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To Study the Influence of Injection Timing, Injector Opening Pressure and Blend Percentage on Engine Performance and Emissions by the Integration of Taguchi and RSM for an Engine Fuelled with CAOME

Varun Kumar Reddy N[1*], Y. Sujatha[2], Arun Kumar G L[3] and Gurushanth B Vaggar[4]

[1]*Assistant Professor, School of Mechanical Engineering, REVA University, Bengaluru 560064, Karnataka, India.*
[*]*E-mail: varunreddy107@gmail.com*
[2]*Professor, Department of Mechanical Engineering, B V C Engineering College, Allavaram 533210, Andhra Pradesh, India. E-mail: ysujathareddy340@gmail.com*
[3]*Assistant Professor, Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Bengaluru 560064, Karnataka, India. E-mail: arunglmech@gmail.com*
[4]*Sr. Assistant Professor, Department of Mechanical Engineering, Alva's Institute of Engineering and Technology, Moodbidri 574225, Karnataka, India. E-mail: gvgr.aiet@gmail.com*

Abstract

Carbon neutral fuels must have a control over global warming. Even through passenger vehicle can be replaced with electrical and hybrid vehicles, but it is extremely difficult to replace goods transport vehicles which uses hydrocarbon fuels. Biofuels are one that can be obtained from various feedstock's including grains and green matter with high starch and sugar content such as corn, sugar cane and sugar beets. The castor oil methyl esters, which is non-edible in nature fulfils the requirement of fuel for internal combustion engine. The conventional experimental scheme needs more time for optimization and substantial number of experiments need to perform as it is possible to vary a single operating variable at a time and is expensive. Mathematical models of Taguchi method using design of experiments (DOE) give superior results. By using DOE, Taguchi L9 orthogonal array is considered. Analysis of variance (ANOVA), The Regression Equation and signal-to-noise (S/N) ratio are obtained to predict the best parameters and to evaluate the influence of significant conditions on performance, emission and combustion characteristics. The mathematical model obtained by integration of Taguchi method and RSM is successfully validated with accuracy of 95%.

Keywords: *Taguchi, Performance, S/N ratio, ANOVA, Biodiesel*

1.0 Introduction

The nations growth mainly rests on the available energy reserves. With ongoing upsurge in energy utilization, severe pollution rules and exhaustion of fossil fuels resulted in massive outlay in energy division to satisfy the necessity and to find eco-friendly energy resources. Research on biofuels is considered to get enhanced engine output with minimum greenhouse gas emissions.

Energy sustainability plays a major role in overall progress of the nation in terms of industrial development, economic stability and well-being of the society. As of now the energy needs of the society are majorly fulfilled by using fossil fuels

[*]*Corresponding Author*

and the utilization of fossil fuels are increasing at a quicker pace [1, 2, 3]. To fulfil the energy demand majority of the countries are spending ample amount from the budget to import crude, which in turn adversely affecting on the economy [3] and even some countries have gone bankrupt [4]. Research towards invention and enhancement of energy resources using locally available material resources have got a great potential.

The fuels that can be synthesised by using green matter has got great potential in the current market to fulfil the energy needs [5]. Fuels obtained from green matter need to undergo extensive experimentation to certified to be used as fuel in internal combustion engines. The traditional investigational structure needs ample amount of time for optimization and large number of experiments need to perform, since a single parameter can only be varied in each trail. Traditional investigational structure is expensive, and it does not result in interactive result among the selected variables. The amalgamation of mathematical models of Taguchi technique and Response Surface Model (RSM) using design of experiments (DOE) deliver results of high precision, minimizes cost of testing and also gives interactive correlations [6].

The Taguchi technique has a constraint in which it can consider only linear effects, it does not study quadratic equation and interaction effects. By using Taguchi design, L9 orthogonal array is considered and mathematical models are obtained for output parameters using RSM comprising linear, quadratic and interaction terms. The functional relation among responses and independent variables is articulated similar to equation 1.

$$A = f(B_1, B_2, B_3, \ldots \ldots B_n) \quad \ldots (1)$$

Where, f is response function, A is the response and B_1, B_2, B_3, ... B_n are the independent variables.

Analysis of variance (ANOVA), regression equation and signal-to-noise (S/N) ratio are found to estimate optimal parameters and to evaluate the influence of significant conditions on performance, emission and combustion characteristics.

