IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 15, Issue 3 Ver. I (May. - June. 2018), PP 88-96
www.iosrjournals.org

Experimental Investigation on the Performance of the Diesel Engine using different biodiesel blends of the Castor oil

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Abstract: *In this decade, fossil fuel consumption has increased with increase in proportionate industrial growth which consequently increased the vehicle density throughout the world. The emphasis is laid down by many researchers to seek the best alternative fuel resources especially from indigenous renewable feed stocks to meet the current requirement of the fuel demand and to compensate drastic depletion of the fuel reserves. Through many researches made till date biodiesel has proved as a reliable and promising alternate fuel. This paper investigates the effect of Castor biodiesel blends blended with fuel additives like Ethanol and Di Ethyl Ether on the Diesel engine performance. It also deals with the optimization of the BTE and* NO_x *emission using the input parameters like compression ratio, cooling water flow rate and loading. The experiments have been designed using DOE in Minitab 17 and Taguchi's L9 array is employed for forming orthogonal array. ANOVA analysis is used for identifying the contribution of various factor which significantly affects the response followed by Regression analysis to validate the results at optimum set of selected control factors .This study showed the reduction in NOx and improved BTE for Castor biodiesel blended with additives and closely follows the performance given by the diesel as a fuel under same set of parameter levels.*

Keywords*: Taguchi, DOE, ANOVA, Di ethyl ether, Castor, Regression*

Date of Submission: 03-05-2018 Date of acceptance: 18-05-2018

I. Introduction

As in this decade more emphasis is laid down on seeking the best possible alternative fuels to compensate the demands of energy as well as to replace the fossil fuel, biodiesel has been the frequently discussed topic among the researches made till date . In this hour of need when the world is suffering from the problems related to fossil fuel reserves depletion, attempts are being made to adapt the alternative source of fuel which is more reliable and meeting the goals of the era, leading to sustain growth rate , reduction in pollution, meeting stringent pollution norms and regulation laid down by the pollution control boards worldwide. biodiesel has been developed as an alternative fuel for C.I. engine but it shows slightly lower performance ,causes reduction in SO_x , CO, HC, CO_2 emissions as compared with diesel. But due to higher oxygen contain in biodiesel the formation of NOx was observed higher. Additive blended fuels have shown better improvement in combustion performance and emission characteristics of CI engine. The blending of biodiesel increases the thermal efficiency near to that of diesel and also significantly large reduction in NO_x is observed. Literature studied[6] previously showed that the Ethanol and Di Ethyl ether as an additives in biodiesel caused improved performance as well as causes reduction in emission.

J. Jayprabakar et.al[1] carried out an investigation on performance of the direct injection four stroke, vertical, single cylinder, air cooled,4kW diesel engine running at constant speed of 1500 rpm using neem biodiesel bleneded with DEE on volume basis, showed significant reduction in HC, CO, CO_2 , NO_x emission when blended with Neem biodiesel in 10% and 20% by volume and offered better emission performance as compared to neat biodiesel. T. K. Kannan et al.[2] carried the test on diesel engine in which an oxygenated additive diethyl ether (DEE) was blended with biodiesel in the ratios of 5%, 10%, 15% and 20% ,the results concluded smoke opacity and NOx emission were found to be reduced by 14.63% of and 15% respectively for 20% DEE blends at full load which was the highest reduction among the blends also BTE was found to be 29.9% which was 5% higher than that of biodiesel . D.D. Nagdeote [3] performed the tests on single cylinder, four stroke D.I engine of capacity 3.7kW running at constant speed of 1500 rpm using Mahua biodiesel blended with additives like Ethanol and Di Ethyl Ether to form different blends ,the result revealed BSFC for the biodiesel-diesel blended with DEE(BDET) found to be reduced as compared to biodiesel blended with the Ethanol(BDE) and Ethanol blend had almost same consumption as B20 blend .Both BDE and BDET reduced the emission significantly in which highest smoke reduction was offered by BDET as compared to BDE and B20. Highest reduction in NO_X was observed for BDET while it was slightly increased in case of BDE and

