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Multiple Response Optimizations on Performance Characteristics and Emissions of CRDI Diesel Engine Fuelled with Neem Biodiesel Blends

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Abstract:

Biodiesel is a clean and alternative fuel for replacing traditional petroleum diesel. It has high lubricating property and burns cleaner when compared to diesel in existing unmodified diesel engines. Biodiesel consists of fatty acid esters obtained by transesterification of vegetable oil. The seeds of Neem contain 30-40% of oil and biodiesel is obtained from Neem oil through transesterification process. Tests are conducted for Neem biodiesel blends (NB5, NB10, NB15 and NB20) by varying engine performance parameters such as Injection time, Injection pressure and load on unmodified computerized CRDI diesel engine. Taguchi is used for Design of experiments (DoE) to minimize number of experiments. An L16 orthogonal array with four columns (Blend, IT, IP and Load) and 16 rows is considered to conduct experiments. Grey relation analysis is used to find the multiple response optimizations and S/N ratios are used to find the significance of independent variables on output responses. S/N ratio mean plot signifies that blend percentage of NB15, IP 480 bar, IT 23˚ bTDC and load of 9kg (A3B2C3D3) is the optimum combination corresponding to low emissions and maximum performance of CRDI engine.

***Keywords:** aguchi, Grey relation analysis, Neem Biodiesel*

I. INTRODUCTION

Indian energy companies are looking to diversify the energy supply source and cut down the high dependency on the imported crude oil [1]. Biofuels obtained from renewable resources are been identified as the supplements to meet the increasing demand for transportation fuels. National Biodiesel Mission (NBM) identified Jatropha (Jatropha Curcas) as the most suitable inedible oilseed for the production of biodiesel and to achieve the target of 20 % blend with conventional diesel by 2017. Since the Jatropha seeds quality is not consistent and yields are poor and hence, biodiesel production in India is commercially unviable. As a result, biodiesel units started to use alternative feedstock such as edible oil waste, animal fats and other inedible vegetable oils [2].

Rudolph diesel demonstrated the use of vegetable oil as a fuel at paris exposition of 1900[3]. The viscosity of raw vegetable oils is very high compared to conventional diesel and they cause blockage in the fuel lines, filters and cause poor atomization. Also vegetable oils have longer duration for combustion and the pressure rise is also moderate. High viscosity of the vegetable oil make not suitable to run CI engine. The problem can be overcome by esterification and blending with neat diesel [4].

Neem oil is extracted from the seed of the Neem (Azadirachta indica) tree which are evergreen and widespread across the India. The percentage of oil content in need seed is of 30 to 40%. Neem oil is bitter in taste and has a strong odor. It is generally brown in color[5, 6].

Atul Dhar et al. studied the combustion, emission and performance analysis of Neem biodiesel

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blends (NB5, NB10, NB20, NB50, & NB100) and were been compared with mineral diesel. It was observed that Brake Specific Fuel Consumption (BSFC), Brake Thermal Efficiency (BTE) of Neem biodiesel blends was increases compared to diesel. Whereas the emissions like carbon monoxide (CO) and hydrocarbons (HC) were lesser compared with mineral diesel; however the nitrogen oxides (NOx) were higher than diesel. The combustion of Neem biodiesel blends starts early but the duration of combustion was shorter. The net heat release rate was identical for both Neem biodiesel blends and pure diesel. Biodiesel produced from high FFA Neem oil is found to be marginally inferior compared to mineral diesel [7]. K. Anbumani et al. investigated on the viability of using two edible oils mustard and Neem as diesel substitute and comparative study on their combustion characteristics on a C.I. engine were made. The oils were converted into biodiesel through estification process and were been blended with diesel with 20:80, and 25:75 by volume. The experimentation was conducted by varying loads at a constant speed (1500rpm). From the investigation it was revealed that both the oils at 20% blend with diesel can be used as a diesel substitute [8]. S. Arunprasad et al. aimed to optimize the engine parameters such as load, blend and compression ratio for highest BTE using taguchi method. Experiments were conducted with Neem oil biodiesel blends and diesel. In his study L9 orthogonal array was chosen for experimentation with three parameters at 3 levels. The BTE for 60% blend (NB60) was 6.5% higher compared to diesel at load of 6kg and CR of 18. The BSFC of biodiesel was 0.14 lesser than diesel value [9]. G. Balaji et al. investigated the effect of varying injection pressure in a direct injection diesel engine fuelled with methyl ester of Neem oil. The experiments were conducted for injection pressure 200,220, 240 and 260 bar. From the experimentation it was observed that the BTE and NOx were increased by 2.06% and 1.96% respectively with increase of IP upto 240 bar. The emissions such as CO, CO_2, HC and smoke intensity were reduced with increase of injection pressure (IP) [10].

