function to the amount of energy wasted. DOE recommends orthogonal array (OA) for lying out of the experiments which is significant part of this method. Instead of varying one factor at a time, all factors are varied simultaneously as per the design array and the response values are observed. It has the ability to evaluate several factors in a minimum number of tests. The results of the experiments are analyzed to achieve the following objectives.

- To establish the optimum conditions for the BTHE, BSFC, HC, NO_x;
- To estimate the contributions of individual parameter to the response;
- To predict the response under optimum conditions;
- To run the confirmation test for validation.

The optimum condition is identified by studying the main effects of each of the parameters. The main effects indicate the general trend of influence of each parameter.

The steps involved in DOE method are:

- Identifying the response functions and control parameters to be evaluated;
- Determining the number of levels of the control parameters;
- Selecting the appropriate orthogonal array, assigning the parameters to the array and conducting the experiments;
- Analyzing the experimental results and selecting the optimum level of control parameters;
- Validating the optimal control parameters through a confirmation experiment.

In the present investigation, the S/N data analysis has been performed. The effect of the selected control parameters on the response functions has been investigated. The optimal conditions are established and verified through a confirmation experiment.

4. EXPERIMENTATION AND ANALYSIS

4.1. Selection of control parameters

The following control parameters as given in Table-5 were selected for the investigation since they have influence on the objectives of improving brake power and fuel economy. More parameters are related to the fuel injection and these parameters were found to be suitable for the experiment and could be done with available engine configuration. Four levels were chosen for this investigation.

Table-5. Setting levels for design parameters.

Controlled factors	Level 1	Level 2	Level 3	Level 4
A. compression ratio	17.5	17.7	17.9	18.1
B. Static injection pressure (bar)	230	220	210	190
C. Injection timing (bTDC)	23	25	27	29
D. Fuel fraction (%)	10	20	30	50
E. Power (kW)	3.64	4.16	4.68	5.2

4.2. Selection of orthogonal array

Orthogonal array was selected based on the number of parameters and the levels. Number of experiments = (L-P) +1 where, L is the number of levels and P is the number of parameters, the array is shown in Table-6.

Table-6. L 16 design array of the experiment.

Factors	**Compression ratio** (CR)	**Static injection pressure** (IP) (bar)	**Injection timing** (IT) bTDC	**Fuel fraction** (%)	**Power** (kW)
Run Number	**(A)**	**(B)**	**(C)**	**(D)**	**(E)**
1	17.5	230	23	10	3.64
2	17.5	220	25	20	4.16
3	17.5	210	27	30	4.68
4	17.5	190	29	50	5.2
5	17.7	230	25	30	5.2
6	17.7	220	23	50	4.68
7	17.7	210	29	10	4.16
8	17.7	190	27	20	3.64
9	17.9	230	27	50	4.16
10	17.9	220	29	30	3.64
11	17.9	210	23	20	5.2
12	17.9	190	25	10	4.16
13	18.1	230	29	20	4.16
14	18.1	220	27	10	5.2
15	18.1	210	25	50	3.64
16	18.1	190	23	30	4.68

4.3 Setting optimum conditions and prediction of response variables

The next step in DOE analysis is determining optimal conditions of the control parameters to give the optimum responses. In this work the response variables to be optimized were BTHE, has to be maximized and B.S.F.C. to be reduced as much as possible. Hence the optimum parameter settings will be those that give maximum values of the BTHE and minimum values of B.S.F.C, HC, and NOx. The optimum settings of the parameters were achieved from the S/N Tables of the control parameters.

The optimum value of response variable can be predicted using the additivity law.

$$OPT = \bar{T} + \sum_{i=1}^{n} \left(\bar{X}_i - \bar{T} \right)$$

4.4 Developing a multiple regression model

The empirically developed mathematical model links a quantitative dependent variable BTHE, BSFC, NOx and HC to the selected independent variables or the design and control parameters(A, B, C, D, E) selected. Regression is one of the popular statistical tools. The Mini tab regression tool is used for this. Regression analysis provides a method of linking the performance variable with the design parameters through a mathematical model if more than one design parameter affecting the response parameters are there still linear regression can be used to mathematically link the dependent variable to the independent ones. This is termed as multiple regressions. When there are five design parameters involved the regression model becomes,

$$Y=\beta_0+ \beta_1 XI+ \beta_2 X2+ \beta_3 X3+ \beta_4 X4+ \beta_5 X5+C.$$

This model is natural extension of the simple linear regression model.