B20. P. Shanmughasundaram [4] performed the test on variable compression ratio, single cylinder D.I diesel engine using palm biodiesel and parameters like compression ratio(C.R),injection pressure(I.P) and blend % was optimized for the evaluating the emission performance in terms of HC, NO_x and CO emission. Taguchi and ANOVA was used for arriving at contributing parameter causing significant reduction in emission. confirmation test were performed at optimized parameter levels which confirmed the model with error ±4% and from the Taguchi results, it was found that the optimum parameters levels were CR (20:1), Bio fuel blend (20%) and IP (180 bar) in reducing the emission of CO and HC. ANOVA provided CR ratio as most influencing factor for reduction in CO,HC and NO_X emission followed by IP and blend%. CO and HC emission reduced while NO_X emission increased with increase in CR and IP.HC and CO emission were found to be decreased by 33.33% and 50% respectively for B20 blend at optimum factor levels as compared to diesel.

II. Material And Methods

Evaluation of the properties of the Castor biodiesel and blends preparation

The Castor biodiesel obtained from two stage trans-esterification process was tested for some important physico-chemical properties are given in table 1.

Table 1. Properties of fuels

Sr.No	Properties	Castor Biodiesel	Diesel
1	Density at 27C (g/cm^2)	0.932	0.85
2	Kinematic Viscosity at 27 ^{0}C in cSt	15	3
3	Calorific Value kJ/kg	39510	44800
4	Flash point in ^{0}C	133	68
5	Cetane Number	47.2	47

Three different blends are prepared by blending 15%biodiesel + 15% ethanol +70% diesel, 20%biodiesel + 10% ethanol +70% diesel, 25%biodiesel + 15% ethanol +70% diesel to form namely B15E15D70, B20E10D70, B25DEE10D65 each taken on volume basis. These blends were allowed to mix thoroughly in a blender for 1 hour followed by sonication in a lab to ensure the consistency of the blend throughout the blend volume.

Experimental set up

In present study, investigation was carried out on single cylinder, four stroke, water cooled, 3.7 kW variable compression ratio engine running at 1500 rpm rated speed. Figure1.shows the set up of DAQ assisted computerized variable compression ratio engine. The specification of the engine are presented in table 2.The engine was tested using diesel and Castor biodiesel blends(B15, B20, B25) different compression ratio (16.5,15.5,14.5), cooling water flow rate (400, 450, 500) LPH and loading (20%, 40%, 60%) of full load respectively. Each test carried out on the engine for 10 minutes and performance parameters BTE and NO_X as a emission parameter is evaluated at optimum levels of parameters, emission data were recorded in CUBIC analyzer.

Figure.1 Computerized VCR Diesel engine test rig

Table 2. Specifications of Computerized VCR Diesel engine test rig

Sr.No	Description	Specification
1	No. of cylinders	Single cylinder
2	Stroke	four
3	Rated power	3.7 kW
4	CR	16.5:1 (Variable)
5	RPM	1500
6	Loading	Eddy current dynamometer
7	Temperature sensor	RTD, PT - 100
8	Cooling	Water cooled

Design of experiments by Taguchi method

Taguchi method is one of the simplest and effective approaches for parameter design and experimental planning method which explores the concept of quadratic quality loss function. The value of this loss function is further transformed into signal-to-noise (S/N) ratio and thus uses a statistical measure of performance called signal-to-noise (S/N) ratio, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value i.e. standard deviation (S.D.).Thus SN ratio is the ratio of the mean (Signal) to the standard deviation (Noise). There are three types of S/N ratio depending on type of characteristics the lower-the-better, the higher-the-better, and the nominal-the-better. Based on the signal-to-noise (S/N) analysis, the signal-to-noise (S/N) ratio for each level of process parameters are computed and larger S/N ratio corresponds to better performance characteristics, regardless of their category. In Taguchi's parameter design, following steps are followed.