Goutam Pohit et al. investigated the Engine performances and emission characteristics for Karanja biodiesel. A Taguchi method in combination of grey relational analysis was used to identify the optimum process response through a limited number of experiment runs. Load, blend and compression ratio was identified as the input parameters with 5 levels. L25 orthogonal array using taguchi was been selected for the experimentation. Performance characteristics of the engine, like brake power (BP), BSFC, BTE and emission characteristics of the engine, like carbon monoxide CO, carbon dioxide (CO_2), oxygen (O_2), nitrogen oxides (NO_X) and hydrocarbons (HC) are been identified as the output parameters. The effect of Karanja oil methyl ester diesel fuel blends on performance of engine is investigated. From investigation it was concluded that B50 is most suitable for diesel engine without significantly affecting the engine performance and emission characteristics corresponding to compression ratio of 17 and load of 80% [11].

The objective of the present paper is to optimize the engine performance parameters using Gray-Taguchi Relational Analysis for Neem biodiesel as alternative fuel.

To achieve the objectives, the research is conducted in a methodological way as described in below steps.

- Conversion of Neem oil into biodiesel using two step process

- Evaluation of fuel properties of prepared Neem biodiesel blends [NB5, NB10, NB15 and NB20].

- Evaluation of performance, and emission using Taguchi and multi response optimization.

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II. Conversion Of Neem Oil Into Biodiesel Using Two Step Process

The two step transesterification (catalytic method) is used to convert raw Neem oil into biodiesel. Before starting with the process of conversion, the fatty acid profile was determined using gas chromatography and the % of free fatty acid (FFA) is evaluated using titration process. If the FFA percentage is more than 4 percent, a two step conversion process is used to convert raw oil into biodiesel, which includes both esterification and transesterfication. Esterification is a process in which acid reacts with alcohol to form esters. Where as in transesterification process the exchanging of the organic group R″ of an ester with the organic group R' of an alcohol in presence of base catalyst such as NaOH or KOH [12,15,16].

The three liters laboratory size reactor is designed and fabricated in house and is used for processing the oils into mono alkyl esters. The procedure for trasesterification process is as follows.

Measure 3 liter of Neem oil and transfer into the reactor. The stirrer connected to motor is switched on and a constant 800 RPM is maintained. Hot water from geyser is made to circulate in the rector to maintain constant temperature of 60˚C in the oil. Methanol of 900 ml and NaOH of 30g is stirred well in a separate flask. The prepared methoxide mixture is added slowly to the hot oil through the funnel when the oil temperature reaches to 60°C. The oil is processed for 90mins and the mixture is transferred into the separating flask and allowed it to settle. After separation of glycerin and biodiesel, the glycerin layer is removed from the separating flask carefully and biodiesel is collected in a beaker. The collected biodiesel is washed in hot water and dried [13, 14]. The table 1 shows the % of FFA in various stages while processing the Neem oils.

Table 1: FFA percentage of oils at various stage of process

Sample Name	%FFA in Raw Oil	% FFA content after Esterification of Oils	% FFA content after Transesterification of Oils
Neem	5.86	3.05	1.053

The %FFA of raw oil was of 5.86% which was reduced to 3.05% through acidification process in presence of H_2SO_4 as a catalyst. Further the esterified oil was taken for transesterification process to reduce the %FFA to 1.053% in presence of base catalyst KOH.

III. Evaluation of Fuel Properties of Prepared Neem Biodiesel Blends

In this study, the investigation is carried out on the performance and emission analysis of Neem biodiesel. Investigation is performed on the biodiesel blends NB5, NB10, NB15 and NB20 percent to meet the present target proposed by Government of India (GoI).

From the above table 2, its evidenced that the Oleic, Linoleic, Stearic, Palmitic fatty acids takes the major portion in the composition of fatty acid methyl esters for the selected oil sample.

