Optimisation of Engine Performance Variables Using Taguchi and Grey Relational Analysis

[1]KARTHIKAYAN.S, [2]SANKARANARAYANAN.G

[1]Research Scholar, Department of Mechanical Engineering, Sathyabama University, Chennai - 600 119, India.
[2]Professor & Dean (Research), Sree Sastha Institute of Engineering and Technology, Chennai - 600 123, India.
Email : sskksmit@gmail.com, gs2000narayanan@gmail.com

Abstract

The objective of the work is to apply higher percentage of neat vegetable oil in diesel engine without any fuel treatment. From previous literatures it is well known that the use of neat vegetable oil more than 20% direct to engine operational problems and lube oil dilution. The use of higher percentage of neat Paradise Tree oil (50% by volume 50PTO) in the form of paradise tree oil and diesel blend in an engine using modified engine operating variables are studied in this project. The universal engine operating Variables like compression ratio (CR), intake air temperature (IAT), injection pressure and injection timing were optimised using Taguchi and Grey Relational method. The optimised variables were analysed using ANOVA, to know the influence and percentage contribution of involved variables on expected response variables such as BTE, CO, HC, Smoke and NO. Besides a thorough engine test was conducted using 50PTO to study its performance, emission and combustion characteristics. The results of the experiments proved that the application of 50PTO performed well and emissions were less. The results of the experiments were used to develop a non linear regression equation for various response variables.

Index Terms— Neat vegetable oil, Paradise Tree oil-PTO, engine operating variables, Taguchi, Grey relations, ANOVA, Regression equations, Performance, Emission.

I. INTRODUCTION

The global transport sector is facing the rapid growth rate in terms of primary energy consumption and is currently responsible for more emissions. Biofuels could notably reduce the emissions from the surface transport sector if they were widely adopted. They have been shown to reduce carbon emissions, and may help to increase energy security. There are many different types of biofuels, which are produced from various crops and via different processes. Biofuels can be classified broadly as straight vegetable oil, biodiesel and bio-ethanol. The various types of biofuels currently available are examined, together with potential future conversion-technologies. The performance and emission of biofuels in engine are compared with conventional fuels and evaluated. The vegetable oil is one such alternate fuel and proved to be a good substitute for the compression ignition engines [13], [17], [20], [21]. However, due to its few undesirable fuel properties the direct application of neat vegetable oil more than 20% is prevented [3] and [13]. The main reasons for the above are the heavier molecular structure, higher viscosity and possession of unsaturated fuel molecules [3]. However, many researchers have been found that this could be overcome by Transesterification process. The Transesterification process is a very old process and converts the neat vegetable oil into biodiesel. Though the biodiesel is a perfect and quality fuel for CI engine it has few disadvantages that prevents its application [5]. The main disadvantage of the biodiesel is a bulky chemical reaction and the high cost [5], [8]. Many researchers have tried to apply vegetable oil either in a neat form or biodiesel form. Technologies have been tried by them to apply large varieties of vegetable oils in neat form [12]. These technologies have been eliminated and major disadvantages of biodiesel conversion have laid a path to apply neat vegetable oil in CI engine. Some of the technologies have suggested minor engine modifications and some of them have suggested fuel treatment. The engine modifications suggested by them were very focused on raising the compression ratio, combustion in the adiabatic combustion chamber and the use of hot air for high temperature combustion. They have found that the common problems on neat oil combustion, such as lube oil dilution, a smoky exhaust and carbon deposition were very much reduced by the above methods [9], [11], and [16].

In the present investigation deals with the application of neat PTO in Diesel engine. To perform this, an appropriate blend of neat PTO and standard diesel fuel has been identified and used as a test blend in the present work. The blend of 50% neat PTO and 50% standard diesel fuel (by volume) was identified as the test fuel for this work. To apply this blend successfully in Diesel engine, its operating variables were suitably modified. The general engine operating variables like compression ratio (CR), intake air temperature (IAT), injection pressure and injection timing were optimised by the optimisation tools. In the present work Taguchi method and Grey relations were combined for optimising the engine operating variables. The ANOVA and Regression equations were also used in the work for analyzing the involved variables and forming correlation equations for the output variables respectively. Besides a thorough engine test was also conducted at the end of the work using the optimum level of the engine operating variable. The results indicate that, the application of neat oil in diesel engine is possible without much deviation in its performance and emission levels.