1. Selection of quality characteristics
2. Selection of noise factors and control factors
3. Selection of the orthogonal array
4. Determination of the optimum levels of factor combination by analysis
5. Prediction of performance at optimum levels
6. Confirmation of the design

III. Experimentation

ANOVA & Taguchi analysis

In this study the optimum performance of the Diesel engine is evaluated in terms of Brake Thermal Efficiency and NOx emission , BTE and NO_X were chosen as response parameters, as maximum BTE and minimum NO_x emission is desirable and hence quality characteristic larger is better is selected for BTE while smaller is better is selected for NO_X emission.SN ratio for the selected quality characteristics are expressed in the form mathematical equation (1) and (2) as

$$\frac{S}{N} = -10\log_{10}\left[\frac{1}{n}\sum_i {y_i}^2\right]$$

Eq (1)

$$\frac{S}{N} = -10\log_{10}\left[\frac{1}{n}\sum_i \frac{1}{{y_i}^2}\right]$$

Eq (2)

where, n is number of observations and y is observed data

In the present investigation, the experiments were designed using Taguchi's L9(3^3) orthogonal array. Here (3^3) implies 3 factors and 3 levels of selected factors. Selected factors and their corresponding levels taken into consideration are presented in table 3.Taguchi's L9 array using the different factor and levels selected earlier is used for building the orthogonal array or the test matrix and thus the experiments so designed were carried out by following the experiments as shown in table 4.

Results of SN ratio

Performance test were carried out using L9 array according to the designed experiments in Minitab 17 and the corresponding values of SN ratio obtained for the BTE and NO_X emission are tabulated and shown in table.5 .As stated earlier, higher SN ratio corresponds to best performance of the engine in terms of observed parameter values

Hence, the highest value of SN ratio for BTE represents maximum BTE while that for NO_x emission represents minimum NO_x emission , preferably obtained at corresponding level of control factor. From main effect plots for SN ratio for BTE and NO_X emission as shown in figures 2,3,4 and figures 5,6,7 respectively, the optimum levels of parameters for B15, B20 and B25 for BTE were found to be (16.5CR, 400CWFR, 60% Load), (16.5CR, 450CWFR, 60% Load), (16.5CR, 450CWFR, 60% Load) while Optimum levels of parameters for NO_X emission were found to be (14.5CR, 450CWFR, 20% Load) for all the three blends.

Table 3. Control factors and levels

Factors	Levels		
	1	2	3
Compression Ratio	16.5	15.5	14.5
Cooling water flow rate in LPH	400	450	500
Loading (in % of full load)	20	40	60

Table.4 Orthogonal array (Test Matrix)

Expt.No	CR	CWFR	LOAD
1	16.5	400	20
2	16.5	450	40
3	16.5	500	60
4	15.5	400	40
5	15.5	450	60
6	15.5	500	20
7	14.5	400	60
8	14.5	450	20
9	14.5	500	40

Table.5 Measured values and SN ratios for BTE and NO_x emission

Expt.No	BTE							NO_x Emission						
	Measured values				SN Ratio			Measured values				SN Ratio		
	B15	B20	B25	D100	B15	B20	B25	B15	B20	D100	B25	B15	B20	B25
1	8.3	26.1	31.7	29.1	18.3816	28.3328	30.0212	109	106	80	102	-40.749	-40.506	-40.172
2	14.9	31.1	38.7	32.4	23.4637	29.8552	31.7542	148	129	114	111	-43.405	-42.212	-40.906
3	21	32	42.3	34.9	26.4444	30.103	32.5268	224	194	158	161	-47.005	-45.756	-44.137
4	15.2	16.3	14.4	15.1	23.6369	24.2438	23.1672	147	128	129	113	-43.346	-42.144	-41.062
5	20.1	23.9	21.1	28.7	26.0639	27.568	26.4856	203	177	173	148	-46.15	-44.959	-43.405
6	7.5	14.2	13.6	10.6	17.5012	23.0458	22.6708	106	99	107	87	-40.506	-39.913	-38.79
7	16.4	10	10.2	12.4	24.2969	20	20.172	207	183	164	139	-46.319	-45.249	-42.86
8	7	5	6.9	7	16.902	13.9794	16.777	81	77	96	72	-38.17	-37.73	-37.147
9	11.5	6.8	7	9.8	21.214	16.6502	16.902	142	116	125	103	-43.046	-41.289	-40.257