Table 2: Fatty acid composition of Neem oil

Sample Name			Neem oil
Fatty Acid Composition	Myristic Fatty Acid	C14:0	0.39
	Palmitic Fatty Acid	C16:0	18.37
	Stearic Fatty Acid	C18:0	15.94
	Oleic Fatty Acid	C18:1	47
	Linoleic Fatty Acid	C18:2	13.47
	Linolenic Fatty Acid	C18:3	0.21
	Eicosenoic Fatty Acid	C20:1	0.19

The fuel properties such as viscosity, density, flash point, and calorific value are evaluated for the NB100 as per ASTM Standards and are compared with diesel.

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Table 3: Physicochemical properties of NB100

Properties	ASTM Specification of Biodiesel B100		Diesel	NB100
	Standard	Range		
Calorific Value (MJ/Kg)	-	-	45.128	39.484
Flash point ˚C	ASTM D93	>110	55	230
Density (Kg/m3)	-	860-900	820	860
Kinematic viscosity @ 40˚C (Cst)	ASTM D445	1.9-6.0	2.21	4.38

From the table 3 it is observed that NB100 has less calorific value and higher values of flash point, density and kinematic viscosity compared to diesel. NB100 has 12.5% lower calorific value, 4.6% higher density and 49.5% rise in Kinematic viscosity compared to petroleum diesel.

The blends of Neem biodiesels are prepared by mixing NB100 with neat diesel in B5, B10, B15 and B20 Percent V/V and their physicochemical properties are evaluated using ASTM standards. From the table 4 its evidence that the calorific value of the blends decreases with increase in blend percentage, whereas flash point, density and kinematic viscosity increases proportionally.

Table 4: Physicochemical properties of NB5, NB10, NB15 and NB20

Fuel properties	Calorific Value MJ/Kg	Flash point °C	Density Kg/m^3	Kinematic viscosity @ 40˚C cSt
Diesel	45.13	55	820	2.21
NB05	44.84	68	822	2.25
NB10	44.53	72	823	2.39
NB15	44.19	80	825	2.51
NB20	44.01	88	827	2.62

IV. Experimental Setup

The experimental setup of single cylinder, CRDI VCR engine is as shown fig. 1. The egine has bore dia of 87.5 mm^2, stroke length if of 110mm, power of 3.5KW, rated speed of 1500 RPM and compression ratio of 17:1. It consists of various sensors for measuring parameters such as cylinder pressure, crack angle, airflow, fuel flow, temperature and load. The output signals of the sensors interface with computer through data acquisition device for collecting the required data. Some of the parameters such as injection pressure (IP) Injection Time (IT) etc. controlling the performance of the engine can be varied using programmable open ECU at different compression ratio. The performance study includes Brake Power (BP), Indicated Power (IP), Frictional Power (FP), Brake Mean Effective Pressure (BMEP), Indicated Mean Effective Pressure (IMEP), BTE, Mechanical Efficiency, Volumetric Efficiency, BSFC, Air fuel ratio, heat balance and combustion analysis of CRDI engine is evaluated using various sensors integrated within the engine. The engine exhaust (CO, UHC, and NOx) was analyzed by AVL DIG AS 444 gas analyzer fitted with. The standard or default value of CR, IP and IT specified by the engine manufacturer are 17.5, 600 bar and 23 ˚ bTDC.

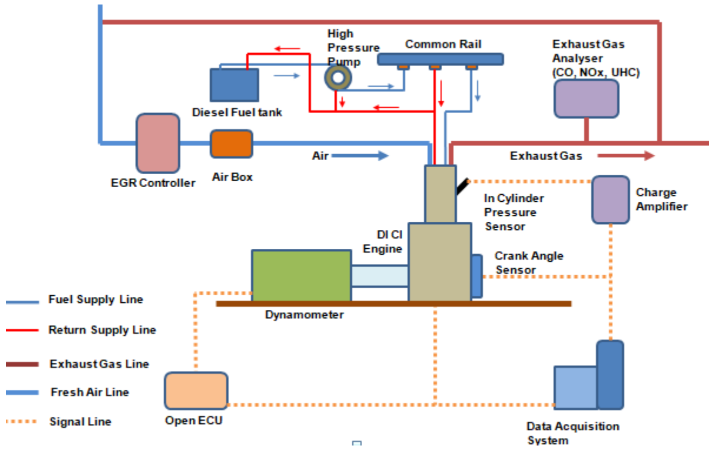

Fig 1: Schematic diagram of experimental setup for CRDI Diesel engine

The experimental setup of single cylinder is supplied with best quality instruments for measuring the variables. The following components listed in the table 5 are integrated with setup for collecting the data through high speed data acquisition device