5. RESULTS AND DISCUSSIONS

5.1. Engine performance

The engine after obtaining the stabilized working condition fuel consumption, torque applied was measured from which BSFC and BTHE were measured.

5.1.1 Brake specific fuel consumption (BSFC)

Effect of compression ratio

The variation in the BSFC of the engine is shown in Figures when biodiesel -diesel fuels are compared to pure diesel fuel. As shown in the Figure-2, the BSFC increases with increase in biodiesel content in the blends. As shown in Figure-2, the best results were obtained at increased CR. The maximum percentage increase of BSFC from the overall mean is 4.9% when the compression ratio is 18:1.

Effect of injection timing

Retarding the start of the fuel delivery yields a reduction in peak combustion pressure and temperature. It can be seen when IT has been advanced from 23° to 29° before TDC of which 23° gives the best value, an increase in BSFC by 2.3%. Advancing the IT meant the combustion occurred earlier in the cycle and more fuel burnt before TDC and the peak pressure move closer to TDC. If the IT is advanced too much a 2% decrease from the overall mean value is observed. This is due to pressure and temperature in the cylinder might be too low to cause auto ignition.

Effect of nozzle pressure

The injection pressures 230bar, 220, 210 and 190 bars were chosen to investigate their influence on BSFC. At very high injection pressures, the fuel coming out of the nozzle undergoes a throttling process and droplets end up almost in the vapour phase aiding very good combustion. There is an improvement in the BSFC. Thus it can be concluded that 210 bar has a little effect in improving fuel economy.

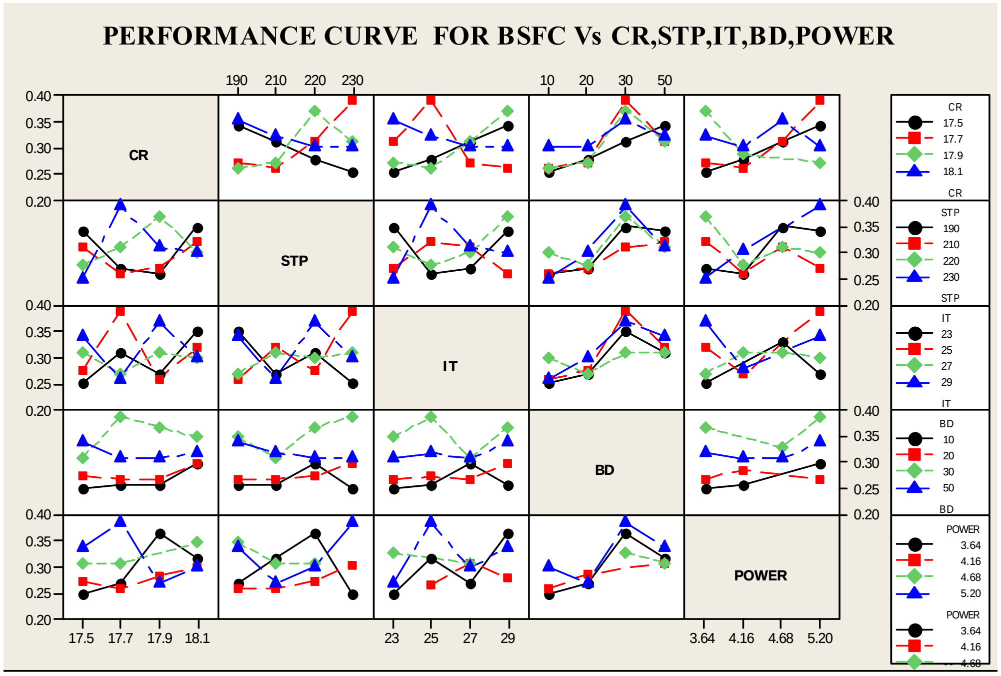

Figure-2. Performance curve for BSFC.