Table6. Response tables for SN ratio for BTE using different blends

Level	B25DEE105D65			B20E10D70			B15E15D70		
	CR	CWFR	LOAD	CR	CWFR	LOAD	CR	CWFR	LOAD
1	20.8	22.11	17.59	17.95	24.45	23.16	16.88	24.19	21.79
2	22.4	22.14	22.77	24.11	25.01	23.94	24.95	23.8	23.58
3	22.76	21.72	25.6	31.43	24.03	26.39	29.43	23.27	25.89
Delta	1.96	0.42	8.01	13.48	0.97	3.24	12.55	0.93	4.1
Rank	2	3	1	1	3	2	1	3	2

Table7. Response table for SN ratio for NO_X emission using different blends

Level	B25DEE105D65			B20E10D70			B15E15D70		
	CR	**CWFR**	**LOAD**	**CR**	**CWFR**	**LOAD**	**CR**	**CWFR**	**LOAD**
1	-40.09	-41.36	-38.7	-41.42	-42.63	-39.38	-42.51	-43.5	-39.81
2	-41.09	-40.49	-40.74	-42.34	-41.63	-41.88	-43.33	-42.6	-43.27
3	-41.74	-41.06	-43.47	-42.82	-42.32	-45.32	-43.72	-43.5	-46.49
Delta	1.65	0.88	4.76	1.4	1	5.94	1.21	0.94	6.68
Rank	2	3	1	2	3	1	2	3	1

