Journal of Energy Research and Environmental Technology (JERET)
p-ISSN: 2394-1561; e-ISSN: 2394-157X; Volume 6, Issue 3; July-September, 2019; pp. 182-186

http://www.krishisanskriti.org/Publication.html

A Comparative Study of Multi-Objective Optimization Methods for I.C. Engine Performance Study of Koroch Blend Biodiesel

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Abstract—*In this paper, a comparative study between two different multi objective optimization methods namely -Assignment of weights and Grey Relational Analysis (GRA) has been carried out for I.C. engine performance study of Koroch blend biodiesel. The operating parameters namely blend ratio, load and speed were chosen as the factors at different levels (i.e., low, medium and high) for the responses such as Brake thermal efficiency (η_{bth}), Brake specific fuel consumption (BSFC) and exhaust like CO%, HC and NO_X (both in ppm). Taguchi's orthogonal array L_9 was used for running the experiments at different treatment conditions (TC). The Multi Response Performance Index (MRPI) obtained from both the methods arrived at the same optimal setting. The study shows that the optimal setting was obtained at medium level of blend ratio (i.e., B20), high level of load (i.e., 100%) and high level of speed (i.e., 1520 rpm). The confirmation run agreed with the obtained setting. From the ANOVA using Grey Relational Grade (GRG) it was experienced that load was found to be the only and most significant parameter followed by speed and blend ratio over the performance of the engine.*

1. INTRODUCTION

The exponentially growing demand for fuel and also at the same time the increasing concern for the environment due to the use of fossil fuel have led to the search of bio fuel as a useful alternative and environment friendly energy resource. Nowadays the biomass resources are widely used for the energy purposes. The seed of a locally available tree Koroch (i.e., Pongamia glabra Vent.) is one among them which could be used as an energy source [1]. It has been used in India and neighbouring regions mostly as a source of animal fodder, green manure, timber and fuel [2]. The study reveals the suitability of Koroch blended biodiesel up to B30 as fuel for a diesel engine mainly used in generating sets and the agricultural applications in India without any significant drop in engine performance [3]. To reduce the uncertainties associated with the petro-diesel, the present investigation is undertaken to study the I.C. engine performance of koroch pure biodiesel (B100) and their blends with high speed diesel (HSD) using two different multi objective optimisation methods namely -Assignment of weights and Grey Relational Analysis (GRA). The obtained results from both the methods were compared and validated. From the study it has been experienced that the blended bio-diesel resulted in the performance comparable with those of HSD over the characteristic responses [3].

2. METHODOLOGY

Experiments were carried out in a batch stirred reactor of 1000ml volume. This reactor was provided with temperature and speed controller. After initial experimentation the impeller speed was set at 600 rpm to avoid mass transfer limitations. To carry out the tests, koroch oil was added to the reactor, fitted with a reflux condenser. After the set temperature of 30^0C was reached, the catalyst diluted in methyl alcohol was introduced in the reactor. The total reaction time was observed to be 90 min. During the experiments, pressure and impeller speed were maintained constant. The conversion to biodiesel was achieved quickly after a few minutes from the start of the action, depending on the reaction conditions.

2.1 Engine Specification

Tests were conducted in the lab on a kirloskar made single cylinder four-stroke naturally aspirated, direct injection compression ignition (CI) engine. The specifications of the test engine are shown below:

Table 1: Test engine specification

Particulars	Specification
Rated Power	5.9kW @1500 rpm
Compression ratio	17.5:1
Stroke length	110mm
Cylinder bore	95mm
Fuel injection timing	26^0 BTDC (Before top dead centre)
Injection opening pressure	200 bar

Engine was coupled to a 5kVA electric generator. An AVL Digas analyzer was used to measure CO, CO_2 and NO_X by non-dispersive IR gas analyzer. Hydrocarbons were measured with heated flame ionisation detector. Reading taken during each set of experiments was used for calculation of engine characteristics.

2.2 Specification of factors and their levels

In this experiment, the operating parameters taken as factors with their respective levels are arranged as follows:

2.3 Running of the experiments and data collections:

Table 2: Factors with respective levels

Factors		Level 1 (Low)	Level 2 (Medium)	Level 3 (High)
A	Blend ratio (BXX)	B00	B20	B100
B	Load (%)	20	60	100
C	Speed (rpm)	1480	1502	1520

Based on the degree of freedom for above factors, Taguchi's orthogonal array L_9 has been selected. Accordingly the experiments were run and the data were collected as shown in the Table3.