II. Abbreviations and Acronyms

CI-Compression Ignition, SVO-Straight Vegetable Oil, PTO-Paradise-Tree Oil, DI-Direct Injection, CO-Carbon monoxide, HC- Hydro Carbon, NOx- Oxides of nitrogen, CO2-Carbon-di-oxide, BSFC-Brake Specific Fuel Consumption, BTE-Brake Thermal Efficiency, IP-Injection Pressure, IT-Injection Timing, CR-Compression Ratio, IAT-Inlet Air Temperature, TDC-Top Dead Center NA-Naturally aspirated, Untreated vegetable oil, Engine Operating Variables, Performance, Emission.

III. Literature review

Straight vegetable oil (SVO) can be used as fuel for CI engine without any modification. The performance of engine with SVO, SVO-diesel blend is inferior to diesel [4]. Lower brake thermal efficiency and higher brake specific fuel consumption found compared to diesel. Higher SVO percentage in blends, results in poor emission characteristics and very high fuel consumption [4]. Agarwal and Rajamanoharan [1] investigated the performance of single cylinder DI diesel engine using neat karanj oil and blends of karanj oil and diesel fuel. It has been found that the specific fuel consumption of blend increases compared to diesel. This was attributed towards the lower calorific value of karanj oil. The heat release rate is also lower for all blends and neat karanj oil compared to diesel due to lower volatility of karanj oil and high viscosity. Elango and Senthilkumar [6] investigated performance of diesel engine with neat non-edible oils and blend of non-edible oil and diesel fuel. Brake specific fuel consumption and BTE were measured for all blends and untreated oils. It is reported that, both parameters were measured higher with blends compare to diesel and B10 has the lowest fuel consumption and brake specific fuel consumption compared to remaining blends. Agarwal and Agarwal [2] tested performance of Jatropha oil and diesel blends in DI diesel engine. The oxygen present in the oil improves completeness of combustion and in turn thermal efficiency. Effect of viscosity on performance is also measured in this work. It has been found that the viscosity varied by either preheating the fuel or blending Jatropha oil with diesel. The blend which is having comparable viscosity to diesel has performed very close to diesel. Emission of CO and HC was more with higher percentage of oil proportion due to larger droplet diameter and incomplete combustion. NOx emission is reduced when compared to diesel due to lower exhaust gas temperature with lower heat release rate.

IV. METHODOLOGIES

In this work the following methodology used for optimisation. The objective of the work is to apply large fraction of untreated PTO in DI diesel engine and the engine operating parameters are suitably optimized for it.

The first part determines the suitable blend consisting of higher percentage of neat PT oil and diesel fuel. This blend was declared as the test fuel and it was used while optimising the engine operating variables. The optimisation experiments used are Taguchi [7], [14] and grey relation method [14], to optimize the involved operating variables. The Taguchi method was used to select the number of trials required for optimisation experiment and the grey relations was used to abridge the optimisation process. The objective of the grey relational analysis is to provide solution for multi-response optimisation process. Using the above techniques suitable level of engine operating variables were identified and used consequently in the experiments to obtain engine performance, emission and combustion characteristics. An ANOVA was performed for the involved control variables to identify the percentage contribution of involved variables over the desired response. A multiple regression equation was also performed for the experimental results to generate correlation equations for the response variables. Some of the steps involved in the experiment are listed below to get an over view of the experiment.

Table 1.Engine specifications

	Engine specifications	
Sl. No.	***Make and Model***	***Kirloskar, TAF1***
1	General details	Four stroke, compression ignition, constant speed, vertical, air-cooled, direct injection
2	Number of cylinders	One
3	Bore	87.5 mm
4	Stroke	110 mm
5	Cubic capacity	661 cc
6	Compression ratio	17.5:1
7	Rated speed	1500 rpm
8	Rated output	4.4 kW
9	Fuel injection timing	23º bTDC
10	Diesel injector opening pressure	180 bar

- Selection of blend suitable for investigation
- Selection of Engine operating variables and their levels
- Selection of orthogonal array using Taguchi method
- Preparation of Experimental layout
- Conducting experiment using the experimental layout
- Observation of response variables
- Normalisation of observed response variables using Grey relational analysis
- Formation of Grey coefficients
- Determination of Grey Grades
- Determination of Mean Grey Grades for operating variables
- Depiction of response graph
- Selection of optimum levels from the response graph
- ANOVA for involved variables
- Detailed engine experiment using optimum settings.
- Formation of Regression equations.