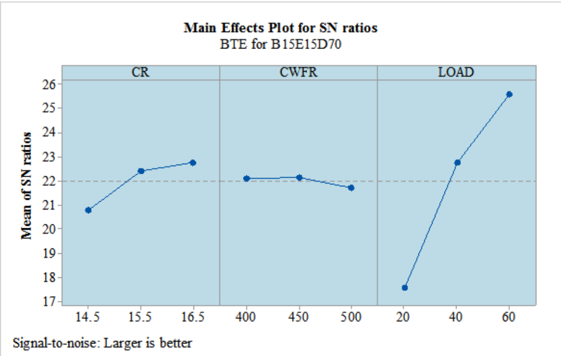

Figure.2 Main effect plots for SN ratio for BTE using B15 blend

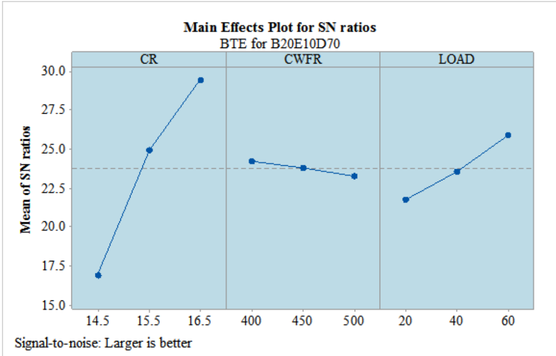

Figure.3 Main effect plots for SN ratio for BTE using B20 blend

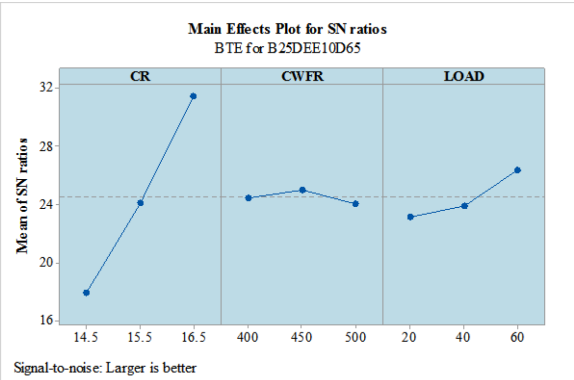

Figure.4 Main effect plots for SN ratio for BTE using B25 blend blend

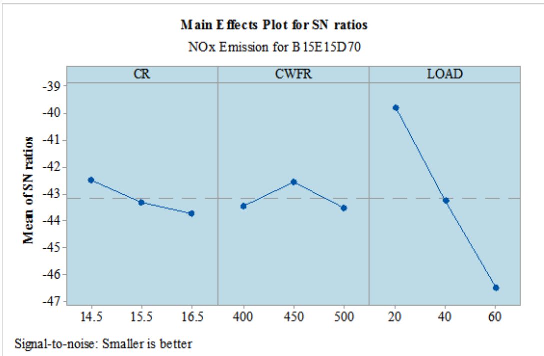

Figure.5 Main effect plots for SN ratio for NO_X using B15

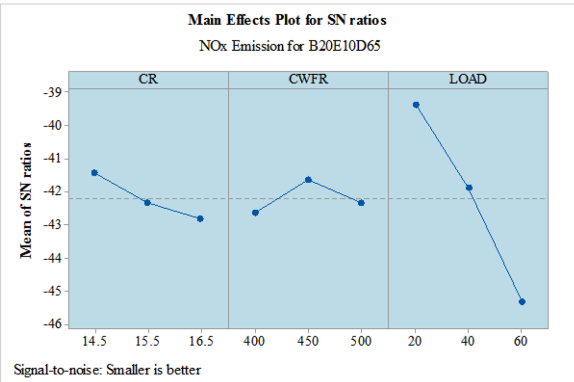

Figure.6 Main effect plots for SN ratio for NO_X using B20 blend

Figure.7 Main effect plots for SN ratio for NO_X using B25 blend

Results of ANOVA

In order to find out the statistically significant parameters which has highest effect the response and consequently on the engine performance, analysis of variance is employed. ANOVA also helps to find out percentage contribution of each parameter in the response variation. In the ANOVA there is P value for each independent parameter. When this P value is less than 0.05 i.e ($P < 0.05$), the parameter is said to be statistically highly significant. Table 8. shows the ANOVA for SN ratio using different blends. For B15, B20, B25 blends the major contributing factors which affects the BTE were found to be (CR 93.4%, CR 88.67%, Load 93.05%) followed by (Load 5.85%, Load 9.27%, CR 6.13%) and (CWFR 0.48%, 0.47%, 0.3%) for the respective blends. It was found that the BTE of the engine increases with increase in CR and Load while the least effect of CWFR was observed on the BTE. The BTE of B25 & B20 blend was increased from 10.2% to 42.3% & 10% to 32% when the CR was increased from 14.5 to 16.5 at 60% of full load.BTE of B15 blend was found to be increased from 7% at 14.5 CR and 20% of full load to 21% at 16.5 CR and 60% of full load. This can be attributed to the fact that better atomization of fuel at higher CRs and Loads leading to better combustion. This infers the small volume of Di Ethyl Ether as an additive with Castor biodiesel might have caused smooth combustion, better atomization and spray formation due to improved viscosity and density of the overall blend. For B15, B20, B25 blends the major contributing factors causing the NO_x emission were found to be (Load 91.22%, 93.67%, 85.58%) followed by (CR 5.2%, 3.19%, 10.34%) and (CWFR 2.68%, 2.37%, 2.98%) for the respective blends. It was found that the NO_x emission of the engine decreases with decrease in CR and Load while the least effect of CWFR was observed on the NO_x emission reduction. The NO_x emission of B25 & B20 blend was decreased from 102 ppm to 72 ppm & 106 to 77 ppm when the CR was decreased from 16.5 to 14.5 at 20% of full load. NO_x emission of B15 blend was found to be increased from 7% at 14.5 CR and 20% of full load to 21% at 16.5 CR and 60% of full load. This can be attributed to the fact that better atomization of fuel at higher CRs and Loads leading to better combustion. This infers the small volume of Di Ethyl Ether as an additive with Castor biodiesel might have caused smooth combustion, better atomization and spray formation due to improved viscosity and density of the overall blend. This can be attributed to the fact that poor atomization of fuel and lower combustion chamber temperature at lower CRs and Loads leading to incomplete combustion. On the other hand B15E15D70 blend attributed the NO_x emission of 81 ppm at 14.5 CR and at 20% of full load whereas at 16.5CR it was 109 ppm. This shows marginally smaller improvement in NO_x for B20 and B15 blend as compared to B25 blend, perhaps due to increase in the percentage of Ethanol in the blend combined with Castor biodiesel on volume basis might have increased the oxygen content of the overall blend . As ethanol posses higher oxygen content as compared to di-ethyl ether leading to yield higher combustion chamber temperature and lower ignition delay causing complete combustion resulting in increased NO_x emission even at lower CR and lower loading.