2.0 Materials and Methods

Experimentations are conducted on 4 stroke single cylinder engine fitted with re-entrant toroidal combustion chamber at injector opening pressure of 240 bar, injection timing of 27°BTDC and furnished with nozzle having 6 holes each of 0.1 mm diameter, the performance and emission characteristics are evaluated.

Castor oil was procured from the local industry, biodiesel is synthesised by using transesterification method and the properties of the same are evaluated as per ASTM standards [7] and mentioned in Table 1. The line diagram of engine test set up is shown in Figure 1 and the engine specifications are mentioned in Table 2.

Castor Oil Methyl Esters

Raw castor oil comprises 80 to 90% of hydroxyl fatty acid, ricinoleic acid and about10% of non-hydroxylated fatty acids, mostly oleic and linoleic acids. Such an unusual composition has put limitation on biodiesel production and

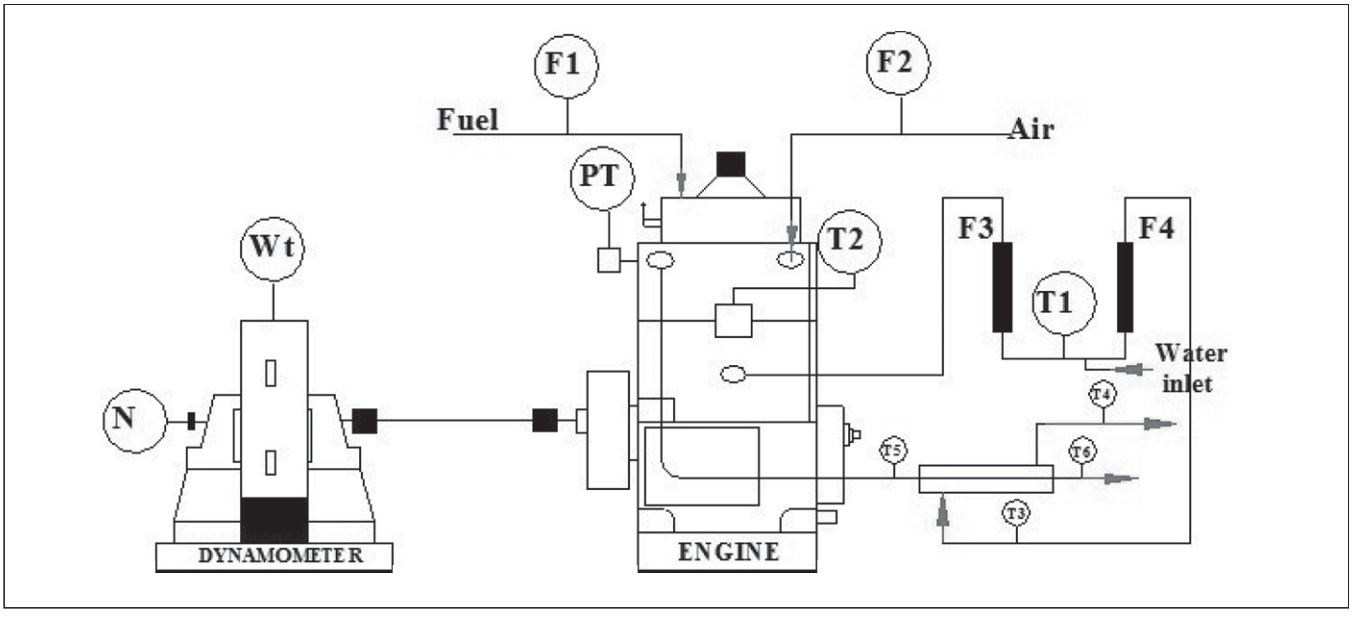

Figure 1: Schematic line diagram of engine test setup

Table 1: Properties of Fuels

Fuel	Density (kg/m^3)	Viscosity (cSt)	Calorific value (CV) (kJ/kg)	Specific gravity	Flash point (ºC)
Raw Castor Oil	956	52	29323	0.956	320
Diesel	834	2.38	42250	0.834	60
CAOME Biofuel	927	5.57	37730	0.927	189