V. RESULTS AND DISCUSSION

A. Selection of blend

Based on the objectives the various proportions of PT oil and diesel blends were prepared on a volume basis by the simple blending process. Before preparing various blends, a miscibility test was conducted to check the miscible nature of two different fuels. As the two fuels have hydrophobic nature, they miscible are miscible in each other without separation. To ensure this, the samples of various blends are kept for a period of two weeks. The lower proportions such as 10PTO and 20PTO were not used in this experiment as the objective of the experiment is to apply higher percentage of neat PT oil in Diesel engine. Hence, the proportions 30%, 40%, 50% and 60% PT oil diesel blends were prepared and used in the engine optimized for diesel fuel. The properties of various PTO-diesel blends are shown in Table 2. The samples did not indicate corrosion also.

Table.2. Properties of Pto-Diesel Blends

	Properties of PTO-diesel blends				
Sl. No.	***Name of the Blend***	***Blend ratio (Volume basis)***	***Density kg/m3***	***Viscosity mm2/sec***	***Calorific Value MJ/kg***
1	100D	0% PTO 100% D	820	5	42.7
2	30PTO	30 %PTO 70% D	841	11.2	41.5
3	40PTO	40 %PTO 60% D	852	14.9	40.9
4	50PTO	50 %PTO 50% D	862	18.5	40.3
5	60PTO	60 %PTO 40% D	873	22.1	39.6
6	100PTO	100%PTO 0% D	905	56	38.1

The fuel blends such as 30%, 40%, 50% and 60% were admitted one by one to test the engine performance, emission and combustion characteristics. The suitable blend for investigation was identified based on diesel replacement, BTE, CO and smoke. The blend that offered moderate BTE, CO and smoke was considered as the test fuel. Based on the above 50PTO was selected as suitable blend and considered as the test fuel for the rest of the investigation. Table 3 shows the experimental results of PTO-diesel blends in an un-altered engine.

Table 3. PTO-diesel blends in an un-altered engine.

	Properties of PTO-diesel blends				
Sl. No.	***Blend***	***Diesel replacement***	***BTE***	***CO***	***Smoke***
1	30PTO	30%	High	low	low
2	40PTO	40%	High	low	low
3	50PTO	50%	Moderate	Moderate	Moderate
4	60PTO	60%	Low	High	High

B. Engine operating Variables and their levels

Present investigation considers four engine operating variables such as compression ratio, intake air temperature, injection pressure and injection timing for the optimisation. All variables are allowed to vary in three levels. These variables are called control factors and are believed to be controlling the desired response. The range of each variable was selected based on previous experience and preliminary engine experiments. The list of involved variables and their levels are given in Table 4.

Table 4. Engine operating Parameters and their levels

	Engine operating Parameters and their levels				
Sl. No	***Symbol***	***Parameters***	***Level 1***	***Level 2***	***Level 3***
1	A	Injection Pressure (bar)	225	250	275
2	B	Injection timing (°b TDC)	25	27	29
3	C	Compression Ratio	17.5	18.5	19.5
4	D	Inlet Air Temperature (IAT) (° C)	50	65	80

C. Taguchi method

Taguchi Design of Experiments (DoE) offers a systematic approach for optimizing various performance variables involved in the production of response variables. The Taguchi method uses an orthogonal array (OA) for the design of experimental layout. The selection of orthogonal array depends upon degrees of freedom of involved variables. The minimum number of experiments required for selection of optimum level can be determined using the following relation

$$N = [(L-1) P] + 1. \qquad (1)$$

N = Total number of test runs
L= Number levels of variables
P= Number of control variables

Table. 5.Layout of L18 Orthogonal Array

	Layout of L_{18} Orthogonal Array			
Sl.. No.	***Injection Pressure***	***Injection Timing***	***CR***	***IAT***
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	1	2
5	2	2	2	3
6	2	3	3	1
7	3	1	2	1
8	3	2	3	2
9	3	3	1	3
10	1	1	3	3
11	1	2	1	1
12	1	3	2	2
13	2	1	2	3
14	2	2	3	1
15	2	3	1	2
16	3	1	3	2
17	3	2	1	3
18	3	3	2	1