5.1.2 Brake thermal efficiency

Effect of compression ratio

In general increasing the CR improved the efficiency of the engine. The mean BTE of the engine increased by more than 20% when CR was raised from 17.5 to 18.1. This improved performance of the engine at higher compression ratio may be due to reduced ignition delay. The CR 17.9 was to be best.

Effect of injection timing

It can be seen that BTE increased with increase in IT in most cases. The mean BTE was found to increase by 10% when IT was advanced from 23° to 29°. This improvement in thermal efficiency with injection advances could be due to the allowances provided by such advanced timings to the fuel quantities for proper combustion. Thus injection advance was found to have more effect on improvement of BTE for the higher percentage of biodiesels in the blends.

Effect of nozzle pressure

The BTHE was found to decrease at maximum pressure 230 bar whereas at 210 bar it gives the maximum efficiency as shown in Figure-3. Compared to diesel fuel, the changes in BTE of the engine for all fuel blends at different IPs are depicted in Figure-3, it is minimum at 230 bar.

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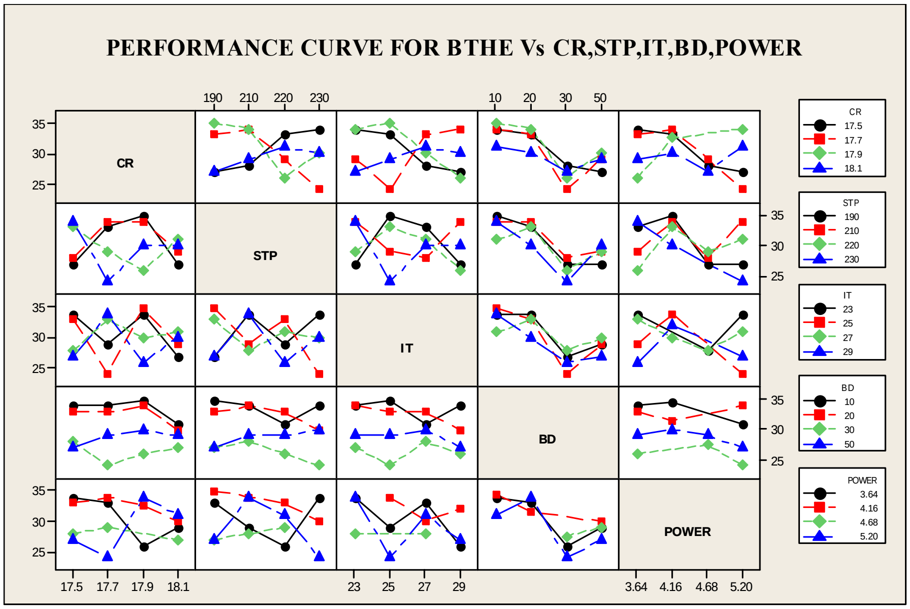

Figure-3. Performance curve for BTHE.

5.2 Optimal combination of engine performance parameters

5.2.1 Brake thermal efficiency (BTHE)

For the engine performance, the response variable BHTE was higher-the -better. The criteria for optimization of the response parameters was based on the Higher the better S/N ratio.

The experimental results were substituted in eq.1 to calculate the S/N ratios for all response variables it is shown in Figure-4. From the value the optimization of engine parameters were obtained: CR-17.9, IP-210 bar, IT-23° bTDC, Blend -B10, Power -4.16 kW.

OPT BTE = Ybar + (Abar3 - Ybar) + (Bbar3- Ybar) + (Cbar1-Ybar) + (Dbar1- Ybar) + (Ebar2-Ybar)

The value of BTHE is 37%.