From main effects plot for SN ratio, the optimum levels of factors for BTE and NO_x emission were found out and at this optimum level of factors the SN ratio predicted by the Taguchi in Minitab are presented in the table 9.

IV. Validation of results

Multiple linear Regression Model

For the validation of the results obtained, multiple linear regression model is used to form the mathematical model in which SN ratio of the response variables BTE , NO_x emission for each blend is expressed linearly in terms of control factors (CR, CWFR, Load) . The value of SN ratio of response variable is expressed at optimum values of control factor using multiple linear regression model formed in Minitab 17. The obtained value of SN ratio of response at optimum control factor level for a particular blend corresponds to Actual value of SN ratio. This actual value of SN ratio was compared with the SN ratio predicted earlier using Taguchi in Minitab 17 at optimum level of control factors and finally the percentage error for each compared value is computed and presented in table.9

Table 8. Analysis of variance for SN ratio using different blends

Blends	Factors	BTE				NO_x Emission			
		DF	F-Value	P-Value	%C	DF	F-Value	P-Value	%C
B15	CR	2	12.04	0.077	6.13	2	5.84	0.146	5.2
	CWFR	2	0.61	0.622	0.3	2	3.01	0.249	2.68
	Load	2	182.66	0.005	93.05	2	102.4	0.01	91.22
	Error	2				2			
	Total	8			100	8			100
Summary		S	R-sq	R-sq	R-sq	S	R-sq	R-sq	R-sq

				(adj)	**(pred)**			**(adj)**	**(pred)**
		0.5203	99.49%	97.96%	89.68%	0.5286	99.22%	96.88%	84.18%
B20	CR	2	56.19	0.017	88.67	2	4.09	0.197	3.19
	CWFR	2	0.3	0.769	0.47	2	3.04	0.248	2.37
	Load	2	5.88	0.145	9.27	2	119.9	0.008	93.67
	Error	2				2			
	Total	8			100	8			100
Summary		**S**	**R-sq**	**R-sq (adj)**	**R-sq (pred)**	**S**	**R-sq**	**R-sq (adj)**	**R-sq (pred)**
		1.4701	98.42%	93.69%	68.04%	0.5103	99.11%	96.44%	81.96%
B25	CR	2	361.27	0.003	93.4	2	9.58	0.094	10.34
	CWFR	2	1.89	0.347	0.48	2	2.76	0.266	2.98
	Load	2	22.63	0.042	5.85	2	79.25	0.012	85.58
	Error	2				2			
	Total	8			100	8			100
Summary		**S**	**R-sq**	**R-sq (adj)**	**R-sq (pred)**	**S**	**R-sq**	**R-sq (adj)**	**R-sq (pred)**
		0.6151	99.74%	98.97%	94.76%	0.465	98.92%	95.68%	78.13%

Table9.Prediction of SN ratio at optimum factor levels

Blend	**BTE**				**NO_x Emission**			
	Optimum factor level			**Predicted value**	**Optimum factor level**			**Predicted value**
	CR	**CFWR**	**Load**		**CR**	**CFWR**	**Load**	
B15	16.5	450	60	26.5294	14.5	450	20	-38.5178
B20	16.5	400	60	32.066	14.5	450	20	-38.0485
B25	16.5	450	60	33.8397	14.5	450	20	-37.3357

The values of optimum parameters when substituted as shown in the regression equations for BTE are given by equations 3,4,5 for B25, B20, B15 blends respectively as follows

Regression equation for B25DEE10D65 blend
SNRA actual = -81.35 + 6.742 CR - 0.00420 CWFR + 0.0810 Load
Eq (3)
SNRA actual = -81.35 + 6.742 (16.5) - 0.00420 (450) + 0.0810 (60)
SNRA actual = 32.863
Regression equation for B20B10D70 blend
SNRA actual = -73.5 + 6.277 CR - 0.0093 CWFR + 0.1026 Load
Eq (4)
SNRA actual = -73.5 + 6.277(16.5) - 0.0093(400) + 0.1026 (60)
SNRA actual = 32.50
Regression equation for B15E15D70 blend
SNRA actual = 0.53 + 0.979 CR - 0.00385 CWFR + 0.2002 Load
Eq (5)
SNRA actual = 0.53 + 0.979 (16.5) - 0.00385 (450) + 0.2002 (60)