The OA facilitates the experimental design by assigning variables and its level in the appropriate columns. Taguchi method provides a simple and effective solution for the effect of control variables on the desired response using minimum number of experimental trials. This is a very proven method and suitable for all experimental investigations. The present study has 4 variables and 3 level and the total degrees of freedom of control variables are 8. Hence, L18 orthogonal array having 17 degrees of freedom has been chosen for this investigation. The layout of L18 orthogonal array, experimental layout and results of response variables are shown in Table 5, 6 and 7 respectively.

Table 6.Experimental Layout of L18 Orthogonal Array

	Experimental Layout of L_{18} Orthogonal Array			
Sl.. No.	***Injection Pressure***	***Injection Timing***	***CR***	***IAT***
1	225	25	17.5	50
2	225	27	18.5	65
3	225	29	19.5	80
4	250	25	17.5	65
5	250	27	18.5	80
6	250	29	19.5	50
7	275	25	18.5	50
8	275	27	19.5	65
9	275	29	17.5	80
10	225	25	19.5	80
11	225	27	17.5	50
12	225	29	18.5	65
13	250	25	18.5	80
14	250	27	19.5	50
15	250	29	17.5	65
16	275	25	19.5	65
17	275	27	17.5	80
18	275	29	18.5	50

D. Grey Relational Analysis

Grey relational analysis is the statistical data processing tools, which helps to identify the optimum level of control parameters involved in the creation of multiple responses. Unlike Taguchi method it helps to provide simple analysis to determine optimum level of control parameters [10], [15]. The steps involved in the grey relational analysis are given below

1. Normalization of data or generation of grey relations.
2. Formation of grey coefficients.
3. Determination of grey grades.
4. Tabulation of mean grey grade for the control variables and their levels.
5. Determination of optimum level of involved variables using response graph.

The normalised values of response variables, Grey relational coefficients and Grey grades of L18 orthogonal experiments are shown in Table 8.

Table 7.Response variables and results of L18 orthogonal experiment

	Response variables and results of L_{18} orthogonal experiment				
Sl. No.	***BTE (%)***	***NO (g/kW h)***	***Smoke (BSN)***	***CO (g/kW h)***	***HC (g/kW h)***
1	22.6	9.0	4.5	58.1	2.1
2	27.0	10.7	5.3	69.4	2.5
3	29.6	11.7	5.8	75.9	2.7
4	25.5	10.1	5.0	65.4	2.3
5	27.7	11.0	5.4	71.0	2.5
6	29.9	11.9	5.9	76.7	2.7
7	26.1	10.4	5.1	67.0	2.4
8	30.5	12.1	6.0	78.3	2.8
9	26.1	10.4	5.1	67.0	2.4
10	28.3	11.2	5.6	72.6	2.6
11	23.3	9.2	4.6	59.7	2.1
12	27.7	11.0	5.4	71.0	2.5
13	27.0	10.7	5.3	69.4	2.5
14	29.2	11.6	5.8	75.1	2.7
15	26.7	10.6	5.3	68.6	2.5
16	30.2	12.0	5.9	77.5	2.8
17	25.5	10.1	5.0	65.4	2.3
18	27.4	10.9	5.4	70.2	2.5

The mean Grey grades for various levels of operating variables are shown in Table 9 and the response graph for operating variables is shown in Figure 1. The optimised levels of operating variables are shown in Table 10.