Table 3: Responses of treatment conditions

TC No.	Factors			Responses				
	A	B	C					
	Blend ratio (BXX)	Load (%)	Speed (rpm)	η_{bth} (%)	BSFC (kg/kW-hr)	CO (%)	HC (ppm)	NOx (ppm)
1	B00	20	1480					
2	B00	60	1502	26.75	0.3058	0.04	45	2383
3	B00	100	1520	26.45	0.3092	0.89	74	2169
4	B20	20	1502	13.72	0.5959	0.04	37	1227
5	B20	60	1520	24.46	0.3344	0.05	47	2989
6	B20	100	1480	26.70	0.3064	0.71	82	2906
7	B100	20	1520	11.15	0.7333	0.05	29	1254
8	B100	60	1480	23.09	0.3542	0.06	41	3063
9	B100	100	1502	24.43	0.3348	0.98	57	2864

2.4 Analysis:

2.4.1 Analysis based on Assignment of weights method:

Based on different types of quality characteristics, such as larger the better for the response Brake thermal efficiency and smaller the better for the responses BSFC, CO, HC and NO_X the weights are determined accordingly. For larger the better characteristics the individual response (data) is divided by the total response, where as for smaller the better characteristics the reverse normalization procedure is used. Finally the MRPI of different treatment conditions are calculated as follows:

$$(MRPI)_i = W_1Y_{11} + W_2Y_{12} + ...+ W_jY_{ij}$$

Where $(MRPI)_i$= MRPI of the i^{th} treatment condition

W_j=Weight of the j^{th} response/dependent variable

Y_{ij}= Observed data of i^{th} treatment condition under j^{th} response

Following the above relation, the MRPI for different treatment conditions have been calculated. Table 4 shows the MRPI for different treatment conditions.

Table 4: MRPI as response

TC No.	Factors			MRPI
	A	B	C	
1	1	1	1	216.358
2	1	2	2	219.000
3	1	3	3	219.015
4	2	1	2	216.461
5	2	2	3	218.718
6	2	3	1	219.308
7	3	1	3	216.122
8	3	2	1	218.093
9	3	3	2	218.510

From the data given in Table 4, the level totals of different factors are found and summarised as shown in Table 5.

Table 5: Level totals of MRPI

Operating Parameters/ Factors		LEVEL TOTALS OF MRPI		
		Level 1 (Low)	Level 2 (Medium)	Level 3 (High)
A	Blend ratio(BXX)	654.373	654.487	652.725
B	Load (%)	648.941	655.811	656.833
C	Speed (rpm)	653.759	653.554	653.855

From the above Table 5, the optimum setting has been obtained at 2, 3 and 3 i.e., **medium level of blend ratio *(i.e., B20),* high level of load *(i.e., 60%)*** and **high level of speed *(i.e., 1520 rpm).*** For validation of this setting a confirmation run was performed and that agreed the result.

2.4.2 Analysis based on Grey Relational Analysis (GRA):

Under the same design strategy as above and under different quality characteristics as mentioned earlier, the S/N ratios of all nine treatment conditions are first calculated as shown in Table 6 and then the following steps are followed in GRA.

Table 6: S/N ratios (treatment condition wise)

TC No.	S/N ratios (treatment condition wise)				
	η_{bth} (%)	BSFC (kg/kW-hr)	CO (%)	HC (ppm)	NOx(ppm)
1	22.85	4.60	26.03	32.87	60.84
2	28.55	10.29	27.96	33.06	67.54
3	28.45	10.19	1.02	37.38	66.73
4	22.75	4.50	27.75	31.36	61.78
5	27.77	9.51	25.81	33.44	69.51
6	28.53	10.27	3.01	38.28	69.27
7	20.95	2.69	13.71	29.25	61.97
8	27.27	9.02	26.78	32.26	69.72
9	27.76	9.50	0.18	35.12	69.14

Step 1: *Normalization of S/N ratio*

Normalization of the S/N ratio prepares the initial data for the analysis where the original sequence is transferred to a comparable sequence. Normalization of the S/N ratio transforms the data in the range between zero and unity. It is known as grey relational generation. In the present study, "larger-the-better" criterion is calculated for Brake thermal efficiency using (1) and "smaller-the-better" is used for normalization of BSFC, CO, HC and NO_X using (2).