Table 2: Engine specifications of tested engine

Parameters	Specifications
Engine type	TV1 (Kirloskar make)
Software used	Engine soft
Injector operating pressure	200 to 225 bar
Static injection time	23ºBTDC
Governor type Mechanical	Centrifugal type
No of cylinders	Single cylinder
No of strokes	4 stroke
Fuel oil	High Speed Diesel
Rated power	5.2 kW at 1500 rpm
Cylinder diameter (Bore)	0.0875 m
Stroke length	0.11 m
Ratio of compression	17.5:1

its viscosity quite higher compared to vegetable oils [8]. To overcome this disadvantage, castor oil biodiesel is blended with petro diesel to achieved biofuel standards [7]. Castor oil has excellent cold flow properties due to its high content of unsaturated fatty acid and its high solubility in alcohol makes it easier to convert it to biodiesel even at low temperature [9, 10].

3.0 Experimental Results and Discussion

The parameters and chosen levels are presented in Table 3 and layout of the experimental for the current study is represented in Table 4. Each trial of the experiment is

Table 3: Parameters and Chosen Levels

Level Parameter	Level 1	Level 2	Level 3
IT (°CA)	23	27	31
IOP (Bar)	220	240	260
BLEND (%)	10	20	30

Table 4: Layout of the Experiment

IT (°CA)	IOP (Bar)	BLEND (%)
23	220	10
23	240	20
23	260	30
27	220	20
27	240	30
27	260	10
31	220	30
31	240	10
31	260	20

simulated five times, the averaged values are taken as the response and are presented in Table 5. These investigational results are used to obtain the mathematical model using the Taguchi method and RSM from MINITAB software.

4.0 Analysis of Variance (ANOVA)

ANOVA is performed to identify the significant parameters on BTE, emissions such as SO, HC, CO, NO_x and combustion parameters namely PP, ID, CD. Table 6 to 13 mentioned below provides the contribution of each parameter on the output. For reliable statistical analyses, error values must be smaller than 20% [11].

BTE

The Table 6 represents the ANOVA results with contribution of each parameter. It is observed that for BTE of the engine which is highly influenced by IOP (36.263%) followed by blend percentage (30.859%) and IT (27.243%).

Smoke Opacity

ANOVA mentioned in Table 7 shows that smoke emissions of the engine is influenced by both IOP and blend in equal proportions which accounts for 34.507% followed by IT, which accounts for 30.082%.

Table 5: Response values

BTE%	SO HSU	HC ppm	CO ppm	NO_x ppm	PP Bar	ID°CA	CD°CA
26.64	53	43	0.151	1056	64	10.52	48
28.54	48	38	0.141	1080	71	9.97	40
27.37	51	42	0.147	1066	66	10.37	45
28.32	48	38	0.141	1078	70	9.99	41
29.45	47	37	0.134	1088	72	9.95	39
27.56	50	40	0.144	1066	68	10.14	43
26.85	52	42	0.146	1072	65	10.42	46
27.48	50	40	0.144	1069	67	10.24	44
28.22	49	39	0.142	1074	69	10.06	42

Table 6: ANOVA and fitting results for BTE

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
IT	2	1.7174	0.8587	4.83	0.171	27.243
IOP	2	2.2860	1.1430	6.43	0.135	36.263
BLEND	2	1.9454	0.9727	5.48	0.154	30.859
Error	2	0.3553	0.1776			5.636
Total	8	6.3040				100

Table 7: ANOVA and fitting results for Smoke opacity

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
IT	2	9.5556	4.7778	43.00	0.023	30.282
IOP	2	10.8889	5.4444	49.00	0.020	34.507
BLEND	2	10.8889	5.4444	49.00	0.020	34.507
Error	2	0.2222	0.1111			0.7041
Total	8	31.5556				100

HC Emission

ANOVA mentioned in Table 8 shows that HC emissions from the engine are equally influenced by all the three parameters with equal contribution of 33.121% i.e., IT, IOP and blend.

CO Emission

ANOVA mentioned in Table 9 shows that CO emissions from the engine is highly influenced by IT followed by IOP percentage and blend. The most influencing parameter is IT, which accounts for 38.12%.

NO_x Emission

ANOVA mentioned in Table 10 shows that NO_x emissions from the engine is highly influenced by blend followed by IOP percentage and IT. Blend percentage has a profound influence on engine cylinder temperature hence it is a significant parameter for NO_x emissions, which accounts for 46.19%.