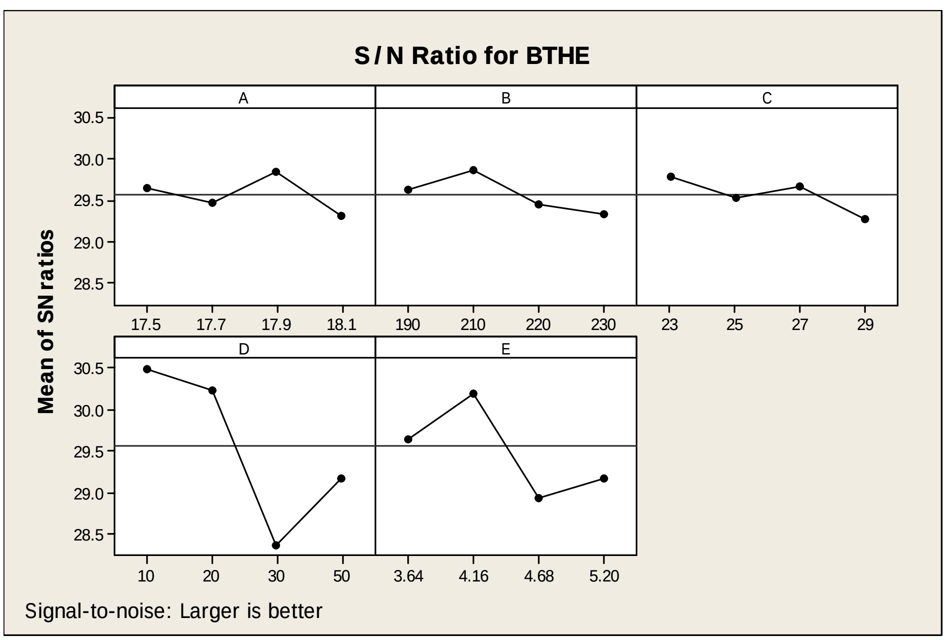

Figure-4. Shows the values of S/N ratio of BTHE.

VOL. 7, NO. 4, APRIL 2012 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

5.2.2 Brake specific fuel consumption (BSFC)

To calculate BSFC, the S/N ratio with a lower-the-better characteristic can be used.

The experimental results were substituted in eq.2 to calculate the S/N ratios for all response variables shown in Figure-5.

From the value the optimization of engine parameters were obtained: CR-18.1, IP-220 BAR, IT-29°Btdc, Blend -B30, Power -5.2 kW.

BSFC = Ybar + (Abar3- Ybar) + (Bbar1- Ybar) + (Cbar3- Ybar) + (Dbar4- Ybar) + (Ebar1-Ybar)

The value of BSFC is 0.3107 kg/Kw -hr.

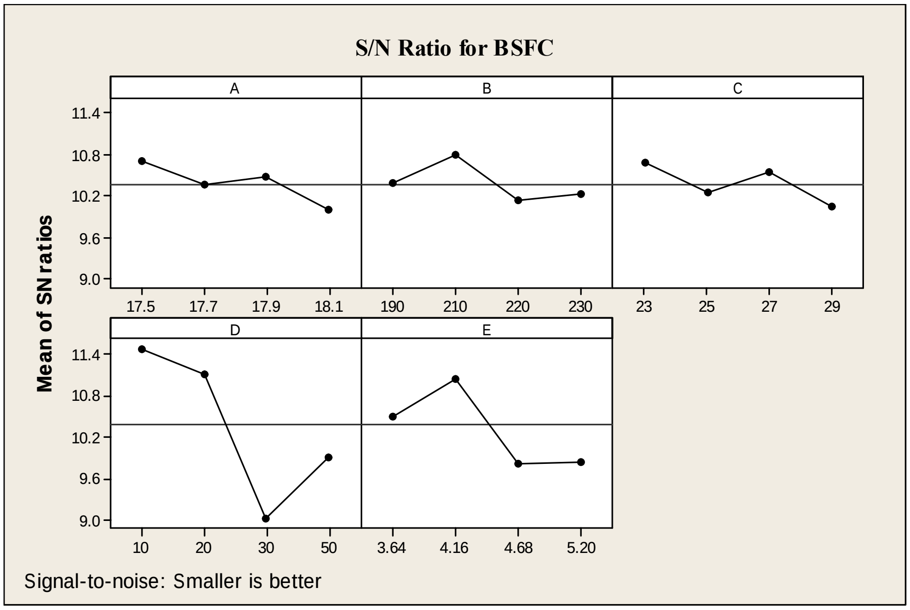

Figure-5. Shows the value of S/N ratio for BSFC.

5.2.3 Emissions HC

To calculate HC emissions, the S/N ratio with a lower-the-better characteristic can be used.