Table 8.Grey relational Coefficients and Grey grades of L18 experimental results

10											
Sl. No.	***Normalised Values***					***Grey Relation Coefficient***					***GRG***
	BTE	***NO***	***Smoke***	***CO***	***HC***	***BTE***	***NO***	***Smoke***	***CO***	***HC***	
1	0.005	1.006	1.031	0.999	1.031	0.334	1.012	1.066	0.998	1.066	0.895
2	0.562	0.443	0.454	0.440	0.454	0.533	0.473	0.478	0.472	0.478	0.487
3	0.881	0.121	0.124	0.120	0.124	0.807	0.363	0.363	0.362	0.363	0.452
4	0.363	0.644	0.660	0.639	0.660	0.440	0.584	0.595	0.581	0.595	0.559
5	0.642	0.362	0.371	0.360	0.371	0.583	0.439	0.443	0.438	0.443	0.469
6	0.920	0.080	0.082	0.080	0.082	0.863	0.352	0.353	0.352	0.353	0.454
7	0.443	0.563	0.577	0.559	0.577	0.473	0.534	0.542	0.532	0.542	0.524
8	1.000	0.000	0.000	0.000	0.000	1.000	0.333	0.333	0.333	0.333	0.467
9	0.443	0.563	0.577	0.559	0.577	0.473	0.534	0.542	0.532	0.542	0.524
10	0.721	0.282	0.289	0.280	0.289	0.642	0.410	0.413	0.410	0.413	0.458
11	0.085	0.926	0.948	0.919	0.948	0.353	0.870	0.907	0.861	0.907	0.779
12	0.642	0.362	0.371	0.360	0.371	0.583	0.439	0.443	0.438	0.443	0.469
13	0.562	0.443	0.454	0.440	0.454	0.533	0.473	0.478	0.472	0.478	0.487
14	0.841	0.161	0.165	0.160	0.165	0.758	0.373	0.375	0.373	0.375	0.451
15	0.522	0.483	0.495	0.480	0.495	0.511	0.492	0.497	0.490	0.497	0.498
16	0.960	0.040	0.041	0.040	0.041	0.926	0.343	0.343	0.342	0.343	0.459
17	0.363	0.644	0.660	0.639	0.660	0.440	0.584	0.595	0.581	0.595	0.559
18	0.602	0.402	0.412	0.400	0.412	0.557	0.456	0.460	0.454	0.460	0.477

Table 9.Mean Grey relational Grade for operating parameters

	Mean Grey relational Grade for operating variables				
Sl. No.	***Symbol***	***Parameters***	***Level 1***	***Level 2***	***Level 3***
1	A	Injection Pressure (bar)	0.486	0.502	0.590
2	B	Injection timing (°b TDC)	0.479	0.564	0.535
3	C	Compression Ratio	0.457	0.486	0.636
4	D	Inlet Air Temperature (IAT) (º C)	0.490	0.597	0.491

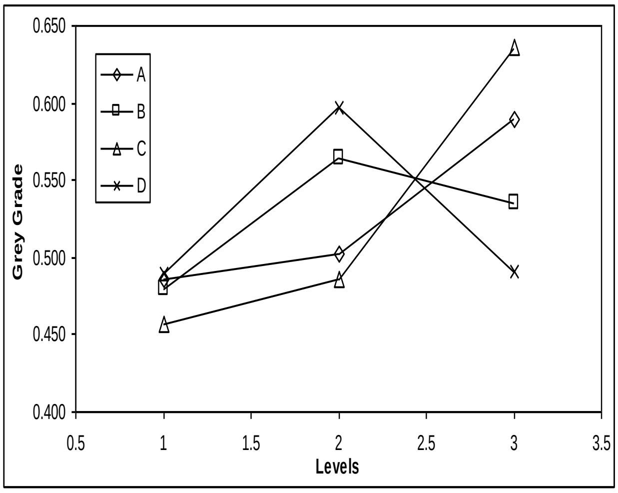

Fig 1. Response graph for operating variables

Table 10.Optimum level of Variables

	Optimum level of Variables			
Sl.. No.	***Injection Pressure***	***Injection Timing***	***CR***	***IAT***
1	A3	B2	C3	D2

E. Analysis of variance

Analysis of variance (ANOVA) helps to establish the effect of control variables on the desired response. It is proved that all control variables are not equally contributing in the production of response variables. Each one contributes with various percentages in the production of desired response. ANOVA also helps to know the variables that are most contributing and least contributing. A parameter called F- test shows significance and insignificance of involved control variables. The parameters that have F-test value lower than four is consider as insignificant parameters and effect over desired response is meager. Similarly, the variable that has highest F-test value is considered as most significant variable and its effect over desired response is higher. The results of ANOVA for the involved variables are shown in Table 11.