Regression equations for NO_x emission are given by equations 6,7,8 for B25, B20, B15 blends respectively as follows
Regression equation for B25DEE10D65 blend
SNRA actual = -24.78 - 0.825 A + 0.00303 B - 0.1191 C
Eq (6)
SNRA actual = -24.78 - 0.825(14.5)+ 0.00303 (450) - 0.1191 (20)
SNRA actual = -37.761
Regression equation for B20B10D70 blend

SNRA actual = -26.80 - 0.701 CR + 0.00314 CWFR - 0.1485 LOAD
Eq (7)
SNRA actual = -26.80 - 0.701(14.5) + 0.00314(450) - 0.1485(20)
SNRA actual = -38.52
Regression equation for B15E15D70 blend
SNRA actual = -26.93 - 0.604 CR - 0.00048 CWFR - 0.1671 LOAD
Eq (8)
SNRA actual = -26.93 - 0.604 CR - 0.00048 CWFR - 0.1671 LOAD
SNRA actual = -39.24

The comparison between the predicted and actual values of SN ratio for different blends to calculate the resulting percentage error are given table.9

Table 9. Error for SN ratio for BTE and NO_x using different blends

Sr. No	Response Variable	Blend	SNRA Predicted	SNRA Actual	% Error
1	BTE	B15E15D70	26.52	26.96	0.0165
2		B20E10D70	32	32.5	0.0156
3		B25DEE105D65	33.83	32.86	0.0286
4	NO_x Emission	B15E15D70	-38.51	-39.24	0.018
5		B20E10D70	-38.52	-38.04	0.0124
6		B25DEE105D65	-37.33	-37.76	0.0115

V. Conclusion

Taguchi method provides the optimal setting of the engine for the set of control factors taken into consideration and tends to offer better engine performance in terms of BTE and NO_x emission. The results of the present investigation using additive blended Castor biodiesel blends and corresponding optimal setting are summarized as:

i. Di Ethyl Ether and Ethanol when blended with biodiesel offered better kinematic viscosity, density and reduced flash and fire points which promotes fine atomization and spray formation and increases oxygen content of the blends.

ii. Among the three factors studied during investigation, it was found that CR and Loading has a significant effect on the selected quality characteristics for the response parameter.

iii. For BTE, the optimum level of parameters found to be 60% load 16.5 CR and 450 CWFR for all the three blends. CR and load were found to be most influencing and contributing factors and corresponds to higher Brake Thermal Efficiencies

iv. For NOx emission, optimum level of parameters found to be 20% load 14.5 CR and 400 CWFR for all the three blends. CR and load were found to influencing the and contributing factors and corresponds to Lowest NOx emission values.

v. BTE for all the three blends was found to be higher at higher compression ratios and at higher loads. The best results were obtained for the B25 biodiesel blend at 16.5CR and at 60% load of the full load. The results were found well comparable and even better under similar set of conditions as compared to diesel provided both in the studied literature and the obtained results.CR and load were found to be contributing factors for best results of BTE. B25 biodiesel blend at 16.5CR and at 60% load of the full load offered slightly higher BTE than that of the diesel while for other blends BTE was slightly lower.

vi. NOx emissions were reduced with decrease in CR as well as load. The NOx emission of B25 & B20 decreased from 102 ppm to 72 ppm & 106 to 77 ppm and that for B15 was decreased from 109 to 81 ppm when CR and load decreased from 16.5 CR to 14.5 CR at 20% load. B25 offered the lowest emission that was found to be comparable but slightly higher than the diesel as a fuel under same operating conditions studied in the literature and obtained results.

vii. The predictions made by Taguchi parameter design technique found to be in good agreement with the confirmed results.

viii. Regression analysis validated all the results predicted within specified range of limits.

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