The experimental results were substituted in eq.2 to calculate the S/N ratios for all response variables shown in Figure.6 From the value the optimization of engine parameters were obtained: CR-18.1, IP-190 BAR, IT-23° Btdc, Blend -B30, Power 5.2 kW. The value of HC is 45 PPM.

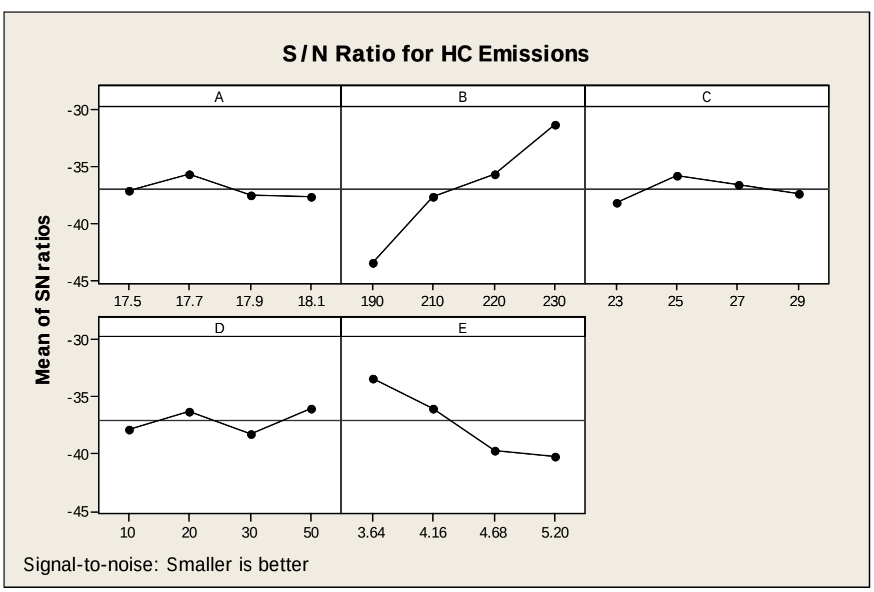

Figure-6. Shows the value of S/N ratio for HC emissions.

5.2.4 Emissions NO_x

To calculate NO_x emissions, the S/N ratio with a lower-the-better characteristic can be used.

The experimental results were substituted in eq.2 to calculate the S/N ratios for all response variables shown in Figure-7. From the value the optimization of engine parameters were obtained: CR-17.5, IP-230 BAR, IT-29° Btdc, Blend -B20, Power 4.16. Kw, The value of NOx is 318 PPM.

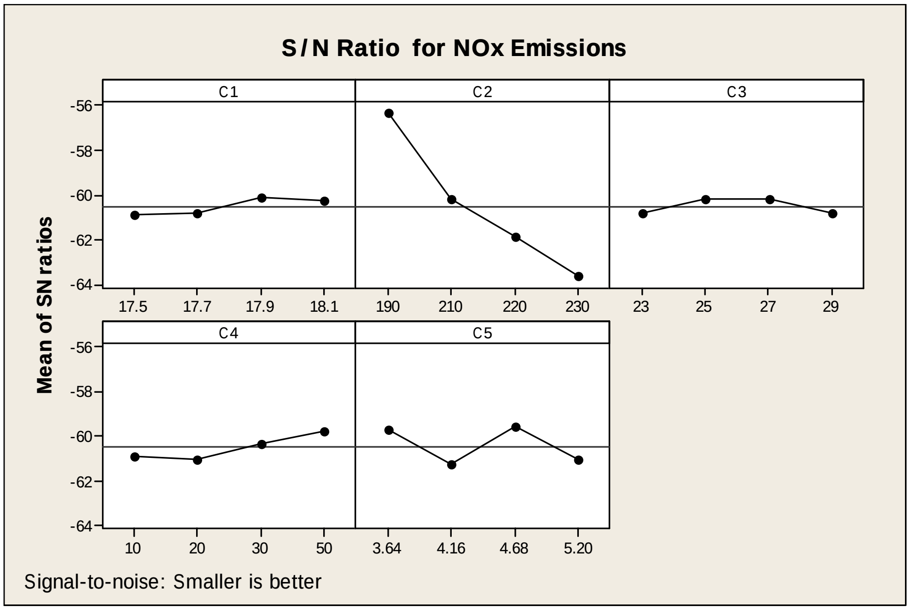

Figure-7. Shows the values of S/N ratio of NO_x

Using single objective optimization the optimum parameter obtained are given in Table-7

Table-7. Optimum parameter for single objective optimization.