Table 11.ANOVA results for variables used for optimisation

Sl.No	**ANOVA results for variables used for optimisation**									
	Symbol	***Factors***	***Level 1***	***Level 2***	***Level 3***	***DOF***	***SS***	***MS***	***F***	***% P***
1	A	IP	0.479	0.564	0.535	2	0.011	0.006	61.8	10.3
2	B	IT	0.486	0.502	0.590	2	0.019	0.009	104.3	17.4
3	C	CR	0.457	0.486	0.636	2	0.055	0.028	308.0	51.3
4	D	IAT	0.490	0.597	0.491	2	0.023	0.011	125.7	21.0
Total							0.108	0.054		100

F. Detailed Engine experiment using optimum level of variables

The identified optimum level of engine operating variables has been used in the test engine setup before conducting a detailed engine experiment. The test fuel 50PTO was used in the same engine test rig through regular fuel injection system and the performance, emission and combustion characteristics of the engine have been observed at all load conditions. The same engine was tested by the standard diesel fuel and other PTO blends such as, 40PTO and 60PTO to compare the performance and emission characteristics of 50PTO. The results of the experiments are presented in graphical form to understand the performance and emission trend of various PTO blends.

G. Regression Equations

The regression equations are very helpful to predict the response variable of the levels that are not visited by the orthogonal experiment. In the present study DATAFIT 9.0 statistical software specially meant for regression analysis has been used for generating regression equations for the response variables observed during the orthogonal experiment. Equations 1, 2 and 3 are the regression equations for the response variables BTE, CO and Smoke. The variables of the equations and its coefficients are listed in Table 12.

Table 12.Variables and Coefficients of various response variables

	Variables and Coefficients of various response variables				
Sl. No.	***Variable***	***BTE***	***CO***	***Smoke***	***Variable***
1	a	1.11E-03	1.11E-03	1.07E-03	a
2	b	8.14E-03	8.32E-03	9.09E-03	b
3	c	8.88E-02	8.91E-02	8.94E-02	c
4	d	-1.91E-03	-1.90E-03	-1.83E-03	d
5	e	1.23E+00	2.16E+00	-4.32E-01	e

The regression equations shown below were observed for 95% confidence interval. The software tested several model such as linear, exponential and power series. Out of all tested models the model that has higher correlation coefficient (R2) is considered as the best regression equation. The adequacy of the model and significance of the coefficients are tested by applying analysis of variance.

$$BTE = \exp(a*x1+b*x2+c*x3+d*x4+e). \quad (2)$$

$$CO = \exp(a*x_1+b*x_2+c*x_3+d*x_4+\tilde{e}) \quad (3)$$

$$Smoke = \exp(a*x_1+b*x_2+c*x_3+d*x_4+\tilde{e}) \quad (4)$$

H. Lubrication oil quality verification

A common problem of neat vegetable oil application in Diesel engine is lubrication oil dilution. The heavier molecular structure and higher viscosity of neat oils are the main reasons for the lube oil dilution. The heavier molecular structure, higher viscosity and poor volatility of neat oils not permit the fuels to combust in a shorter duration. Hence, a part of unvapourised fuel spray remains inside the cylinder has been wiped out and mixed with the oil pool by the reciprocating piston. This mixture reduces the viscosity of lubrication oil and lubricating properties. A capillary tube viscometer shown in Figure 2 has been used for measuring the lubrication oil viscosity and oil blends viscosity.

Capillary Tube Viscometer

The viscosity of lubrication oil (SAE 40)

Before experiment = 160 cSt (measured at 40ºC)
After experiment = 158 cSt (measured at 40ºC)

It shows that the lubrication oil properties were not affected due to application SVO combustion.

VI. CONCLUSION

- The experiments reveal that the 50PTO performed well in the modified engine and offered better performance and emission characteristics.
- The 50PTO offered 29.6 % BTE at full load and it is almost equal to the diesel fuel's efficiency in a standard diesel engine at full load (un-altered diesel engine).
- 50PTO emitted 14% higher CO, 19% higher HC, 14% higher smoke and 15 % lower NO than that of diesel fuel used in the modified engine.
- The modified engine successfully used 50% neat PTO oil without much drop of engine performance and emission characteristics.
- Higher CR and higher IAT are contributing considerably in raising the performance of 50PTO blend. More specifically, they have contributed 51.3% and 21% respectively.

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