Table 5: List of components for data acquisition

Components	Make
Programmable ECU	Nirai7rSweden
In cylinder pressure sensor	PCB Piezotronics, USA
Crankangle decoder	Kubler, Germany
Fuel flow transmitter	Yokogawa, Japan
Pressure transmitter	Wika, Germany
High speed data acquisition device	National instruments, USA
Load sensor	VPG Sensotronics
Temperature sensor	Radix

V. Performance and Emission Analysis Of Neem Biodiesel

The design of an experiment with Grey-Taguchi method is used to perform multi response optimization and analyze engine performance. The steps are as follows:

1. Selection of input variables with appropriate level settings
3. Identifying appropriate orthogonal array
4. Assigning the input variables to each column
5. Conducting the experiments according to DoE
6. Analyzing the data using Grey relation analysis for multi-response optimization
7. Perform variance analysis
8. Conducting the confirmation test for optimum level
9. Inference

To evaluate optimum condition for maximizing the performance and minimizing the emissions of Neem biodiesel in CRDI engine, four major input parameters are identified viz.. Blend Percentage (A), IP (B), IT (C) and load (D). The independent parameters and their respective levels are as defined in the table 6. Each parameter has 4 levels within their limits.

Table 6: Design factors and their levels

Sl. No	Symbol	Parameters	Level-1	Level-2	Level-3	Level-4
1	A	Blend percentage	5	10	15	20
2	B	Injection pressure (bar)	420	480	540	600
3	C	Injection timing (˚bTDC)	19	21	23	25
4	D	Load (kg)	3	6	9	12

The performance and emission parameters such as BSFC, BTE, CO, NOx and UHC are selected to be the output responses. Since there are four input parameters with four levels, a large number of experiments had to be conducted to cover entire combination. To minimize the number of experiments and experimentation time a systematic approach Design of Experiments (DoE) is used.

The minimum number of experiments to be conducted based on the input parameters and their level is calculated using following formula

N_{exp} = 1+ NP (L – 1)

N_{exp} = Number of experiments to be conducted

NP = Number of parameters = 4

L = Number of levels = 4

Hence, N_{exp} = 1+ 4 (4-1) = 13 (preferred L16 array)

Therefore an L16 orthogonal array is selected to perform experimentation systematically (Table 7). Taguchi method is more suitable to single performance characteristics optimization. Since the present study intended for multiple performance characteristics with conflicting goals, Grey-Taguchi method is used for multiple response optimization. Grey relation analysis is used to find the multiple response optimizations and S/N ratios are used to find the significance of independent variables on output responses.

Table 7: L16 Orthogonal array for experimentation

Trial No	Input parameters			
	Blend percentage	Injection Pressure	Injection Time	Load
1	5	420	19	3
2	5	480	21	6
3	5	540	23	9
4	5	600	25	12
5	10	420	21	9
6	10	480	19	12
7	10	540	25	3
8	10	600	23	6
9	15	420	23	12
10	15	480	25	9
11	15	540	19	6
12	15	600	21	3
13	20	420	25	6
14	20	480	23	3
15	20	540	21	12
16	20	600	19	9

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Experiments are conducted as per the experimental layout defined and response values for BTE, BSFC, NOx, CO, and UHC are collected as in table 8. The experimental results are normalized in the range between zero to one and average GRG is evaluated to perform multiple variable optimizations[11]. From the collected response values, gray analysis is performed to predict the optimum level of operating parameters. The average Grey relational grades that represent the multiple objectives as a single objective are obtained and given in Table 9. The optimal combination is determined using the higher the better characteristic using Minitab14 for avg. GRG value.