Larger – the – better

$Z_{ij} = (Y_{ij} — min(Y_{ij,i}=1,2,...,n))/(max(Y_{ij,i}=1,2,...,n) — min(Y_{ij,i}=1,2,...,n)$............(1)

Smaller – the - better

$Z_{ij} = (max(Y_{ij,i}=1,2,...,n) — Y_{ij})/(max(Y_{ij,i}=1,2,...,n) — min(Y_{ij,i}=1,2,...,n))$.......... (2)

Where, Z_{ij} is the value obtained by grey relational generation, Y_{ij} is the ith normalised value of the jth response/dependent variable. The normalized values are given in Table 7.

Table 7: Normalized values of S/N ratios

TC No.	Normalized S/N ratios				
	η_{bt}	BSFC	CO (%	HC (p	NOx (p
1	0.251	0.748	0.069	0.400	0
2	1	0	0	0.422	0.754
3	0.987	0.013	0.969	0.900	0.663
4	0.237	0.762	0.008	0.234	0.106
5	0.898	0.103	0.077	0.464	0.976
6	0.998	0.003	0.898	1	0.949
7	0	1	0.513	0	0.127
8	0.832	0.167	0.042	0.333	1
9	0.896	0.104	1	0.650	0.935

Step 2: *Determination of Deviation Sequence*

The deviation sequence Δ_{ij} is the absolute difference between the reference sequence Y_{oj} and Y_{ij} (the comparability sequence after normalization). It is determined using (3) and is computed in Table 8

$\Delta_{ij} = |Yoj — Yij|$ ……… (3)

Step 3: *Determination of Grey Relational Coefficient*

Grey Relational Coefficient for all the trials expresses the relationship between the ideal (best) and actual normalized S/N ratio. If the two sequences agree at all the points, their grey relational coefficient is 1. The grey relational coefficient (GC_{ij}) can be expressed by (4) and is shown in Table 8

$GCij = (\Delta min+ \lambda \Delta max)/ (\Delta ij+\Delta max)$............ (4)

i=1, 2…n – experiments

j = 1, 2… m –responses

Where, $\Delta ij = |Yoj — Yij|$=Absolute difference between *Yoj* and *Yij* , which is a deviation from target value and can be treated as quality loss. *Yoj* is the ideal normalised value of the *j*th response and *Yij* is the *i*th normalised value of the *j*th response variable.

λ is the distinguishing coefficient which is defined in the range $0 \leq \lambda \leq 1$ but it is generally taken as 0.5. In the present study, λ is taken as 0.5. *Δmin* is the minimum value of *Δij* and *Δmax* is the maximum value of *Δij*.

Table 8: Table of quality loss values

TC No.	$\Delta\ \eta_{bth}$	Δ_{BSFC}	Δ_{CO}	Δ_{HC}	Δ_{NOx}
1	0.749	0.252	0.931	0.600	1
2	0	1	1	0.578	0.246
3	0.013	0.987	0.030	0.100	0.337
4	0.763	0.238	0.993	0.766	0.894
5	0.102	0.897	0.923	0.536	0.024
6	0.002	0.997	0.102	0	0.051
7	1	0	0.487	1	0.873
8	0.168	0.833	0.958	0.667	0
9	0.104	0.896	0	0.350	0.065

Step 4: *Determination of Grey Relational Grade (G_i)*

The overall evaluation of the multiple performance characteristics is based on the Grey Relational Grade (G_i) as shown in Table 9. The next step of grey relational analysis is the calculation of grey relational grade and is calculated using (5) given below.

$G_i = 1/m\ (\Sigma GC_{ij})$...................... (5)

where m is the number of responses

A higher value of the grey relational grade means that the corresponding process parameter is close to optimal. In other words, optimization of the complicated multiple process responses is converted into optimization of a single grey relational grade [6].

Table 9: Table of grey relational coefficient (GCij) and grey grade values (Gi)

TC No.	GC η_{bth}	GC $_{BSFC}$	GC_{CO}	GC $_{HC}$	GC_{NOx}	G_i
1	0.400	0.664	0.349	0.454	0.333	0.4401
2	1	0.333	0.333	0.463	0.670	0.5598
3	0.974	0.336	0.943	0.833	0.597	0.7366
4	0.395	0.678	0.335	0.394	0.358	0.4320
5	0.830	0.357	0.352	0.483	0.954	0.5951
6	0.996	0.334	0.831	1	0.907	0.8135
7	0.333	1	0.507	0.333	0.364	0.5073
8	0.748	0.375	0.343	0.428	1	0.5828
9	0.828	0.358	1	0.588	0.885	0.7320

Step 5: *Selection of optimal levels*

The optimal levels for the factors are selected based on maximum average G_i value.