Peak Pressure

ANOVA shows that peak pressure in the engine cylinder is highly influenced by IOP and blend percentage compared to IT. Peak pressure in the engine cylinder is a function of combustion temperature. The ANOVA for peak pressure in cylinder is mentioned in Table 11.

Table 8: ANOVA and fitting results for HC emissions

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
IT	2	11.5556	5.7778	52.00	0.019	33.121
IOP	2	11.5556	5.7778	52.00	0.019	33.121
BLEND	2	11.5556	5.7778	52.00	0.019	33.121
Error	2	0.2222	0.1111			0.7041
Total	8	34.8889				100

Table 9 ANOVA and fitting results for CO emissions

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
IT	2	0.000069	0.000034	14.71	0.064	38.12
IOP	2	0.000065	0.000032	13.86	0.067	35.91
BLEND	2	0.000042	0.000021	9.00	0.100	23.2
Error	2	0.000005	0.000002			2.76
Total	8	0.000181				100

Table 10: ANOVA and fitting results for NOx emissions

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
IT	2	150.889	75.444	27.16	0.036	21.652
IOP	2	213.556	106.778	38.44	0.025	30.644
BLEND	2	326.889	163.444	58.84	0.017	46.91
Error	2	5.556	2.778			0.7972
Total	8	696.889				100

Table 11: ANOVA and fitting results for PP

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
IT	2	18.0000	9.0000	27.00	0.036	30
IOP	2	20.6667	10.3333	31.00	0.031	34.444
BLEND	2	20.6667	10.3333	31.00	0.031	34.444
Error	2	0.6667	0.3333			1.11
Total	8	60.0000				100

Ignition delay

Diesel fuel displays higher ignition delay [12], hence percentage of biofuel in the blend has a profound influence on ignition delay and the same is obtained from ANOVA as well. The percentage influence of blend on ignition delay is 40.486% and ANOVA for ID is shown in Table 12

Combustion Duration

The combustion duration of the fuel is influenced by both IOP and blend in equal proportions which accounts for 35.161%. ANOVA for CD is shown in Table 13.

Table 12: ANOVA and fitting results for ID

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
IT	2	0.115289	0.057644	105.88	0.009	31.863
IOP	2	0.098956	0.049478	90.88	0.011	27.3493
BLEND	2	0.146489	0.073244	134.53	0.007	40.486
Error	2	0.001089	0.000544			0.301
Total	8	0.361822				100

Table 13 ANOVA and fitting results for CD

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
IT	2	20.2222	10.1111	91.00	0.011	29.355
IOP	2	24.2222	12.1111	109.00	0.009	35.161
BLEND	2	24.2222	12.1111	109.00	0.009	35.161
Error	2	0.2222	0.1111			0.323
Total	8	68.8889				100

5.0 Regression Equation

To assess the non-linearity effect, three levels are considered for independent variables. A second order mathematical model using RSM is developed with IT, IOP, BLEND and is expressed in the form of equation 2 [13].

$$A = \beta_0 + \beta_1 (IT) + \beta_2 (IOP) + \beta_3 (BLEND) + \beta_{11} (IT^2) + \beta_{22} (IOP^2) + \beta_{33} (BLEND^2) + \beta_{12} (IT, IOP) + \beta_{13} (IT, BLEND) \quad ... (2)$$

Where, Y - Output, B_0, B_1, B_2, ... B_{13} are regression coefficients.

RSM based mathematical equations are obtained from regression analysis to find (predict) BTE, SO, HC, CO, NO_X, PP, ID and CD are mentioned in the form of equations 3 to 10. These equations can be used to predict the output parameters by substituting the values of IT, IOP and blend percentage values in the range.

$$BTE = -120.9 + 1.804 \times IT + 1.008 \times IOP + 0.3353 \times BLEND - 0.05792 \times IT^2 - 0.002400 \times IOP^2 - 0.005750 \times BLEND^2 + 0.005667 \times IT \times IOP - 0.001833 \times IT \times BLEND \quad ... (3)$$

$$SO = 424.3 - 6.521 \times IT - 2.304\ I \times OP - 1.092 \times BLEND + 0.1354 \times IT^2 + 0.005000 \times IOP^2 + 0.02000 \times BLEND^2 - 0.004167 \times IT \times IOP + 0.008333 \times IT \times BLEND \quad ... (4)$$