Table 8: Experimental results of engine performances and emissions

SFC	BTE	CO	NOx	HC
0.63	12.76	0.022	487	9
0.40	20.03	0.025	613	7
0.34	23.13	0.047	686	9
0.35	22.72	0.121	489	8
0.34	23.16	0.095	395	11
0.32	24.93	0.206	266	9
0.62	12.78	0.024	617	6
0.40	19.99	0.025	767	4
0.34	23.75	0.165	163	5
0.36	21.94	0.046	445	1
0.43	18.37	0.018	326	5
0.67	11.90	0.017	438	5
0.43	18.65	0.013	465	5
0.62	12.97	0.015	415	5
0.35	23.10	0.104	263	5
0.37	21.65	0.042	296	5

From the response table 8 it is evidenced that the BTE NOx, and CO increasing significantly with increase in load, whereas SFC decreases with increase in load. The maximum BTE of 24.93 % at full load condition is observed for parameters viz., NB10, IP of 480 bar and IT of 19˚bTDC.

However, increasing the load will lead to decrease in ignition delay and help in complete combustion which may contribute to better performance of the engine. At the same time, the higher engine loads direct to high level of emissions such as HC, CO, and NO. Hence, the engine loads are chosen in all intervals (25%, 50%, 75%, and 100%) [11,17]. From the above Gray relation grade analysis trial no 10, that is A3B2C4D3 level have been selected as an optimum condition for CRDI engine fueled with Neem biodiesel.

Analysis of Variance for S/N ratios is used to find the effect of noise factors on the responses and also to identify the controllable factors. The input variables with highest S/N ratio will determine the optimum quality with the least variance. Fig 2 shows the variation of S/N ratio for each input parameters and their significance level shifting from one level to another. The difference between extremes of S/N values for each parameter is calculated. A greater difference shows that the parameter has a more influence on the output response. It is also essential to understand the percentage contribution of these individual variables on the response variables. Taguchi analysis is performed on the average GRG value to find the individual contribution of independent variables on the overall performance of the engine. S/N ratio mean plot (fig. 2) signifies that blend percentage of NB15, IP 480 bar, IT 23˚ bTDC and load of 9kg (A3B2C3D3) have the peak points indicating as optimum condition for maximizing the avg. GRG value .

Based on the variance analysis, it is evident that the blend percentage is the most influencing parameter offering 57.10% influence on the desired response for using Neem biodiesel as fuel in CRDI engine. The second most influencing parameter is load with 32.79% of contribution. Whereas IT has least significance with 1.15% influence on the overall performance of CRDI engine. The detailed ANOVA table with percentage contribution of involved parameters is shown in Table 10. The levels indicated from Taguchi mean of S/N ratio is a level untouched in grey relation analysis, hence a confirmation test is conducted for level indicated from S/N ratio mean plot.

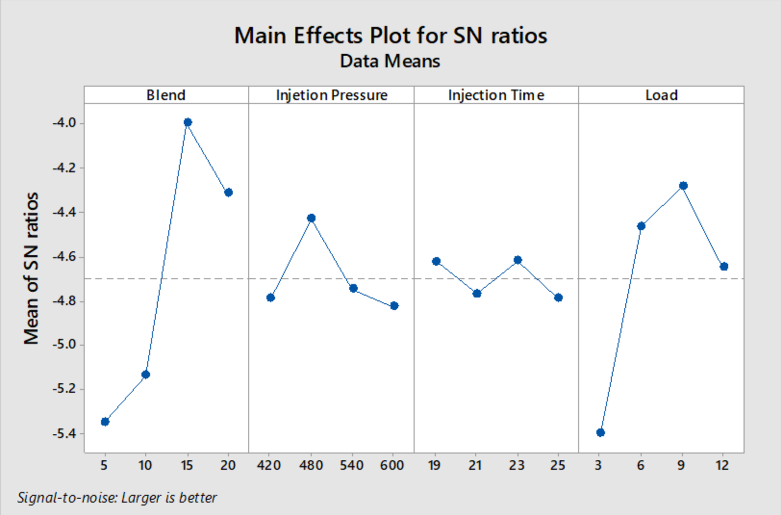

Fig 2: Mean effect plot for S/N Ratio

Table 9: Grey relational coefficients and Grey grades of L16 experimental results