Table 10: Mean of Gi (MRPI) values for factors at different levels

Factors	Levels		
	1	2	3
A	0.5788	0.6135	0.6073
B	0.4598	0.5792	0.7607
C	0.6121	0.5746	0.6130

From the above Table 10, the same optimum setting as previous has been obtained at 2, 3 and 3 i.e., **medium level of blend ratio *(i.e., B20)*, high level of load *(i.e., 60%)*** and **high level of speed *(i.e., 1520 rpm)*.** For validation of this setting a confirmation run was performed and that agreed the result as shown in Table 11.

Table 11: Results of Confirmation run

Factors			Responses of Confirmation run				
A	B	C					
Blend ratio (BXX)	Load (%)	Speed (rpm)	η_{bth} (%)	BSFC (kg/kW-hr)	CO (%)	HC (ppm)	NOx (ppm)
B20	100	1520	28.77	0.2994	0.03	27	1005

2.4.3 ANOVA (Analysis of Variance):

Using the above obtained Grey Relational Grade (GRG) values in the Table 9, the ANOVA was calculated as shown in the Table 12.

From the table it was experienced that factor B (i.e., Load) was found to be the only and most significant parameter followed by speed and blend ratio over the performance and emissions of the engine. The percentage contribution of load (94.5%) is the most dominant parameter followed by speed (1.58%) and blend ratio (1.03%).

Table 12: ANOVA using GRG (G_i)

Factor	SS	DOF	MS	F-ratio	C (%)	Rank
A	0.0015	2	0.00075	0.3571	1.03	3
B	0.1375	2	0.0687	*32.71	94.5	1
C	0.0023	2	0.00115	0.5476	1.58	2
Error	0.0042	2	0.0021		2.89	
Total	0.1455	8			100	

3. RESULTS AND DISCUSSIONS:

From the study it has been observed that both the optimisation methods i.e., Assignment of Weights and GRA arrived at the same conclusion for engine performance and emissions with the Koroch blend biodiesel. Thus the results were also validated. It was also experienced that the Koroch blend biodiesel exhibited similar combustion trend with conventional diesel. Here the following observations both in engine performance and emissions were revealed in the study.

Engine Performance:

From the analysis it was experienced that the enhanced quality characteristics namely larger the better for Brake thermal efficiency and smaller the better in case of Brake specific fuel consumption were satisfied at medium level of blend ratio (i.e., B20), high level of load (i.e., 60%) and high level of speed (i.e., 1520 rpm). At high engine speed the fuel combustion is improved due to better mixing of fuel and air. While at high engine load, the combustion is improved due to higher in-cylinder temperature after successive working of engine at this load improving fuel atomization and evaporation processes leading to partial improvement in fuel air mixing [4]. From the point of view of bio-diesel it may be attributed to lower calorific value and higher density of biodiesel fuel. The performance of B20 in case of thermal efficiency was found to be most successful, which may be due to availability of O_2 present in the biodiesel itself helping the complete combustion of fuel. The absence of B100 in the optimal setting may be attributed to poor fuel combustion due to relatively high viscosity and poor volatility.

Engine Emissions:

Carbon monoxide (CO), hydrocarbon (HC) and Oxides of nitrogen (NO_x) were measured for the quality characteristic of smaller the better in case of exhaust emission at different load, speed and blend conditions. Here the optimum result was obtained at medium level of blend ratio (i.e., B20), high level of load (i.e., 60%) and high level of speed (i.e., 1520 rpm).

The high level of load and speed corresponds to the better mixing of fuel which finally resulted in proper burning leading to less exhaust [4]. The blend B20 showed a better performance out of all, which may be due to lower viscosity and availability of adequate oxygen present in the fuel itself.The decreasing nature of CO emission was observed from biodiesel as CI engine fuel. It was also observed that use of biodiesel instead of pure diesel resulted in reduction of HC emission. However, emissions of NO_x from biodiesel were found to be slightly higher than diesel in CI engines emission [5].

4. ACKNOWLEDGMENTS

The authors express their sincere thanks and gratitude to Department of Mechanical Engineering of IIT (Delhi) and Assam Engineering College for providing the facility of tools and equipment for doing the experimental research work.

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