$$HC = 466.6 - 6.958 \times IT - 2.704 \times IOP - 0.9167 \times BLEND + 0.1458 \times IT^2 + 0.005833 \times IOP^2 + 0.02167 \times BLEND^2 - 0.004167 \times IT \times IOP + 0.000000 \times IT \times BLEND \quad ... (5)$$

$$CO = 1.123 - 0.01469 \times IT - 0.006400 \times IOP - 0.000975 \times BLEND + 0.000344 \times IT^2 + 0.000014 \times IOP^2 + 0.000023 \times BLEND^2 - 0.000017 \times IT \times IOP - 0.000008 \times IT \times BLEND \quad ... (6)$$

$$NO_x = -920.0 + 26.15 \times IT + 13.44 \times IOP + 2.592 \times BLEND - 0.4896 \times IT^2 - 0.02792 \times IOP^2 - 0.07833 \times BLEND^2 + 0.000000 \times IT \times IOP + 0.04167 \times IT \times BLEND \quad ... (7)$$

$$PP = -510.2 + 8.958 \times IT + 3.729 \times IOP + 0.9917 \times BLEND - 0.1875 \times IT^2 - 0.007917 \times IOP^2 - 0.02833 \times BLEND^2 + 0.004167 \times IT \times IOP + 0.008333 \times IT \times BLEND \quad ... (8)$$

$$ID = 52.32 - 0.7929 \times IT - 0.2536 \times IOP - 0.09358 \times BLEND + 0.01479 \times IT^2 + 0.000521 \times IOP^2 + 0.002667 \times BLEND^2 - 0.000000 \times IT \times IOP - 0.000583 \times IT \times BLEND \quad ... (9)$$

$$CD = 683.9 - 10.56 \times IT - 4.050 \times IOP - 1.125 \times BLEND + 0.1979 \times IT^2 + 0.008333 \times IOP^2 + 0.03167 \times BLEND^2 - 0.000000 \times IT \times IOP - 0.008333 \times IT \times BLEND \quad ... (10)$$

S/N Curve

S/N ratios are expressed on a decibel scale and are found from the quadratic (quality) loss function for each experiment. The word 'signal' specifies the mean value and the word 'noise' specify the variance value (undesirable) for the output response of the process. This method is used to find the controllable aspects that decrease the effect of the uncontrollable (noise) aspects on the response [14]. Main effect plot for S/N for all output parameters are shown in Figure 2 to Figure 9.

Advanced IT by 4°CA, from manufacturer specified IT of 23°BTDC, improvement in combustion occurs as a significant portion of injected fuel burns in premixed mode and further increase in IT leads to drop in BTE and also increased fuel combustion for a specified power output.

Best results in terms of peak BTE and minimum emissions are obtained for a blend B20 at an IT of 27°BTDC and 240 IOP, but resulted in increased NO_x emissions.

BTE

The most influencing parameter level for response variable BTE are IT 27°BTDC, IOP 240 bar and B20, with these parameter levels maximum thermal efficiency can be achieved and same is illustrated in Figure 2. For these optimized operating parameters, better fuel atomization is achieved, which enhances BTE.

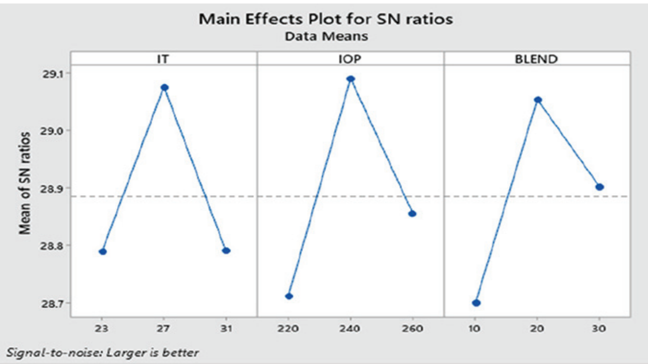

Figure 2: Main effect plot for S/N of BTE

Smoke opacity

The most influencing parameter level for response variable smoke opacity are IT 27°BTDC, IOP 240 bar and B20, with these parameter levels minimum smoke opacity is achieved and same is illustrated in Figure 3.

HC emissions

The most influencing parameter level for response variable HC emissions are IT 27°BTDC, IOP 240 bar and B20, with these parameter levels minimum HC emissions is achieved and same is illustrated in Figure 4. For these optimized operating parameters, increased combustion efficiency result in decrease in HC emissions.