Normalizing					Grey Relation Coefficient					Avg GRG	Rank
BSFC	BTE	CO	NOx	UHC	BSFC	BTE	CO	NOx	UHC		
0.114	0.934	0.953	0.464	0.200	0.886	0.708	0.047	0.536	0.800	0.511	15
0.771	0.376	0.938	0.255	0.400	0.229	0.713	0.062	0.745	0.600	0.569	10
0.943	0.138	0.824	0.134	0.200	0.057	0.629	0.176	0.866	0.800	0.566	12
0.914	0.170	0.440	0.460	0.300	0.086	0.866	0.560	0.540	0.700	0.518	14
0.943	0.136	0.575	0.616	0.000	0.057	0.619	0.425	0.384	1.000	0.557	13
1.000	0.000	0.000	0.829	0.200	0.000	0.693	1.000	0.171	0.800	0.577	8
0.143	0.932	0.943	0.248	0.500	0.857	0.931	0.057	0.752	0.500	0.503	16
0.771	0.379	0.938	0.000	0.700	0.229	0.842	0.062	1.000	0.300	0.581	7
0.943	0.091	0.212	1.000	0.600	0.057	1.000	0.788	0.000	0.400	0.635	4
0.886	0.229	0.829	0.533	1.000	0.114	0.757	0.171	0.467	0.000	0.695	1
0.686	0.503	0.974	0.730	0.600	0.314	0.718	0.026	0.270	0.400	0.636	2
0.000	1.000	0.979	0.545	0.600	1.000	0.584	0.021	0.455	0.400	0.567	11
0.686	0.482	1.000	0.500	0.600	0.314	0.822	0.000	0.500	0.400	0.610	6
0.143	0.918	0.990	0.583	0.600	0.857	0.733	0.010	0.417	0.400	0.571	9
0.914	0.140	0.528	0.834	0.600	0.086	0.668	0.472	0.166	0.400	0.621	5
0.857	0.252	0.850	0.780	0.600	0.143	0.812	0.150	0.220	0.400	0.636	3

Table 10: Analysis of Variance for the Input Parameters

Factors	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Blend percentage	3	5.0390	5.039	1.67965	12.73	0.033	57.10
Injection Pressure	3	0.3960	0.396	0.132	1.00	0.500	4.49
Injection Time	3	0.1011	0.1011	0.03368	0.26	0.854	1.15
Load	3	2.8939	2.8939	0.96464	7.31	0.068	32.79
Residual Error	3	0.3957	0.3957	0.13191			4.48
Total	15	8.8256					

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Table 11: Confirmation test at optimum level-A3B2C3D3 identified from mean plot of S/N ratio

Factors	Level	Response variables value					Avg. GRG value
		BSFC	BTE	CO	NOx	UHC	
Blend percentage	A3	0.34	22.45	0.045	375	3	0.727
Injection Pressure	B2						
Injection Time	C3						
Load	D3						

Confirmation test

From S/N ratio mean plot the level A3B2C3D3 is identified as the optimum condition for maximizing the avg. GRG value using higher the better characteristic. The indicated level is untouched in the defined L16 orthogonal array. A confirmation test through experimentation is performed at optimum combination A3B2C3D3 and response results are tabulated as shown in above table 11. The avg. GRG value is evaluated for the responses and is compared with A3B2C4D3 level. The avg. GRG value is of 0.727 for the optimum level identified through mean S/N plot which is 4.60% higher than the previously identified level. The rise in avg. GRG value indicates the improvement in the overall performance of CRDI engine fueled with Neem biodiesel with blend percentage of NB15, IP 480 bar, IT 23˚ bTDC and load of 9kg.

VI. Conclusion

In this study, attempt was made to optimize multiple responses the CRDI engine fueled with Neem biodiesel blends. The response parameters viz. SFC, BTE, NOx, CO and UHC are been optimized by varying the combinations of input parameters such as Blend Percentage, IP, IT and Load at four levels. To cover the entire combination of input parameters a large number of experiments had to conduct. To minimize the number of experiments and experimentation time a systematic approach Design of Experiments (DoE) using Taguchi method is adapted. An L16 orthogonal array is selected to perform experimentation systematically. Subsequently, grey relation analysis is used to convert the multiresponse problem into a single one to obtain the optimum combinations of selected input parameters. S/N ratio mean plot signifies that blend percentage of NB15, IP 480 bar, IT 23˚ bTDC and load of 9kg (A3B2C3D3) as the optimum combination corresponding to minimum emission and better performance of CRDI engine.

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