Controlled factors	BTHE	BSFC	HC	NO_x
A. Compression ratio	17.9	18.1	18.1	17.5
B. Static injection pressure (bar)	210	220	190	230
C. Injection timing (bTDC)	23	29	23	29
D. Fuel fraction (%)	10	30	30	20
E. Power (kW)	4.16	5.2	5.2	4.16

The single objective optimization gives different results. To obtain an optimal combinations of engine parameters considering performance and emissions Multi-optimization techniques is used The weighting factor of each response variable is given in Table-8.

Table-8. Weighing factor of each response variable.

S. No.	Response variable	Weighing factor
1	BTHE	0.25
2	BSFC	0.25
3	NOx	0.25
4	HC	0.25

The weighting factor plays a very important role in this type of analysis. For the output performance variables there are two parameters of engine performance and emissions. Equal weights were given to performance and emissions, the experimental results were used to Calculate S/N ratios for all the response variables. From this value it can be observed that A3 B1 C3 D4 E1, i.e. CR-17.9, IP-230 bar, IT-27° btdc, B30. B.P-3.64 Kw is the optimal combination which achieves multiple-performance characteristics of the engine.

Table-9. Values of response variable.

S. No.	Response variable	Values
1	BTHE	29.25 %
2	BSFC	0.328 kg/kW-hr
3	NO_x	1206 PPM
4	HC	24 PPM

6. MULTIPLE REGRESSIONS EQUATION

Regression model is predication model within the influence space, for the response variable BTHE, BSFC and NO_x Regression model is given by:

Y BTHE = -1.353A-0.032B -0.301C-0.1278D-1.586E+79.60 (3)

Y BSFC = 0.0344A+0.00032B+0.0033C+0.0014D+0.0202E-0.59 (4)

Y NOx = -121.50 A+22.07B +1.74C-4.77D+99.95E-1764 (5)

Y HC = 40.5 A-3.12 B-1.64C-0.170 D+43.9 E-115 (6)

Where A, B, C, D and E are controlled factors. Using the above equation the values of the response variable are calculated and compared with the results.

7. CONFIRMATORY TESTS

After selecting the optimal levels of the engine, the final step is to verify the results using the optimum design parameter levels in comparison with standard engine parameters with biodiesel fuel. A Confirmation test for the combined objective is conducted by choosing the five design and control parameters as given in Table-5. This setting is for the combined objective with 25% weighted assigned for each output response variable. The results are which runs are well than any of the other combinations in the test. Thus for the engine the optimum set for conditions may be stated as A3 B1 C3 D4 and E1 which is the optimum for the combined objective of minimizing both the fuel consumption and emissions. The confirmation test was conducted with optimized parameters given in Table-10.

Table-10. The comparison of the prediction and confirmation between the initial and the optimal conditions.

S. No.	Response variable	Regression model	Predicted value at optimum condition using Taguchi	Confirmation test value at optimum condition
1	BTHE	29.5 %	29.25 %	29 %
2	BSFC	0.3127	0.328 kg/kw-hr	0.33 kg/kw-hr
3	NO_x	1410 PPM	1206 PPM	1300 PPM
4	HC	30 PPM	24 PPM	28 PPM

8. CONCLUSIONS

The Taguchi's approach analysis has been carried out for optimizing the performance of karanja biodiesels engine. The various input parameters have been optimized using SNR. Based on this study, it can be concluded that BTHE, BSFC and Emissions of diesel engine depend upon biodiesel blend, compression ratio, nozzle pressure and injection timing. The results of this study revealed that almost identical combinations of engine parameters give optimum multiple performances for engine. It was found that a diesel engine operating at a high compression ratio - 17.9, high pressure 230 bar, Injection timing of 27° bTDC, Biodiesel -diesel blend B30. And Brake power-3.64 kW achieves the optimum engine performance. The results are well supported by the findings of our confirmatory test.

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