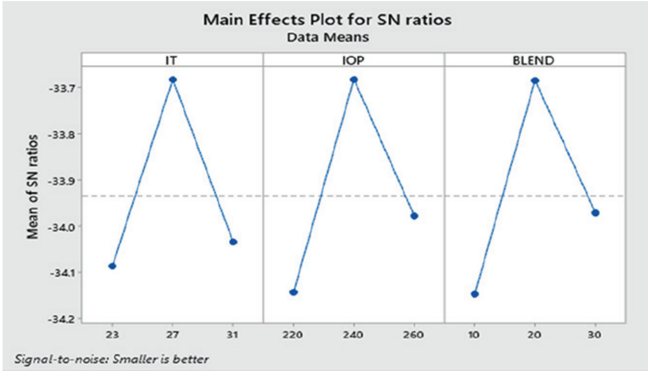

Figure 3: Main effect plot for S/N of Smoke opacity

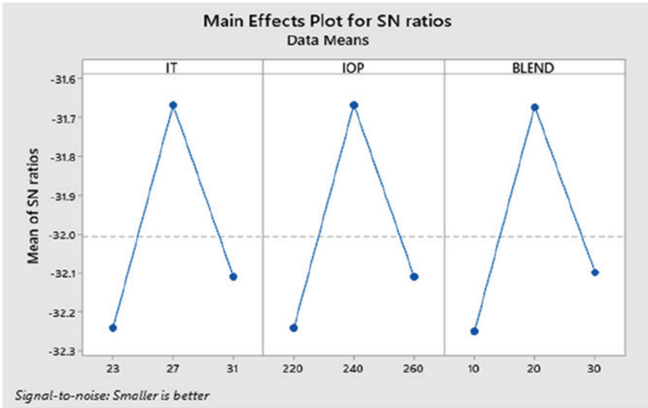

Figure 4: Main effect plot for S/N of HC emissions

CO emissions

The most influencing parameter level for response variable CO emissions are IT 27°BTDC, IOP 240 bar and B20, with these parameter levels minimum CO emissions is achieved and same is illustrated in Figure 5. For these optimized operating parameters, increased combustion efficiency result in decrease in CO emissions.

NO_x Emission

The most influencing parameter level for response variable NO_x emissions are IT 27°BTDC, IOP 240 bar and B20. The increased in cylinder temperature leads to rise in NO_x emissions for these optimized operating parameters and is shown in Figure 6.

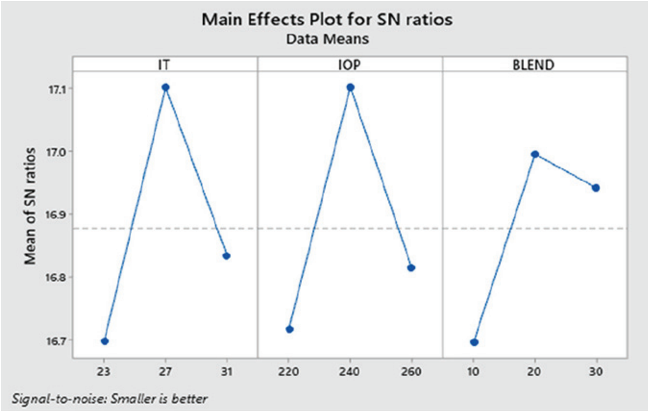

Figure 5: Main effect plot for S/N of CO emissions

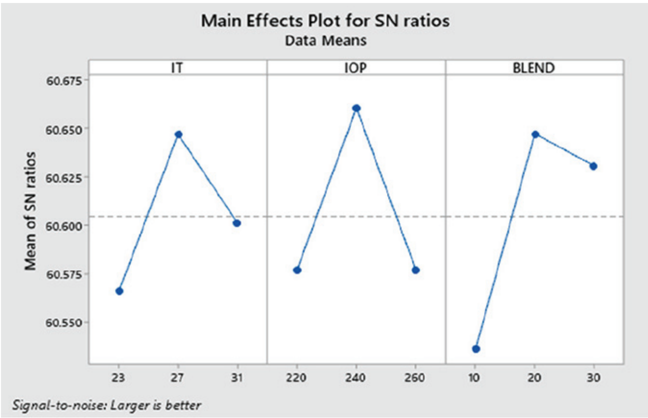

Figure 6: Main effect plot for S/N of NO_x emissions

Peak Pressure

Increased BTE, at optimized values of 27°BTDC, IOP 240 bar and B20, lead to rise in peak pressure, low combustion duration and less ignition delay, the same is illustrated in Figures 7, 8 and 9 respectively.

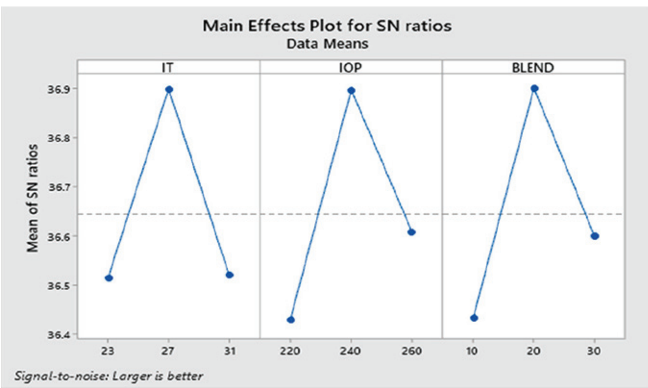

Figure 7: Main effect plot for S/N of Peak Pressure

Ignition delay

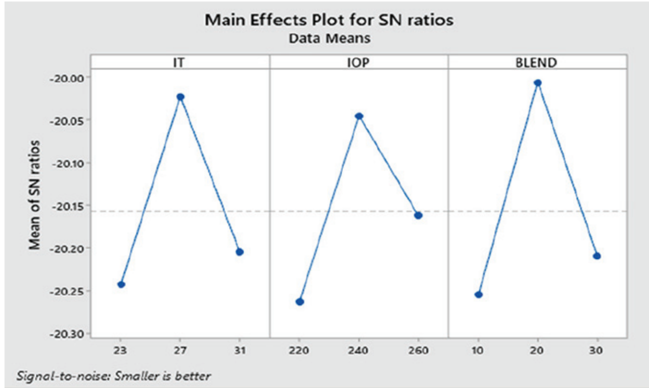

Figure 8: Main effect plot for S/N of Ignition delay

Combustion Duration

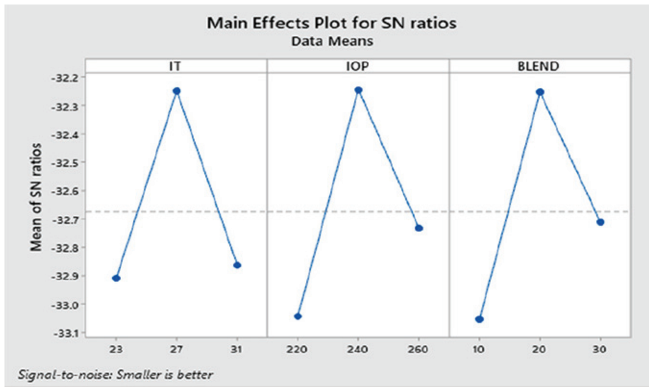

Figure 9: Main effect plot for S/N of Combustion duration

Confirmation test

The confirmation test is conducted for a CAOME B20 at optimized engine parameters, to validate the results obtained

Table 14: Confirmation test for B20 (CAOME) blend, IT 27°BTDC and 240 bar IOP

Parameter	Experimental value	Predicted value	Error (%)
BTE (%)	29.62	29.403	0.733
SO (HSU)	46	45.64	0.783
HC (ppm)	34	35.375	4.044
CO (%)	0.12	0.12276	2.253
NOx (ppm)	1094	1089.549	0.407
PP (bar)	73	73.933	1.278
ID (°CA)	9.9	9.7196	1.82
CD (°CA)	37	36.698	0.816

from the mathematical (Regression) model. The experimental results and predicted values from empirical model are as shown in Table 14. The results obtained from the experiment and the regression value predicts an average percentage of error, which is acceptable and more significant with a minimal error [15].

Conclusions

1. S/N curve predicted best results in terms of peak BTE and minimum emissions for a blend B20 at an IT of 27°BTDC and 240 IOP with minimum emission of CO, HC and SO but resulted in increased NO_x emissions.
2. The mathematical model obtained by integration of Taguchi method and RSM is successfully validated with accuracy of 95%.

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